CGIAR Challenge Program on
WATER & FOOD
Andes • Ganges • Limpopo • Mekong • Nile • Volta

Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices

CONFERENCE PROCEEDINGS

E. Humphreys, T.P. Tuong, M.C. Buisson, I. Pukinskis, M. Phillips

CGIAR RESEARCH PROGRAM ON Water, Land and Ecosystems

CGIAR Research Program on Rice Global Rice Science Partnership

Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices

CONFERENCE PROCEEDINGS

E. Humphreys, T.P. Tuong, M.C. Buisson, I. Pukinskis, M. Phillips

May 2015

ISBN

978-984-33-9151-3

Citation

Humphreys, E., T.P. Tuong, M.C. Buisson, I. Pukinskis and M. Phillips. 2015. Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices Conference Proceedings. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF). 600pp.

The Revitalizing the Ganges Coastal Zone conference was organized by the CGIAR Challenge Program on Water and Food's Ganges Basin Development Challenge. The CGIAR Challenge Program on Water and Food (CPWF) was launched in 2002 and concluded in 2013. CPWF aimed to increase the resilience of social and ecological systems through better water management for food production (crops, fisheries and livestock). It did so through an innovative research and development approach that brought together a broad range of scientists, development specialists, policy makers and communities, in six river basins, to address the challenges of food security, poverty and water scarcity. Learn more at waterandfood.org

CPWF was a partner of the CGIAR Research Program on Water, Land and Ecosystems, which combines the resources of 11 CGIAR Centers and numerous international, regional and national partners to provide an integrated approach to natural resource management research. This program is led by the International Water Management Institute (IWMI). Learn more at wle.cgiar.org.

Financial support for the Revitalizing the Ganges Coastal Zone conference was provided by the CGIAR Research Program on Water, Land and Ecosystems and the CGIAR Global Rice Science Partnership.

Front cover photo: A high yielding rice variety in polder 30 on 2 November 2012 that will be ready for harvest by mid-November, in time for timely sowing of a high yielding/high value rabi crop. Photo credit: Liz Humphreys

Back cover photo: A traditional aman variety is planted in Patuakhali on 21 August 2013. Late planting of old (tall) seedlings is due to the high water depth (a result of poor water management, lack of drainage). The crop will not be ready for harvest until late December. Photo credit: Liz Humphreys

Table of Contents

Foreword

The Ganges coastal zone of Bangladesh and West Bengal, India, is characterized by extremes in terms of both challenges and opportunities. Despite the huge investment in the coastal zone over the past 50 years, the poverty of farming families in the region remains extreme.

The CGIAR Challenge Program on Water and Food's conference 'Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices' brought together researchers, extensionists, development partners and policy makers to share plans, progress and ideas for unlocking the production potential of the coastal zone.

The 41 papers in these proceedings provide up-to-date information on current and likely future water resource availability, and opportunities for improving water management, increasing productivity, and improving livelihoods. Specific topics include:

- the current status of coastal zone surface water resources and likely impacts of key drivers of change, such as climate change, sea level rise and construction of the Ganges Barrage
- opportunities for increasing the productivity of available surface and groundwater resources
- current water governance policy and practice at local and Indo-Bangladesh scales, and proposals for improving water management through improved institutional arrangements
- the importance of homestead production systems, their current (low) productivity, and opportunities for improving productivity and livelihoods and empowering women
- opportunities for increasing the productivity of brackish water aquaculture
- opportunities for increasing the productivity, diversity and resilience of rice-based production systems
- outscaling of improved production technologies and extrapolation domains – which improved cropping systems are most suited to which parts of the coastal zone landscape

The information presented in these papers reveals tremendous opportunities to improve food security and livelihoods in the coastal zone through making much better use of existing land and water resources, through use of improved germplasm, management and cropping systems. The entry point to unlocking the potential is improved drainage management, which requires a community approach.

We trust that you will find these proceedings a valuable resource for donors and policy makers involved in the planning and implementation of development projects for the coastal zones of Bangladesh and West Bengal, as well as for researchers, extensionists, teachers and students.

Manoranjan Mondal
IRRI
Chair, Organizing Committee

Pamela George
WorldFish
Secretary, Organizing Committee

Elizabeth Humphreys
IRRI
Chair, Science Program

Conference Summary

The 'Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices' conference was held in Dhaka, Bangladesh from 21-23 October 2014. Hosted by the CGIAR Challenge Program on Water and Food (CPWF), the event brought together researchers, extensionists, developers and policy makers in a forum to share plans, progress and ideas for unlocking the potential of the coastal zone. In total, 224 people attended the event, with most participating for two to three days. The conference was sponsored by the CGIAR Research Program on Water, Land and Ecosystems and the CGIAR Research Program on Rice, known as the Global Rice Science Partnership.

Day 1

The first day of the conference provided an overview of the challenges and opportunities for the coastal zone before delving into a more focused discussion on the policies, plans and development projects that have potential to shape the region. Md. Shahidur Rahman, Director General of the Bangladesh Water Development Board (BWDB), chaired the inaugural session. Dr. Craig Meisner, co-leader of the CPWF Ganges Coordination and Change Project set the scene with an overview of the region. He touched on the many biophysical constraints to production in the coastal zone, which will be exacerbated by climate change, before emphasizing CPWF's motivation for working in the area: the belief that there is an opportunity to make a 'quantum leap' in food production in the coming decades. Dr. Andrew Noble, director of the CGIAR Research Program on Water, Land and Ecosystem (WLE), followed with a presentation on WLE's plans to build upon the work of CPWF beyond 2014, when the CPWF program concluded.

Photo 1. Inaugural session of the 'Revitalizing the Ganges Coastal Zone' conference. From left to right: Dr. Andrew Noble, Director, WLE; Dr. Shelina Afroza, Secretary, Ministry of Fisheries and Livestock; Md. Shahidur Rahman, Director General, Bangladesh Water Development Board; Barrister Anisul Islam Mahmud, MP and Honorable Minister, Ministry of Water Resources; Dr. Zafar Ahmed Khan, Secretary, Ministry of Water Resources; Dr. Craig Meisner, co-leader of CPWF Ganges Basin Development Challenge.

Following these introductory remarks, special guest Dr. Shelina Afroza, Secretary of the Ministry of Fisheries and Livestock, spoke of the Government of Bangladesh's aspirations to become a middle income country by the year 2021. She underscored the need for collaboration between the research, private and government sectors in order to achieve this goal, as well as effective integration across ministries. Conference attendees then heard from special guest Dr. Zafar Ahmed Khan, Secretary of the Ministry of Water Resources who discussed the role of policy in taking science and knowledge and turning it into programs and practice. He also noted the diversity of ministries in attendance and the value of such an integrated approach to addressing development challenges. Chief guest Barrister Anisul Islam Mahmud, MP and Honorable Minister of the Ministry of Water Resources devoted his presentation to discussing the gap that exists between the knowledge and understanding of policy makers and the reality of what is occurring on the ground. This disconnect, he stated, can result in situations where researchers, policy makers and development practitioners are not working in a concerted effort. He noted the value of meetings such as this for providing a space for professionals from different backgrounds to converge and provide useful input to policy makers. The session concluded with a speech from the Chair, Md. Shahidur Rahman, Director General of BWDB, who underscored the importance of integrated water management in the polders.

The next session was titled 'Coastal Zone Development Program: Towards 'Water Smart Communities''. It featured presentations from Government of Bangladesh officials who each provided an overview of their agency's work in the coastal zone. Attendees heard presentations from: Saiful Alam, Water Resources Planning Organization, on the Bangladesh Water Act and Coastal Zone Strategy; Sarafat Hossain Khan, BWDB, on the Coastal Embankment Improvement Project of the World Bank, and Tahmina Begum, Deputy Director of the Department of Agriculture Extension, on the Blue Gold project.

Photo 2. Members of coastal zone communities participate in Day 1 of the conference. Farmer Altaf Boyati from Amtali Upazila of Barguna District is speaking.

Dr. T.P. Tuong, formerly of IRRI, then provided an overview of the main messages that emerged from the CPWF's decade of work in the Ganges coastal zone. The primary message, he stated, is "Water resources in the coastal zone have largely been misconceived and underutilized. In reality, they are a rich and valuable resource to support agricultural and aquacultural production and livelihood improvement of farming families and communities." Representatives from different development programs and donors were then invited to discuss their work and reflect on whether the CPWF's messages reflected their understanding of the region. Presentations were given by Dirk Smits of Blue Gold, Nicholas Syed of IFAD, Mike Robson of FAO, Md. Khaleduzzaman of the Embassy of the Netherlands, and Jaap de Heer of the Bangladesh Delta Plan. The presenters identified many overlaps.

The final session of the first day was titled 'Revitalizing the Ganges Coastal Zone: Influencing Policies and Implementation Strategies'. The session began with a joint presentation on water smart communities from Liz Humphreys (International Rice Research Institute) and Marie-Charlotte Buisson (International Water Management Institute), who each lead one of the five CPWF Ganges projects. They highlighted the changes needed in water management to realize the huge production potential in the polders of the coastal zone. Furthermore, integrated policy implementation will require greater coordination between institutions responsible for water management, food production and dissemination.

The twenty-four representatives of coastal zone communities, including one member of the Parliament were then invited to comment on what they had heard during the day, and their perceptions of the remaining challenges for intensifying production in the coastal zone. The representative agreed that it is possible to grow three rice crops or two rice crops and one rabi crop in parts of the coastal zone, and integrated rice-fish in highly saline areas, but stated that operation of the sluice gates and coordination of community members remained a large challenge. The session concluded with a panel discussion on policies and priorities for future investments to raise the production potential of the coastal zone. Discussions centered around the need to address waterlogging due to siltation in order to improve the lives of those in the coastal zone.

Days 2 and 3

The second and third days of the conference were devoted to oral and poster presentations on coastal zone findings from a large range of research projects conducted by many Bangladesh, Indian and international organizations. Topics covered included: current and future status of coastal zone water resources and biodiversity; improving water governance; homestead production systems—current status, future opportunities; increasing the productivity of brackish water aquaculture; increasing the productivity and diversity of rice-based production systems, and; outscaling production technologies—what will work best where. Presenters were invited to develop their abstracts into full papers, many of which are presented in the following pages.

Reviewers

All papers published in these proceedings were reviewed by at least one independent reviewer, and most papers had two reviewers. We are grateful to the following people for their contributions to the review process.

M.A.R. Akanda	Mac Kirby
M.R. Akhlas	Tim Krupnik
Olivyn Angeles	Ruben Lampayan
Frederic Aubery	Minhaj Mahmud
Randy Barker	M. Mainuddin
Ram Baskoti	M. Maniruzzaman
Jatish Biswas	Archisman Mitra
Marie-Charlotte Buisson	C.V. Mohan
Romy Cabangon	Manoranjan Mondal
Sarah Castine	Venkatesh Moorthy
Camelia Dewan	Andy Nelson
Nepal Dey	Phong Ngo
Willie Erskine	Mike Phillips
Animesh Gain	Ando Radanielson
Don Gaydon	M.A. Rahman
Glenn Gregorio	Abudal Rashid
Andrew Hartly	M.A. Rashid
Chu Thai Hoanh	M.H. Rashid
M.M. Hossain	Sanjida Ritu
Elizabeth Humphreys	Sukanta Sarangi
M.R. Islam	T.P. Tiwari
Abdel Ismail	T.P. Tuong
Fazlul Karim	Sudhir Yadav
Nandish Kenia	Murat Yakubov

Conference Committees

Organizing Committee
Manoranjan Mondal (chair)
Pamela George (secretary)
Mohammad Alamgir
Benoy Barman
Elizabeth Humphreys
Zahirul Haque Khan
Craig Meisner

Science and Editorial Committee
Elizabeth Humphreys (chair)
To Phuc Tuong
Marie-Charlotte Buisson
Manoranjan Mondal
Michael Phillips

Logistics Committee
Nazneen Ahmed
Bijoy Bhusan Debnath
Hamida Lipi Akter
Minam Huq

Communications Committee
Nitasha Nair
Ilse Pukinskis
Mohammad Mahabubur Rahman
Michael Victor

Budget Committee
Pamela George

Section 1

Coastal Water Resources

Present surface water resources of the Ganges coastal zone in Bangladesh

Z.H. Khan[1], F.A. Kamal[1], N.A.A. Khan[1], S.H. Khan[2] and M.S.A. Khan[3]

[1] Institute of Water Modelling, Bangladesh, zhk@iwmbd.org, fal@iwmbd.org, nkh@iwmbd.org
[2] Bangladesh Water Development Board, Bangladesh, sarafat.khan@gmail.com
[3] Bangladesh University of Engineering and Technology, Bangladesh, msalamkhan@iwfm.buet.ac.bd

Abstract

The water resources in the coastal zone of the Ganges delta are vital for crop production, fisheries, ecosystem sustenance and livelihoods. Beyond water's functions in the hydrological cycle, it also has social, economic and environmental values and is essential for enhancing food production and sustainable development. The main objective of the research presented here was to investigate the temporal and spatial variation of salinity and to map freshwater availability in the Ganges coastal zone of Bangladesh. The present conditions of salinity intrusion and availability of fresh water were analyzed based on historical data, detailed monitoring of salinity, water flow and water level, and on numerical modeling. Field measurements show that salinity remains below 2 ppt in the Kazibacha River and Lower Sholmari River at locations adjacent to Polder 30 until February each year. Storage capacity of the canal systems of Polder 30 is sufficient to store adequate fresh water to enable production of (irrigated) boro (dry season rice) on about 25% of the cultivable area. Scarcity of fresh water is acute in Satkhira District. Here, salinity remains above 2 ppt (~3 dS/m) throughout the year and peak salinity is about 20 ppt. Thus the river water is never suitable for irrigation of dry season agricultural crops, however, it is a valuable resource for shrimp cultivation. In contrast to Satkhira, there is abundant fresh water for irrigation in most of Barisal Division throughout the entire year. This area receives a huge volume of fresh water from the Lower Meghna River through the Tentulia, Bishkhali and Burishawar (Payra) rivers. The monthly minimum average flow in the Payra River is about 5400 m3/s during the dry season. The river salinity remains below 1 ppt during the whole year. This implies that there is plenty of water for irrigation for the rabi, kharif-1 and kharif-2 crop seasons. Furthermore, gravity irrigation is feasible during the kharif-1 and kharif-2 seasons as the river level is above the average land level for significant periods of time due to diurnal tidal water level fluctuations of 2 to 3 m. In addition, drainage is feasible as the river level is also below the average land level for significant periods of time. The coastal zone is rich in water resources that could be used to greatly increase the land and water productivity of agriculture and aquaculture in the Ganges coastal zone of Bangladesh.

Key message: There is abundant fresh water for irrigation in much of the Barisal Division of Bangladesh throughout the dry season. Cropping system intensification and land productivity can be increased utilizing the available water.

Keywords: tide, salinity, water availability, salinity modeling, coastal polder, agriculture, aquaculture

1. Introduction

With increasing pressure from population growth and industrialization, it is more important than ever to assess the availability and productivity of water for agriculture and aquaculture systems in Bangladesh. This is especially so in the Ganges coastal zone of Bangladesh since this area is characterized by multiple problems and opportunities. Coastal water resources not only support agriculture, aquaculture and industrial activities but also provide navigation routes and other ecosystems.

The Ganges coastal zone is characterized by a vast network of river systems, an ever-dynamic estuary, and is the drainage path of a huge river basin covering parts of India, Bangladesh, China and Nepal. In the late 1960s and early 1970s, 139 polders were built in the coastal zone of Bangladesh for intensification of agriculture and protection of lives and livelihoods of the coastal communities. A polder is a low-lying land area protected from tidal inundation and salinity intrusion by a peripheral earthen embankment. About 54 polders are located in the Ganges coastal zone.

The salinity front moves seasonally as well as spatially in the coastal area. The seasonal movements of the salinity front are predominantly governed by the variations in freshwater discharge from upstream, tides, coastal currents and mixing processes. Maps presenting the zones of availability of fresh and brackish water could be used to inform the planning and design of agriculture and aquaculture systems. Research on temporal and spatial variation of salinity, and mapping and quantification of the availability of freshwater in the Ganges coastal zone has been limited. There are huge knowledge gaps on the potential for irrigation during the dry season for cropping intensification in the greater Barisal and Khulna Divisions. Therefore the objectives of the present research were to assess the temporal and spatial variation of salinity and to map freshwater availability in the Ganges coastal zone of Bangladesh.

2. Study area

The study area comprises the coastal zone of the Ganges delta in southwest and south-central Bangladesh (Fig. 1). The area is characterized by a vast network of tidal rivers and creeks. There are 56 polders in the region. Three polders were selected for detailed analysis based primarily on salinity, availability of fresh water and cropping systems. These polders are situated in high (polder 3), medium (polder 30) and low (polder 43/2F) salinity zones.

Tides in the Bay of Bengal are semi-diurnal in nature, exhibiting two high waters and two low waters per day. The amplitudes of the two cycles differ slightly. Over a longer term, a fortnightly variation in amplitude between spring and neap tides is also evident, with spring tide amplitude approximately 2.5 to 3 times higher than that of the neap tide. The tidal range is about 1.8 to 3.3 m during spring tide in the dry season in the Pussure Estuary and the tidal effect penetrates more than 150 km upstream during the dry season. The salinity front moves seasonally as well as spatially in the coastal area. These movements are predominantly governed by variations in freshwater discharge, tides, coastal currents and mixing processes. The availability of freshwater for agriculture and domestic use in the coastal area is mainly dependent on upstream river water flows. The main source of freshwater in the Khulna region is the Ganges River and freshwater flows through the Gorai River to this region. Salinity starts to increase from December with the decrease in upstream fresh water flow in the medium saline zone i.e. in the Rupsha, Kazibacha and Pussur river systems. The main source of freshwater in the Barisal Region is the Lower-Meghna River and salinity in most of Barisal Region remains low throughout the year.

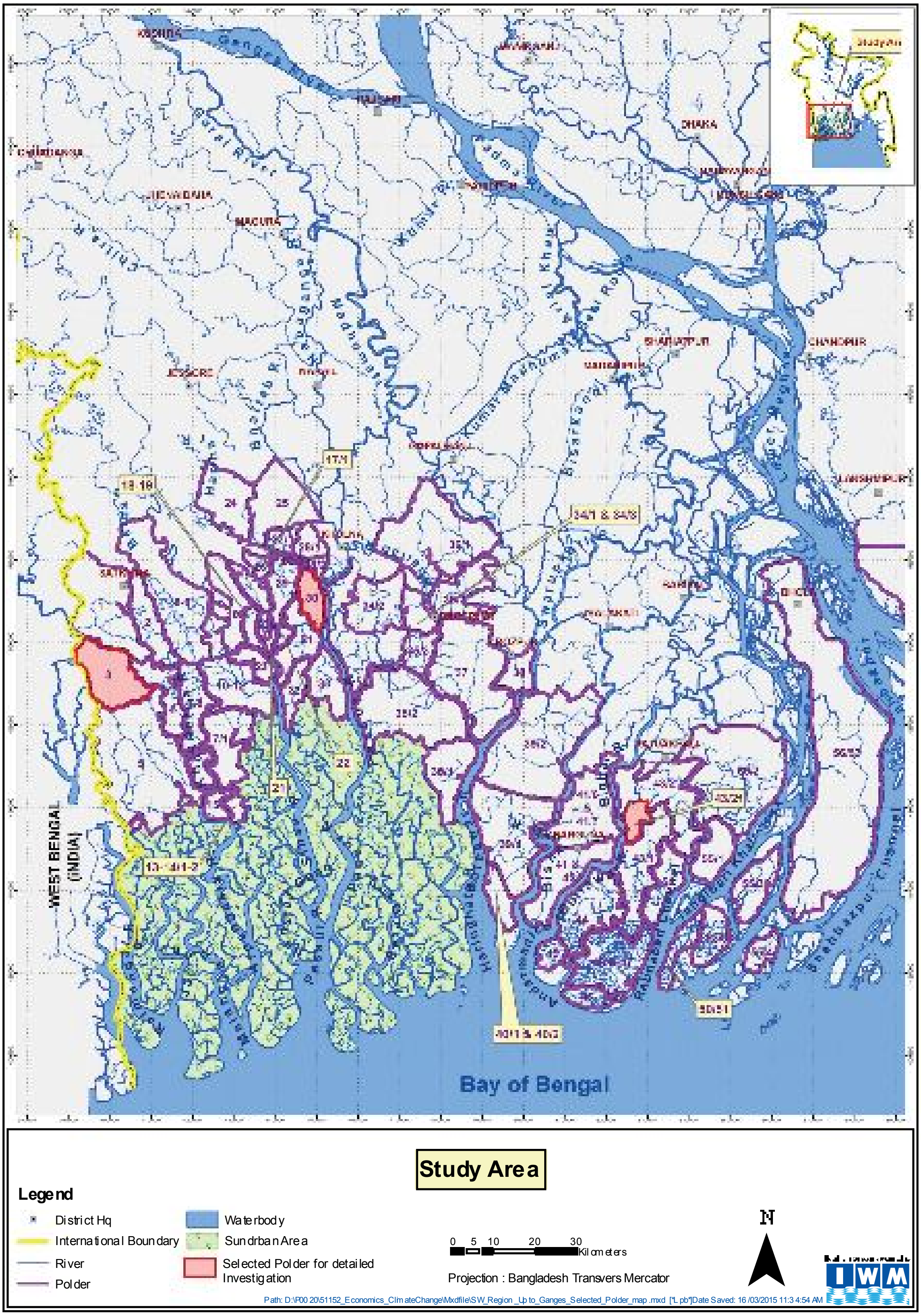


Fig. 1. Map showing the study area. Pink areas are (left to right) polder 3, 30 and 43/2F.

Tidal water level fluctuations in the rivers in the study area are semi-diurnal (Fig. 2). The amplitudes of the two daily tidal cycles differ slightly. Over a longer term, a fortnightly variation in amplitude between spring and neap tides is also evident, with spring tide amplitude approximately 2.5 to 3 times higher than the neap tide amplitude.

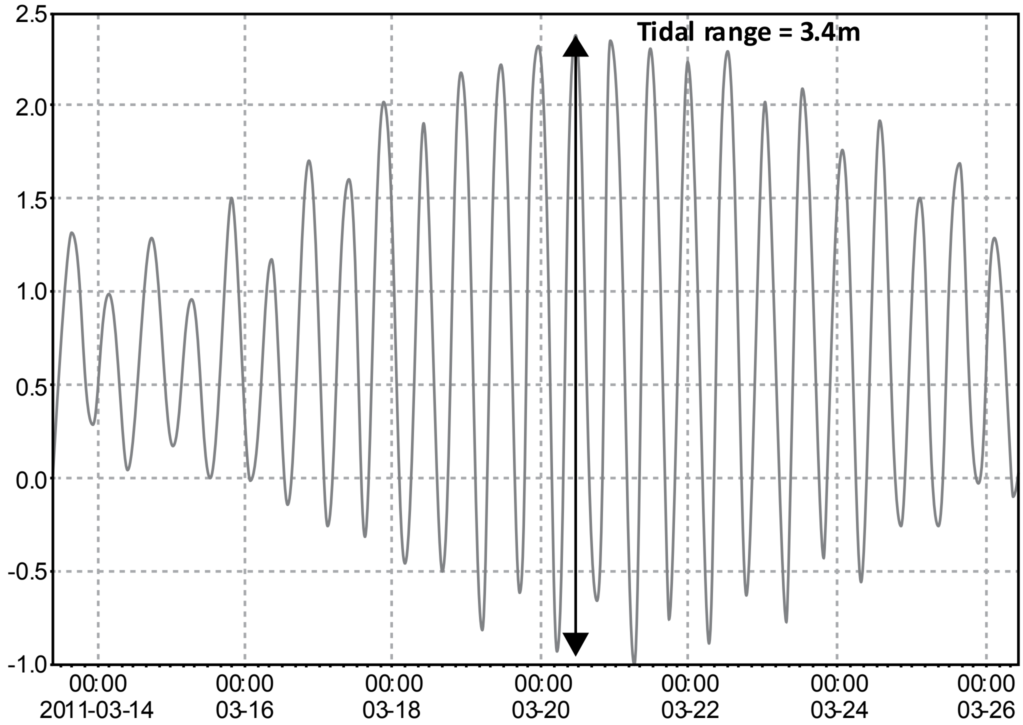


Fig. 2. Variation of tide level during spring and neap tide at Hiron Point in the Pussur River.

Field visits, community consultation and data analysis show that the problems in the polders are diverse and that there are opportunities for intensification of cropping systems if proper water management is put in place.

In Polder 3, located in Satkhira District, salinity is a major problem for agriculture as well as for drinking water. This polder is surrounded by the Ichhamoti River, Kansiali River and Habra Khal. Salinity in these rivers rises above 20 ppt (~31 dS/m) in the dry season. Salinity in the Ichhamoti and Kansiali rivers starts decreasing in mid-June and drops below 5 ppt in mid-July but remains above 2 ppt throughout the year. However, salinity in Habra Khal remains high because there is lack of freshwater flow from upstream. Farmers mainly practice shrimp farming in the southern half of this polder but also transplant aman rice in rotation with shrimp in some parts. Shrimp farmers have installed many pipes and cuts in the polder embankment to flush the shrimp ghers using saline river water during every spring tide (i.e. during the new and full moon) of the shrimp season. However, these cuts and pipes weaken the embankment and thus jeopardize the safety of the polder, and generate huge social problems and conflicts between the Bangladesh Water Development Board (BWDB) and shrimp farmers. The present scenario is very different from that in the 1970s when BWDB constructed the polders and drainage system. Revisiting the problems and improving the water infrastructure of the polder could ensure proper management and improvement of the drainage and flushing systems. This should include construction of planned flushing sluices for shrimp production and excavation of the drainage channels.

Polder 30 is surrounded by the Lower-Sholmari, Kazibacha and Jhapjhapia-Monga rivers and is located in Khulna District. The river receives freshwater through the Gorai River. There is plenty of water flow throughout the year in the peripheral river systems. Salinity varies seasonally and remains below 2 ppt from mid-June to February.

Polder 43/2F is surrounded by the Payra and Gulishakhali rivers, which receive plenty of flow from the Lower-Meghna River. Consequently, the river salinity remains very low, even in the dry season.

3. Methodology

Water level (depth), flow rate and salinity were monitored in the river systems of the study area for over three years. Detailed water level and flow measurements were carried in the peripheral rivers of the three selected polders. The measurements were made at half hour intervals over a full tidal cycle (12 hours and 25 minutes) during neap and spring tides in the dry and monsoon seasons. To assess the variation of salinity over time, measurements were carried out on alternate days at high and low water at 36 stations across the Ganges coastal zone. In addition, secondary data from BWDB were used, especially water discharge in the Ganges River at Hardinge Bridge and in the Gorai River at Railway Bridge.

The current conditions of salinity intrusion and availability of fresh water were analyzed based on historical data, the detailed field measurements over 3+ years as outlined above, and by applying numerical modeling techniques. Numerical models are effective tools to characterize and predict the quantity and quality of water. These models provide a means of generating a continuous time series of water level, flow and salinity at a large number of locations in the study area. The river model developed by IWM for the southwest region (based on the MIKE modeling system) was used to establish hydrologic conditions and variation of salinity over space and time across the entire study area (IWM 2005). The river systems and boundary conditions of the salinity model are shown in Figure 3.

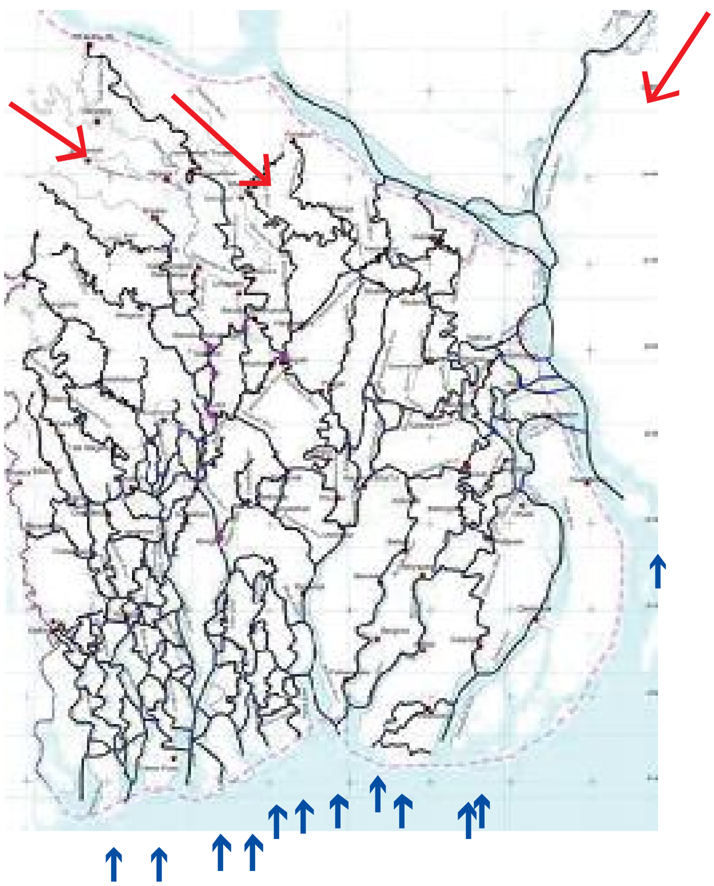


Fig. 3. The river systems and boundary conditions of the southwest region salinity model.

The model was calibrated using measured data for 2012 and validated against measured data for 2011, for water flow, water level and salinity in the different rivers. The agreement between model generated results and measured data was good for both water flow (R^2 from 0.87 to 0.95 in different rivers) and salinity (R^2 from 0.73 to 0.97). Figure 4 shows an example of the good performance of the model in predicting salinity of the Pussur River at Mongla.

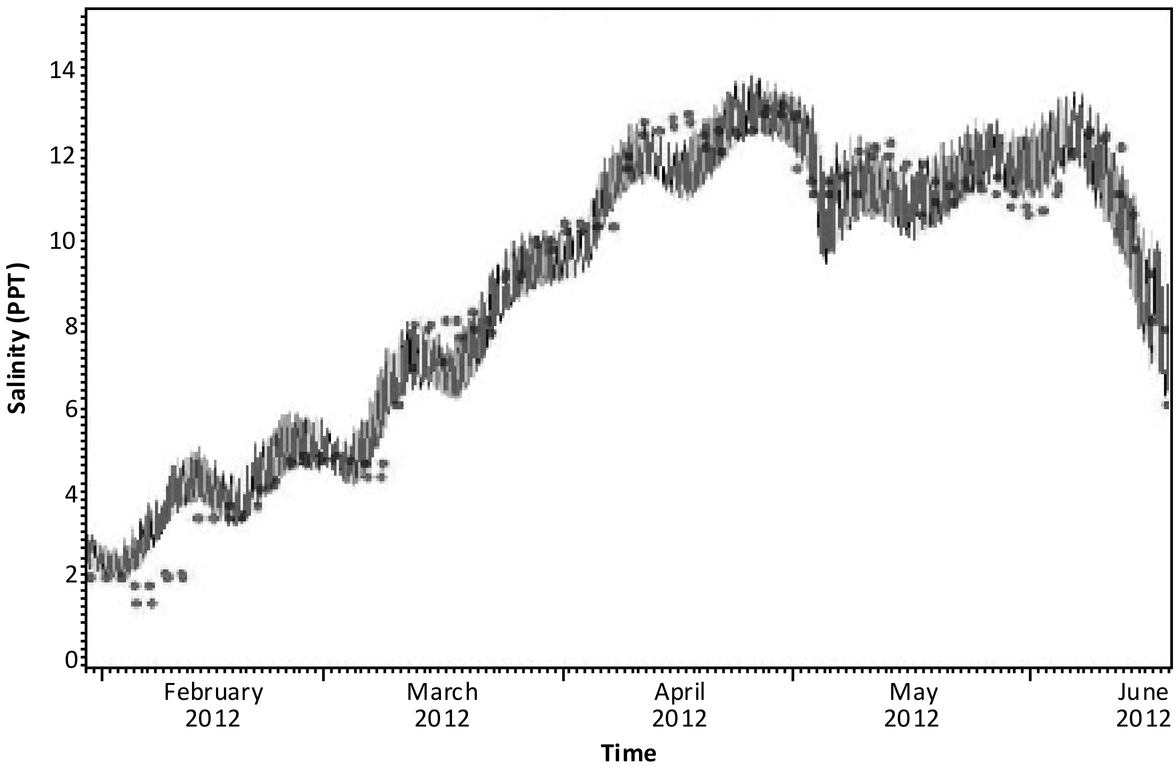


Fig. 4. Calibration results of salinity model in the Pussur River at Mongla (model calibration data set).

4. Results and discussion

The main source of freshwater in Khulna Division is the Ganges River. The flow during November to April is vital in pushing the salinity front downstream and enhancing the freshwater area in the river for irrigation of boro rice and for other domestic and industrial uses. Bangladesh Water Development Board measures the daily water flow in the Ganges River at the Haridinge Bridge. Average daily flow over the period from November to April in 1998 to 2000 was in excess of 3000 m^3/s, but since then it has generally been below 2500 m^3/s, with a record low of 2013 m^3/s (Table 1).

Table 1. Flow statistics at Hardinge Bridge (November-April)

Year	Maximum flow[1] (m^3/s)	Minimum flow[1] (m^3/s)	Average flow (m^3/s)
1998	11061	1038	3247
1999	20965	558	3452
2000	16396	768	3139
2001	6794	452	2388
2002	9297	728	2479
2003	7007	909	2608
2004	13629	1039	3462
2005	7854	775	2230
2006	9328	567	2465
2007	6949	951	2144
2008	8902	765	2456
2009	8789	1058	3108
2010	NA	NA	NA
2011	7916	766	2309
2012	10757	657	2555
2013	5715	826	2013

[1] Instantaneous flow

The dry season flow in the Gorai River depends on the available flow in the Ganges River and on the connectivity of the Gorai with the Ganges at the upstream end. The Gorai River is usually disconnected from the Ganges in the dry season because of the huge amount of sedimentation. Restoration of the Gorai River was done in 2011 to 2013 and as a result there was flow through the Gorai from the Ganges. The average daily flow rate in the Gorai River over the period from November 2011 to April 2012 was 261 m^3/s, while the maximum instantaneous flow rate was about 693 m^3/s. The average daily flow rate is computed as the average of all the daily river flow determinations (m^3/s) for the period 1 November to 30 April. The flow duration curve for that period shows that 90% dependable flow is less than 1000 m^3/s in the Ganges River at Hardinge Bridge during the dry season (Fig. 5).

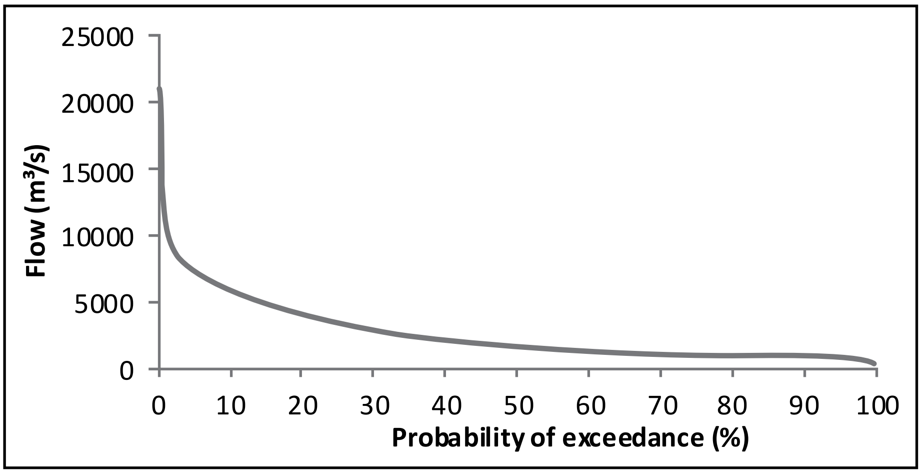


Fig. 5. Flow duration curve for the Ganges River based on average flow for the period November to April from 1998 to 2008.

Salinity in the Lower Meghna River varies from 0 to 2 ppt during the dry season (Fig. 5). The flow in the Lower Meghna River during the dry season is enormous since it carries the combined flow of the Ganges, Brahmaputra and Upper Meghna Rivers. The average daily flow from February to March is about 24000m^3/s in the Lower Meghna River. The Barisal area is connected with the Lower Meghna River through the Sawrupkati-Kocha-Baleswar, Buriswar and Bishkhali rivers. The area also receives flow from the Padma River through Arial Khan River during the dry season.

Field observations showed that river water salinity remained below 0.6 ppt throughout the year in much of Barisal Division (e.g. Fig. 6), and the same was true of simulated salinity (data not presented). Simulated monthly mean daily flow in the Payra River varied from 5400 to 6300m^3/s. It is thus evident that much of the Barisal Division has abundant fresh water available for irrigation, aquaculture and other industrial and domestic uses throughout the whole year. The salinity front of 5 ppt remains along the coastline in Barisal during the dry season (Akhter et al. 2012)

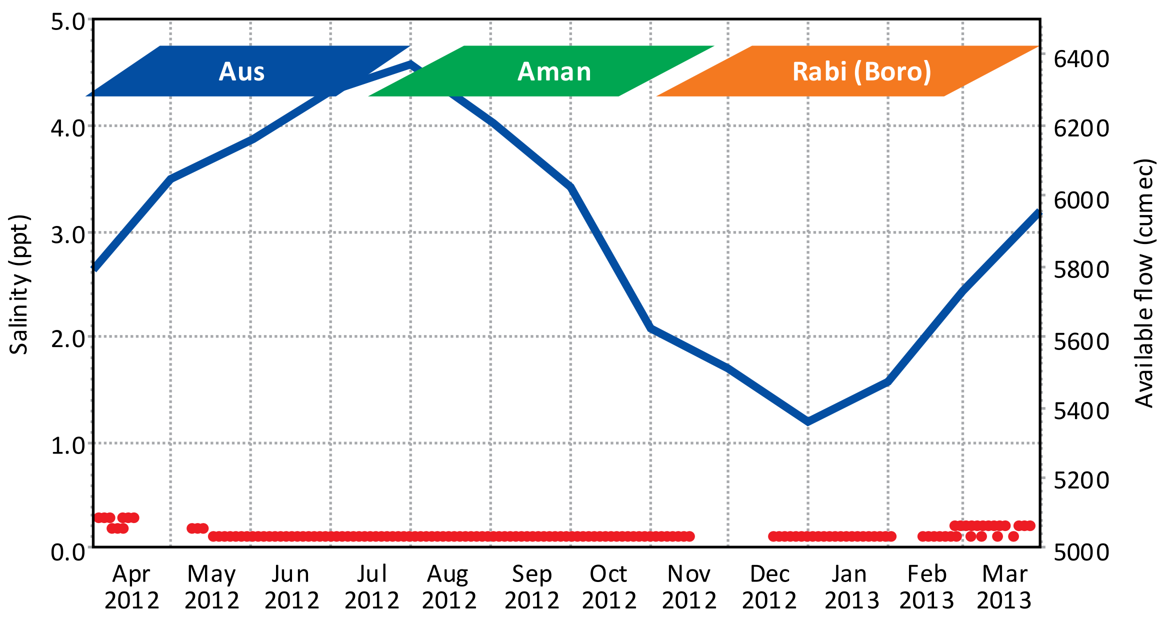


Fig. 6. Variation of salinity (measured, red markers) in the Payra River at a location adjacent to Polder 43/2F and monthly mean daily flow (model-generated data, blue line).

Simulation and monitoring also showed a limited area with available fresh water in March in Khulna Division. Figure 7 presents the map of water salinity in the Ganges coastal zone in March, a critical month for dry season crops, as this is when soil salinity starts to increase rapidly. The map shows that the river water is fresh throughout most of Barisal Division in March, thus the potential for irrigation. However, the present agricultural practices in much of Barisal Division are mainly a rainy season rice crop (aman) using low yielding local varieties, which is sometimes preceded by an aus crop and/or followed by a low yielding (non-irrigated) rabi crop such as grass pea or mungbean. The water resources are underutilized in this area although there is huge potential for enhancing land and water productivity through the use of modern high yielding varieties of rice and rabi crops and cropping system intensification (Bhattacharya et al. 2015; Mondal et al. 2015b; Saha et al. 2015).

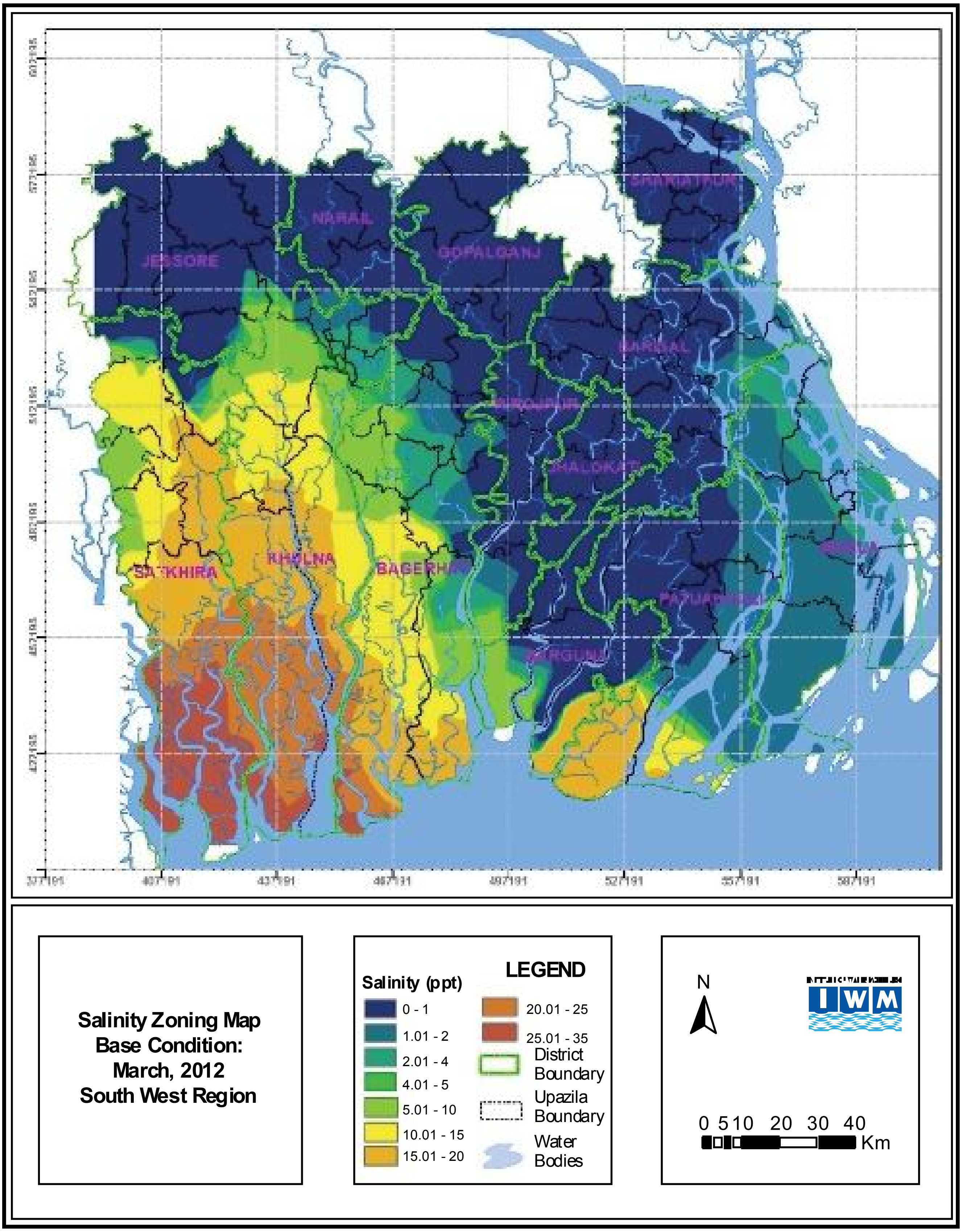
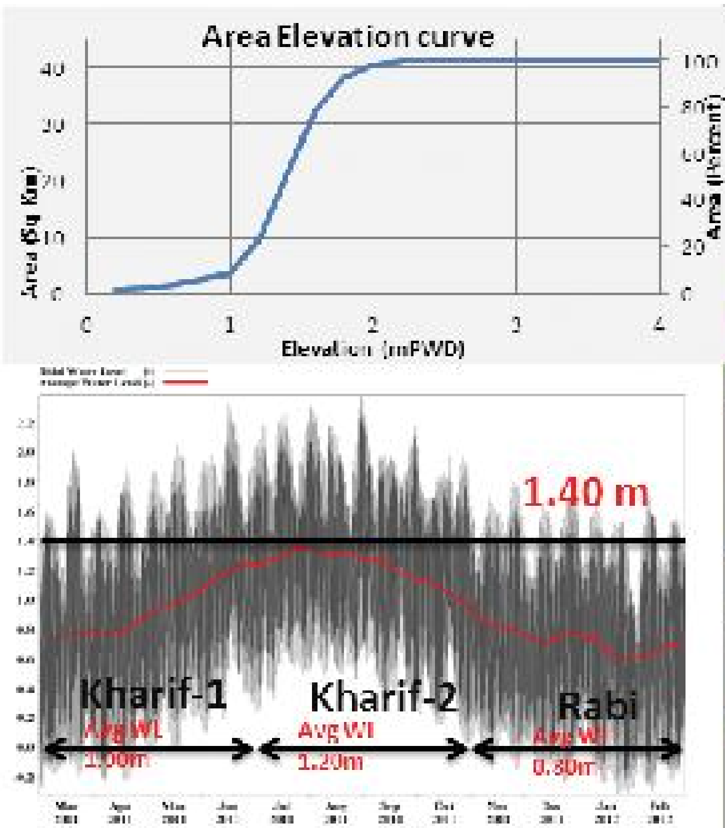
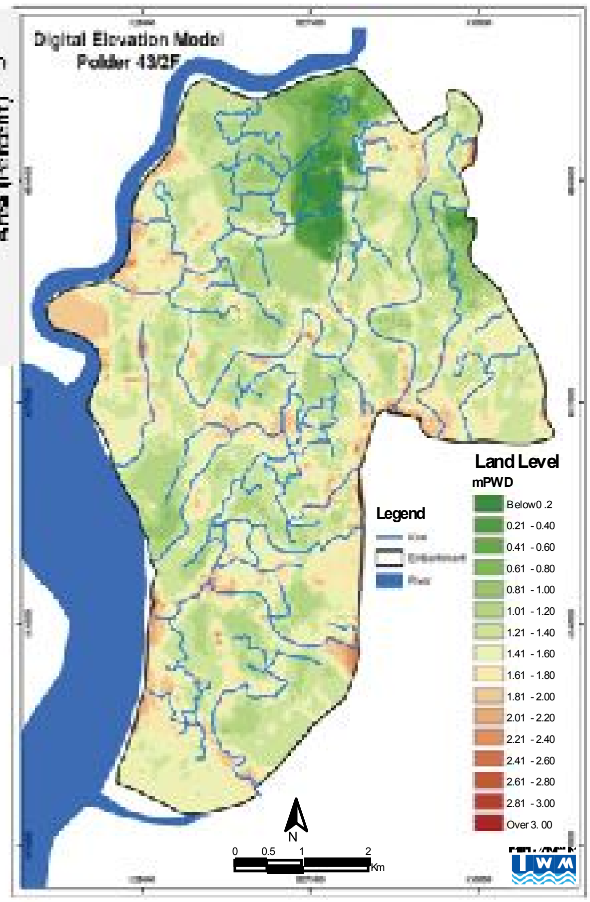


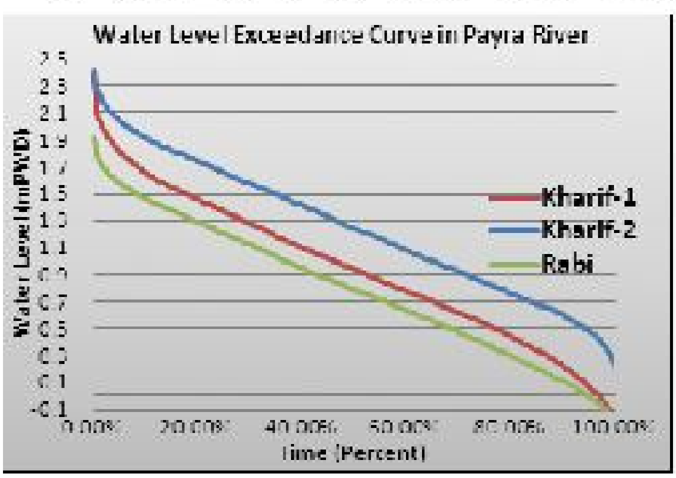
Fig. 7. Model-generated (simulated) river water salinity in the Ganges coastal zone in March 2012 (the blue area, 0-1 ppt, shows that the river water is fresh in large parts of the coastal zone).

Gravity irrigation is feasible in the coastal polders since the high tide level exceeds the average ground level for quite a long time during at least two cropping seasons (Fig. 8). For example, comparison of the tidal water level in the Payra River adjacent to Polder 43/2F and the land elevation inside the polder shows that the river level is above the median land level for 43% of the time during the *kharif-2* season, and for 23% of the time during the *kharif-1*. In the rabi season the potential for gravity irrigation is very low. However, the canals can still be filled by gravity by opening the regulators at high tide, and water can be pumped for irrigation using low lift or axial flow pumps.

Drainage is also feasible as the river level is below the average ground level for much of the time. This creates the possibility of growing high yield varieties of rice that have shorter stature than traditional varieties, bringing the advantage of earlier maturity atnd the opportunity to intensify cropping systems (Bhattacharya et al. 2015; Mondal et al. 2015a,b; Saha et al. 2015).







Level (mPWD)	Area below (%)	Percent of Time Water Level Exceed During Kharif-1	Percent of Time Water Level Exceed During Kharif-2	Percent of Time Water Level Exceed During Rabi
1.0	9	46	65	37
1.2	23	34	53	25
1.4	52	23	41	14
1.8	92	5	16	1
2.0	98	2	7	0

Fig. 8. The potential for gravity irrigation in Polder 43/2F as determined by comparison of land and tidal water levels.

Polder 30 and adjacent areas in Khulna District are characterized as medium salinity areas. Salinity in the peripheral rivers of this polder starts to increase from early December and reaches a peak in April (Fig. 9). Salinity decreases rapidly to less than 2 ppt in June and remains below 2 ppt until late January to mid-February depending on upstream flow and rainfall. The simulated monthly mean daily water flow rate in the Kazibacha-Pussur River ranges from 3700 to 5300 m^3/s throughout the year. The river water can thus be used for irrigation from June to early February. The internal drainage canal network is vast and can be filled by gravity at the end of January. The stored water can then be used for irrigation of boro rice and rabi crops in March and April. Analysis of the canal network for the whole polder shows that about 25 to 30% of the cultivable area of Polder 30 could be brought under rice in the dry season using internal storage to finish off the crop.

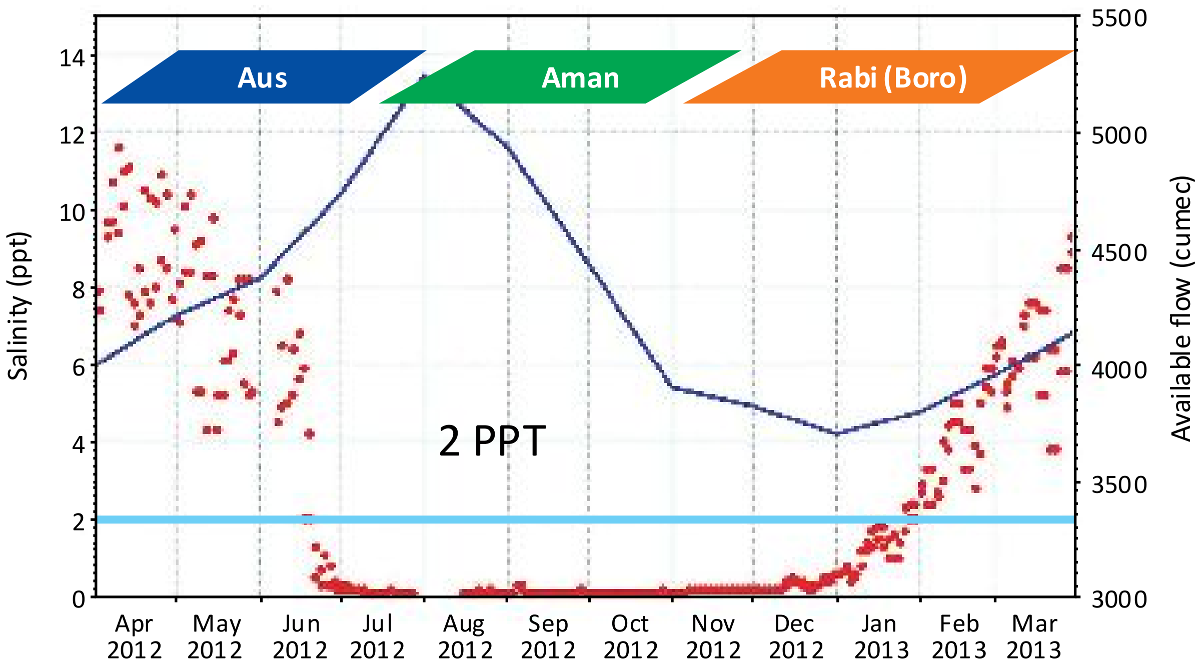


Fig. 9. Variation of salinity (measured, red markers) in the Kazibacha River at a location adjacent to Polder 30 and monthly mean daily water flow (simulated, blue line) in the medium salinity zone.

Salinity is higher in Satkhira District than in the low and medium salinity zones. In this western coastal zone, salinity remains above 2 ppt throughout the year (Fig. 10). Salinity starts to increase gradually in October as rainfall decreases, and increases rapidly from February to May. The high river salinity is due to the absence of freshwater flow from the upstream since the Kobadak and Betna rivers have been cut-off from the Ganges for several decades by sedimentation.

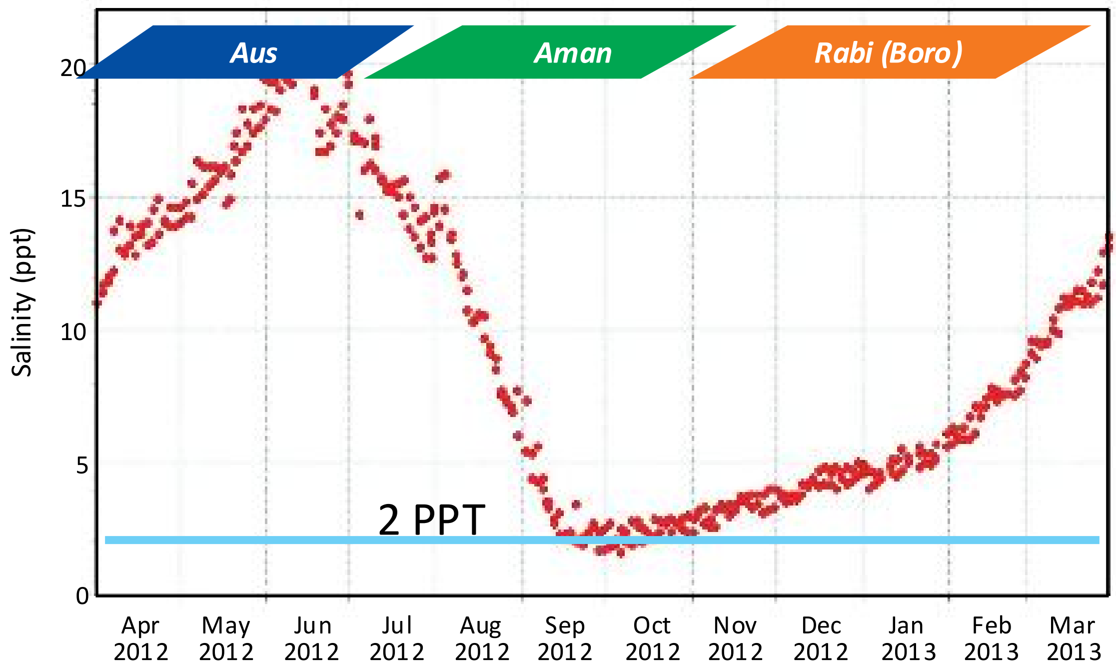


Fig. 10. Variation of salinity in the Ichamoti River adjacent to Polder 3.

In the southwestern part of the study region salinity is more than 4 ppt during the dry season, which has enabled wide-scale practice of brackish water shrimp farming in Satkhira District. To do this, farmers have constructed many informal structures to bring in the saline river water. Thus saline water can be considered an important livelihood resource. It is important to revisit polder design considering the autonomous change of land use by farmers.

5. Conclusions

Although the Ganges Coastal Zone is besieged with multiple problems and constraints it has tremendous potential to create innumerable opportunities for agricultural and aquacultural production through improved use of available water resources. River salinity in the Tentulia, Bishkhali, Buriswar and upstream stretch of Baleswar rivers (i.e. most of Barisal Division) was found to be very low throughout the year. The availability of water (high river flows) is high; simulation results show that the minimum flow in the Payra River (the peripheral river of polder 43/2F) during the dry season is 5400 m^3/s. Simulation results also show that both gravity irrigation and drainage are feasible during the *kharif-1* and *kharif-2* seasons. Irrigation can also be practiced during the dry season by filling the canals at high tide using gravity, storing the water in the canal systems and pumping from the canal systems using low lift pumps.

Fresh water is available in the peripheral rivers of Polder 30 and adjacent polders from June to early February, which can be used for gravity irrigation if needed. The internal drainage canal network is vast and water can be stored during March and April for irrigation of boro rice once the salinity of the river is too high for use for irrigation. About 25 to 30% of the cultivable area of Polder 30 could be brought under rice cultivation in the dry season using water directly from the river until early February, and water stored in the internal canal network to finish the crop off.

In the southwestern part of the study region salinity is higher than 4 ppt during the dry season and many farmers cultivate brackish water shrimp during the dry season using the saline river water. To do this, the farmers constructed many informal structures to bring saline water into the polder. This implies that saline water should be considered an important resource and not a curse. The autonomous change of land use by farmers and operation of regulators for both drainage and flushing also imply that there is a need to revisit the polder design. The present study reveals that the water resources of the coastal zone are enormous and that the polder systems offer huge potential for enhancing land and water productivity in the Ganges coastal zone through making better use of the available water resources and the tidal ecosystem.

Acknowledgements

This paper presents findings from 'G4 Assessment of the impact of anticipated external drivers of change on water resources of the coastal zone', a project of the CGIAR Challenge Program on Water and Food.

References

Akhter, S., Hasan, M. And Khan, Z.H. 2012. Impact of Climate Change on Saltwater Intrusion in the Coastal Area of Bangladesh; Paper presented in the Eighth International Conference on Coastal and Port Engineering in Developing Countries, IIT Madras Chennai, 20-24 February, 2012.

Bhattacharya, J., Mondal, M.K., Humphreys, E., Saha, N.K., Rashid, M.H., Paul, P.C. and Ritu, S.P. 2015. Rice-rice-rabi cropping systems for increasing the productivity of low salinity regions of the coastal zone of Bangladesh. These proceedings.

Brammer, H. 1996. Geography of soils of Bangladesh, University Press Ltd. Dhaka, Bangladesh.

Dasgupta S. and C. Meisner. 2009b. Climate Change and Sea-level Rise: A Review of the Scientific Evidence. Environment Department Paper # 118.The World Bank.

Dhaka Tribune. 2013. Salinity in coastal aquifers alarming. http://www.dhakatribune.com/bangladesh/2013/oct/20/salinity-coastal-aquifers-alarming

Government of Bangladesh: Ministry of Water Resources and Water Resources Planning Organization. 2006. Integrated Coastal Zone Management Program, Bangladesh: State of the Coast.

Hasan, M.R., M. Shamsuddin, and A.F.M.A. Hossain. 2013. Salinity status in groundwater: A study of selected upazilas of southwestern regions in Bangladesh. J. Global Science and Technology (1): 112-122.

IWM. 2014. Closure Report, Ganges Basin Development Challenge.

IWM. 2005. Impact Assessment of Climate Changes on the Coastal Zone of Bangladesh, Final Report.

Kabir, K. A., M. Karim, M. B. Shahrier, S. B. Saha, S. Chakraborty, P. Jharendu and M. J. Phillips 2014. Homestead farming systems in southwest Bangladesh: A survey. CPWF Working Paper Series (submitted).

Karim M.F., and Mimura N. 2008. Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh, Global Environmental Change 18 (3), 490-500.

Mondal, M.K., Humphreys, E., Tuong, T.P., Rahman, M.N. and Islam. M.K. 2015a. Community water management and cropping system synchronization: The keys to unlocking the production potential of the polder ecosystems in Bangladesh. These proceedings.

Mondal, M.K., Paul, P.L.C., Humphreys, E., Tuong, T.P., Ritu, S.P. and Rashid, M.A. 2015b. Opportunities for cropping system intensification in the coastal zone of Bangladesh. These proceedings.

Saha, N.K., Mondal, M.K., Humphreys, E., Bhattacharya, J., Rashid, M.H., Paul, P.L.C. and Ritu, S.P. 2015. Triple rice in a year: Is it a feasible option for the low salinity areas of the coastal zone of Bangladesh? These proceedings.

Tingsanchali, T. and Karim, M. F. 2005. Flood hazard and risk analysis in the southwest region of Bangladesh. Hydrol. Process., 19: 2055–2069. doi: 10.1002/hyp.5666

External drivers of change, scenarios and future projections of the surface water resources in the Ganges coastal zone of Bangladesh

Z.H. Khan[1], F.A. Kamal[1], N.A.A. Khan[1], S.H. Khan[2], M.M. Rahman[2], M.S.A. Khan[3]
A.K.M.S. Islam[3] and B.R. Sharma[4]

[1]Institute of Water Modelling, Bangladesh, zhk@iwmbd.org, fal@iwmbd.org, nkh@iwmbd.org
[2]Bangladesh Water Development Board, Bangladesh, sarafat.khan@gmail.com, mmahfuz82@yahoo.com
[3]Bangladesh University of Engineering and Technology, Bangladesh, msalamkhan@iwfm.buet.ac.bd, akmsaifulislam@iwfm.buet.ac.bd
[4]International Water Management Institute, b.sharma@cgiar.org

Abstract

The surface water resource of the coastal zone of the Ganges basin is vital for crop production, ecosystem sustenance and livelihoods. In the future this resource is likely to be shaped by various drivers of change. Through a series of participatory processes the most important external drivers for the Ganges delta were identified, then future scenarios that are likely to affect water availability and productivity were devised and evaluated using numerical modeling. The main drivers of change were identified as trans-boundary river flow, population growth, and changes in land use, climate, water governance and water infrastructure development. At present, there is an enormous amount of freshwater suitable for irrigation of agricultural crops throughout the year in much of Barisal Division. The quantity of fresh water in the coastal zone is likely to decrease due to the combined effects of external drivers and inadequate transboundary flows that will increase river salinity during the dry season. By 2030, the area suitable for irrigation (less than 2 ppt river water salinity) is likely to decrease by about 11% under a moderate climate change scenario (A1B). However under this scenario in 2030 salinity of the rivers in Barguna, Patuakhali and Jhalokathi Districts will not exceed 2 ppt, meaning continued high availability of river water for irrigation in these regions, even with sea level rise of 22 cm. However, this fresh water pocket in the south-central zone is likely to become more saline (2-4 ppt) with climate change and 52 cm sea level rise in 2050, damaging fish habitat and sources of irrigation water. If the proposed Ganges barrage is built in the Ganges River to divert flow through the Gorai River, an additional 2660 km2 area would be exposed to river water salinity of less than 2 ppt compared to the base condition, i.e. a larger land area would have access to irrigation. With sea level rise of 22 cm, the Ganges barrage would still result in an additional 886 km^2 of land with river water suitable for irrigation.

Key message: River water salinity is predicted to remains less than 2 ppt (suitable for irrigation) in 2030 with moderate (22 cm) sea level rise in much of Barisal Division. However, salinity in that area will increase to 4 ppt and above with 52 cm sea level rise in 2050.

Keywords: climate change, salinity, sea level rise, transboundary flow, Ganges barrage

1. Introduction

The problems related to surface water resource management in the coastal zone of the Ganges delta are numerous, complicated and challenging. Effective resolution of these problems requires a clear understanding of future demand for water and water availability. Hydrological conditions vary seasonally, annually and during extreme weather events. Changes in ecosystem services are almost always caused by multiple interacting drivers. The present and future agriculture, aquaculture and ecosystem services in the coastal zone of the Ganges delta depend to a large extent on the availability of fresh water. Identification of the key drivers of change and assessment of their effects on water resources are important for future planning for the multiple uses of water. Of particular importance is knowledge of the effects of drivers of change on future salinity intrusion, availability of fresh water and drainage.

A driver of change is any natural or human-induced factor that directly or indirectly causes a change in an ecosystem (Carpenter et al. 2006). The categories of global driving forces are demographic, economic, socio-political, cultural and religious, scientific and technological, and physical and biological. Drivers in all categories other than physical and biological are considered indirect. Important direct drivers include changes in climate, land use and water use. Climate change, high population growth rate, rapid urbanization, expansion of infrastructure, increasing pollution and changes in land and water use all translate into changes in water flows and the availability of water. Previous research has been limited to the effects of sea level rise and found that with a 60 cm sea level rise along the coast of the south-central zone the 5 ppt salinity front would move 55 km inland (Akhter 2012). Detailed research was carried out by the World Bank to determine the impacts of sea level rise on salinity intrusion. "Slight saline (<1dS/m)" river area is likely to decrease from 22 percent at the baseline to 13 percent in the worst-case scenarios in the southwest region with 67 cm sea level rise (Dasgupta et al. 2014). The present research was undertaken to identify the key drivers of change in surface water resources in the Ganges delta coastal zone of Bangladesh, to prioritize likely future scenarios and to assess the likely impact of these scenarios on salinity intrusion and fresh surface water availability.

2. Study Area

The study area is the southwest coastal region of Bangladesh, which is bound by the Ganges and the Padma rivers to the north, the Lower Meghna and Tentulia rivers in the east, the Ichamoti River and the Bangladesh-India international boundary to the west and the Bay of Bengal to the south (Fig. 1). A vast network of river systems that are influenced by tidal action characterizes the area. Tides are semi-diurnal, i.e. two high and two low tides per day, the duration of one tidal cycle being 12 hours and 25 minutes. The topography of the region is very flat and strong tidal effects are propagated up to 200 km upstream of the coast at times.

The huge freshwater outflow from the Ganges, Brahmaputra and Meghna rivers induces a large zone of brackish water (salinity from 1 to 30 ppt) in the coastal region of Bangladesh through mixing with seawater (32 to 35 ppt). Seasonal movements of the front between seawater and brackish water govern salinity in the northern-most part of the Bay of Bengal. The Ganges River is the main trans-boundary river in the southwest region. The Bhairab, Kobadak, Nabaganga and Chitra rivers used to receive freshwater flow from the Ganges during the dry season. However, these rivers have been disconnected from the Ganges for several decades due to siltation. There is no freshwater flow through these rivers to the study area from the Ganges, but during the monsoon there are freshwater flows from the local catchment due to rainfall. The water from the Ganges River, which flows through its distributary, the Gorai River, is the only major source of fresh water in the southwest zone during the dry season. However, the offtake of the Gorai remains dry during the dry season (December to May) if it is not dredged. Salinity in the Bay of Bengal is high during the dry season, and saline water intrudes inland through the major rivers, namely the Baleswar, Jamuna, lower Meghna, Malancha, Pussur, Sibsa and Tnetulia, through tidal effects. There is very inadequate upstream flow coming down the Gorai during the dry season. Consequently, the region is severely affected by salinity intrusion.

The Bangladesh Water Development Board built about 56 polders (lands surrounded by large earthen embankments) in the southwest coastal region in the late 1960s and early 1970s. The embankments prevented tidal flooding and salinity intrusion, enabling the production of a traditional rainy season crop and protecting lives. However, siltation of the rivers (a result of reduced flows from India and the construction of the polders), sea level rise and the sinking of the land mean that the restoration of the peripheral rivers and planned sedimentation of the polders is required.

The average annual rainfall of the southwest coastal region is about 1,780 mm and the 80% dependable rainfall is 1,480 mm (Mainuddin et al. 2014). Rainfall is lower towards the Indian border and higher in the east. Average annual potential evapotranspiration (ETo) is 1370 mm. There is a clear surplus of rainfall during the monsoon period from June to October, a balance between rainfall and ETo in the pre- and post-Monsoon months of May and October, and a clear deficit in the boro season months from November to April (Fig. 2).

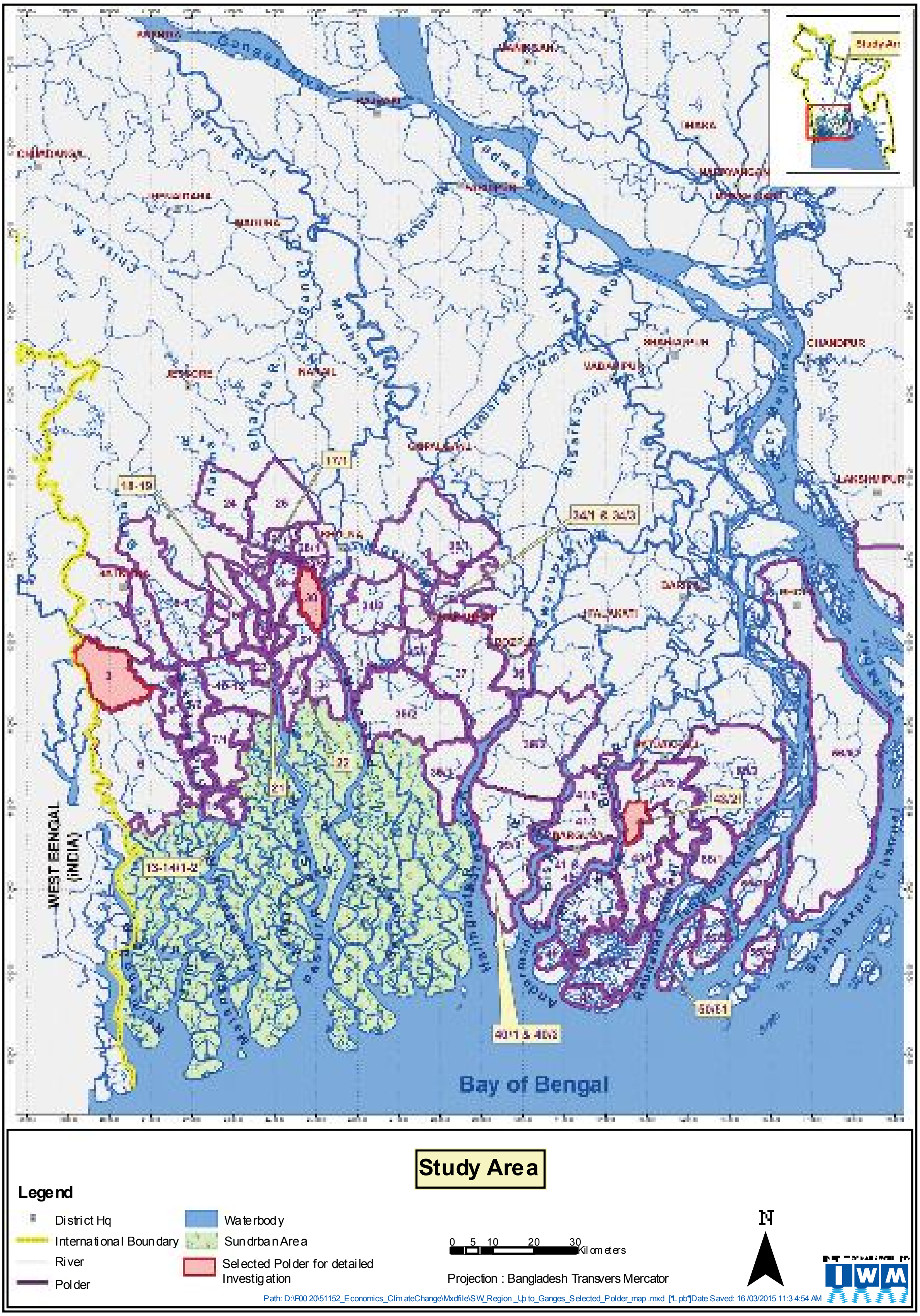


Fig. 1. The study area in the southwest coastal region of Bangladesh.

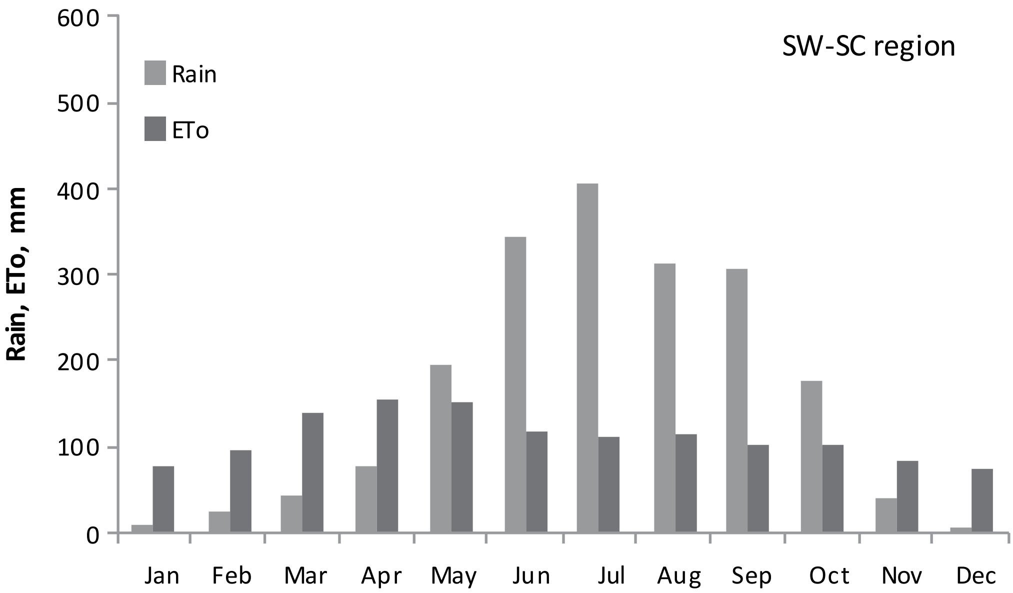


Fig. 2. Mean monthly rainfall and evapotranspiration (ETo) in the southwest coastal region of Bangladesh, during 1985-2010 (Source: Mainuddin et al. 2014).

The availability of fresh surface water resources during the dry season is variable, more so towards the southwestern corner. In the far southwest (Satkhira District) salinity in the river systems rises above 20 ppt during the dry season and starts to decline in June, but remains above 2 ppt even during the monsoon (Khan and Kamal 2015). However, fresh surface water resources in Khulna District (to the east of Satkhira) are plentiful during, and for a couple of months after, the monsoon. Here, river salinity falls to less than 2 ppt in the middle of June. After the end of the monsoon, fresh water (<2 ppt) is available in the Rupsa, Kazibach–Pussur river system from November to mid-February. In the south-central area (Barisal Division) freshwater is available in much of the region throughout the year since the area receives huge freshwater flows from the Lower Meghna River, even in the dry season. Consequently, salinity remains below 0.6 ppt.

3. External drivers of change – methodology and identification

The process for identification and prioritization of external drivers of change for scenario analysis involved a wide range of stakeholders including farmers (agricultural crops and fish), fishers, researchers, academics, and representatives of planning and implementing agencies working in Bangladesh (Fig. 3).

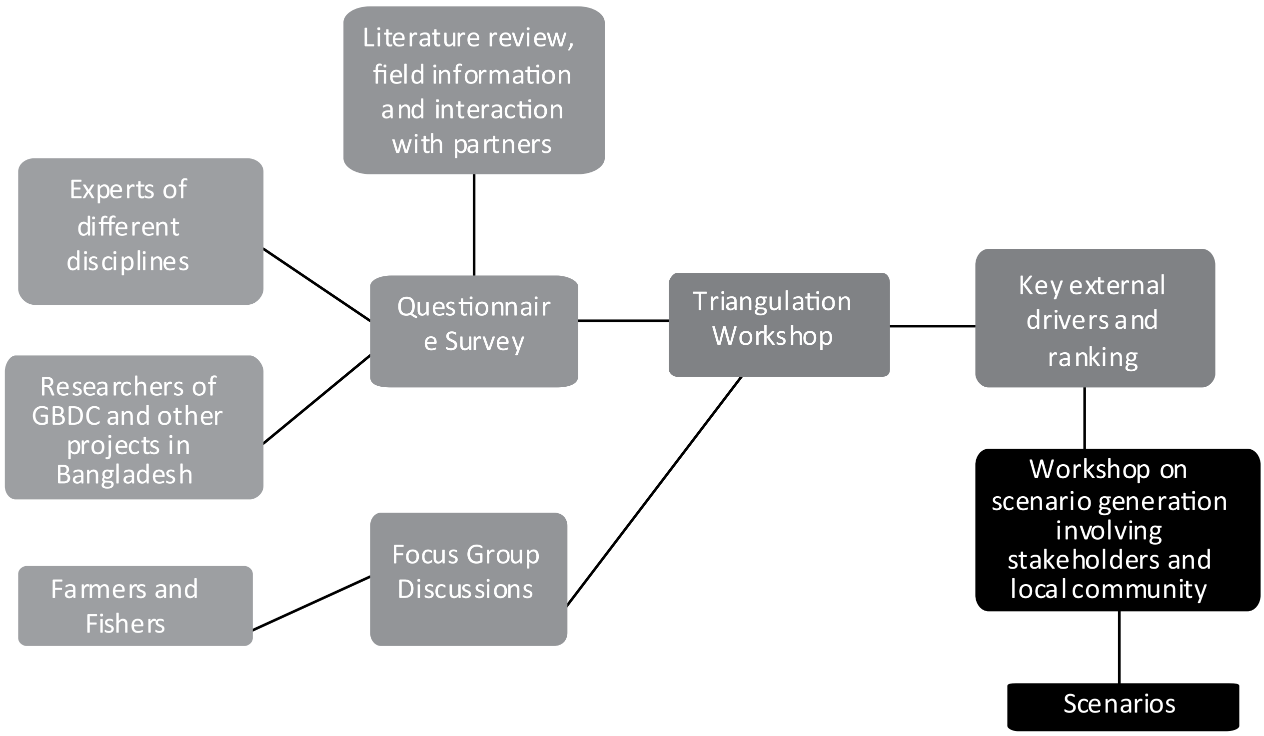


Fig. 3. Flow chart of the process used for identification and selection of key drivers of change for surface water resources in the southwest coastal region of Bangladesh. GBDC stands for the CGIAR Challenge Program on Water and Food's Ganges Basin Development Challenge (http://waterandfood.org/river-basins/ganges/).

Two approaches were used to identify key drivers of change. Firstly, a questionnaire survey was conducted with experts in a range of relevant disciplines, researchers of the CGIAR Challenge Program on Water and Food's Ganges Basin Development Challenge (GBDC), water resources planning professionals and implementing/ operating organizations. The purpose was to compile a list of drivers of change and their ranking. The questionnaire was developed based on the findings of a literature review, field information and consultation with partner organizations. Secondly, focus group discussions were conducted in polders 3 (high salinity), 30 (medium salinity) and 43/2F (low salinity) with farmers, fishers, local traders and women to identify important issues on water, agriculture and fisheries, problems and their causes. The purpose of the discussions was to identify the local communities' anticipated external drivers of change and their likely impacts.

Triangulation and integration of the findings of the two approaches was done through a facilitated workshop involving all stakeholders. The result was consensus on the key drivers of change and their relative importance (Table 1).

Table 1. List and rank of external drivers of change

External Drivers	Rank
Change in trans-boundary flow	1
Population growth	2
Change in water management practices	3
Land use change	4
Climate change (including precipitation, temperature) and sea level rise	5
Change in water governance and institutions (including policy change)	6
Water use change	7
Water infrastructure development	8
Urbanization	9

4. Development of scenarios

Several scenarios were devised (Table 2) based on the prioritized drivers of change using a participatory approach in another workshop with all stakeholders including local community representatives. This was a pioneering effort in Bangladesh to generate scenarios of multiple drivers for integrated water resources management through a participatory approach involving a wide range of stakeholders. A moderate climate change scenario (A1B), with predicted sea level rise of 22 cm in 2030 and 52 cm in 2050, was used in the simulations.

Table 2. Scenarios for assessing the effects of external drivers on water resources in the coastal zone of Bangladesh

No.	Scenario[1]	Outputs
B	Base case Water flow and salinity for the year 2012 is considered as base case/base condition	• Salinity zoning and water availability map
I	Minimum trans-boundary flow + Population growth + Land use change+ Climate change (including pptn, temp & SLR)	• Salinity zoning and water availability map for the coastal zone of Ganges delta in Bangladesh • Water level and flow statistics (max, min, mean) • Projection of water for food production • Projection of domestic water demand • Projection of impact of climate change, SLR
II	Average trans-boundary flow + Population growth + Land use change + Climate change (including pptn, temp & SLR)	• as above
III	Maximum trans-boundary flow + Population growth + Land use change + Climate change (including pptn, temp & SLR)	• as above
IV	Minimum trans-boundary flow + Population growth + Land use change + Climate change (including pptn, temp & SLR) + Ganges Barrage	• as above

[1]pptn = precipitation, temp = temperature, SLR = sea level rise

5. Scenario analysis - water modeling

Numerical modeling was used to examine the likely impacts of the scenarios on surface water resources. The Institute of Water Modelling (IWM) maintains hydrological, hydrodynamic models for river systems and the Bay of Bengal for simulating water flow, drainage and salinity. These models have been tested and verified for the river systems of Bangladesh. We used four IWM models in this study—Rainfall-Runoff, Hydrodynamic, Bay of Bengal, and Salinity—to determine the present and future tidal variation, water flows, spatial variation of salinity, fresh water availability and drainage conditions of the polders.

River salinity in the southwest region depends on the freshwater flow from upstream, rainfall runoff from the adjacent catchment area and the tidal dynamics of the river systems. Tidal waves from the Indian Ocean travel through the deeper part of the Bay of Bengal and approach the coast of Bangladesh from the south. The process of mixing freshwater from the upstream river system and saline water from the Bay of Bengal in the coastal water occurs as turbulence, which is generated by wind and tidal currents. The water flow and salinity modeling processes are illustrated in the following sections.

5.1 Rainfall-runoff modeling

The Rainfall-Runoff module of the MIKE11 modeling system was applied to estimate runoff from rainfall in various catchments of the southwest coastal region. The Rainfall-Runoff model takes into account catchment characteristics, rainfall, soil moisture, irrigation and water extraction from surface or groundwater sources in the catchments, evaporation, percolation and other losses. The model generates runoff, which is the input data for the water flow/hydrodynamic modeling.

5.2 Hydrodynamic modelling

To generate time series tide and water flow/discharge in the river systems of the study region, the hydrodynamic module of the MIKE 11 modelling system was used. Inputs for the Southwest Regional Model include the rainfall runoff estimates from the Rainfall-Runoff model, water flow data (flow gauge data) at the upstream end of the study area (upstream boundary), water level data/tidal variation at the downstream ends of the rivers (downstream boundary), and the cross-section river data at locations along the entire stretch of the rivers. The model simulates continuity and momentum equations and provides water levels at each cross-section location and water flow time series between successive river cross-sections.

The model was calibrated by adjusting the model parameters to achieve good agreement between simulated and observed discharge and water level data (e.g. Fig. 4).

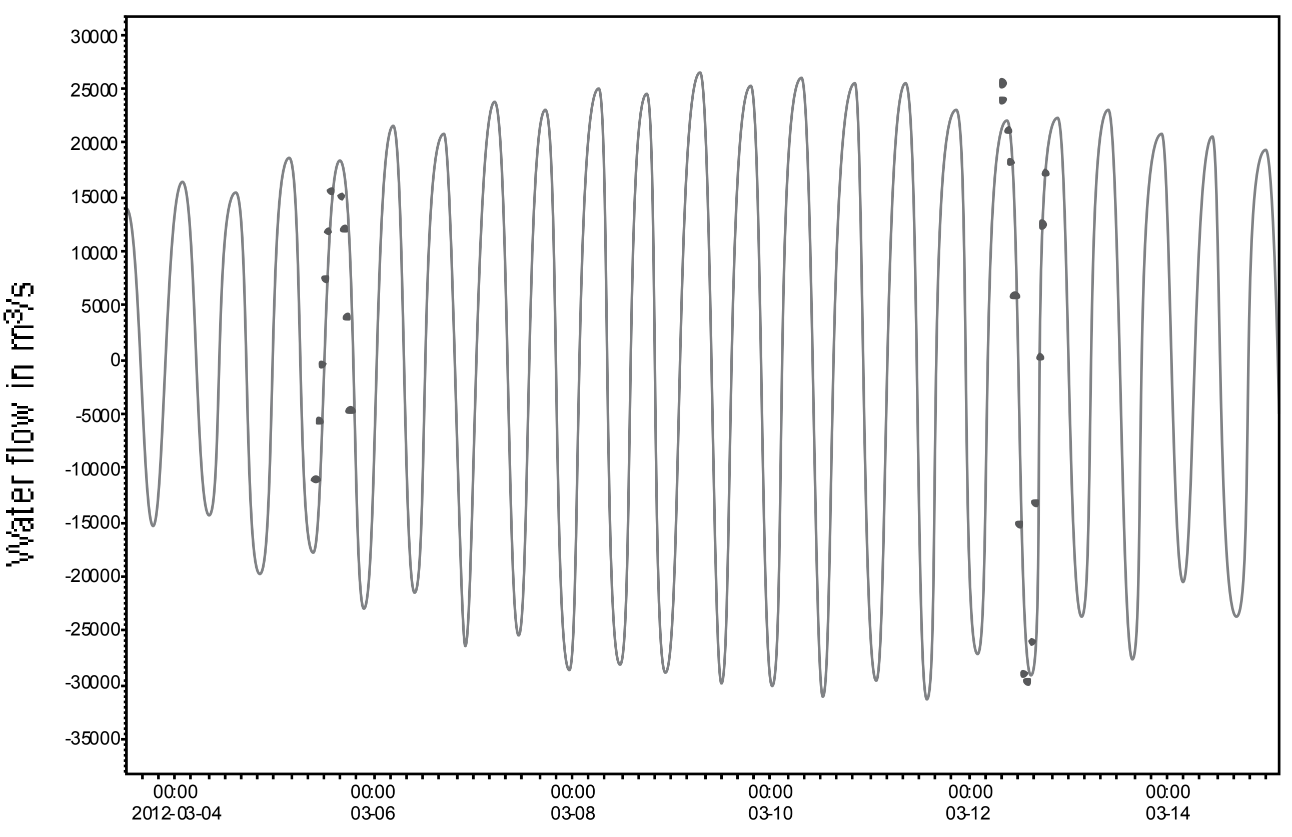


Fig. 4. Simulated (lines) and observed (dots) flow for the calibration of the water flow model at Char Doani in the Bhaleswar River from 4 to 14 March 2012 (-ve sign is for flood tide flow, +ve is ebb tide flow).

5.3 Salinity modeling

Salinity of the Bay of Bengal was simulated using the Bay of Bengal (BoB) model based on the MIKE 21FM modeling system. The BoB model domain extends from Chandpur on the lower Meghna River (23°N) to 16°N in the Bay of Bengal. The BoB model used the water flow estimates at the upstream boundary. The time-series water level data at the downstream boundary were generated from the DHI Global Tide model. Measured concentrations of salinity along the upstream boundary and constant 32 ppt salinity at the downstream boundary were used as salinity inputs.

A salinity model (the advection-dispersion module of MIKE 11) was applied to assess river water salinity in the southwest coastal region. Measured concentrations of salinity along the upstream boundary and generated salinity by the BoB model for the downstream boundary were used as inputs for boundary conditions. The flow chart of the salinity model is presented in Figure 5.

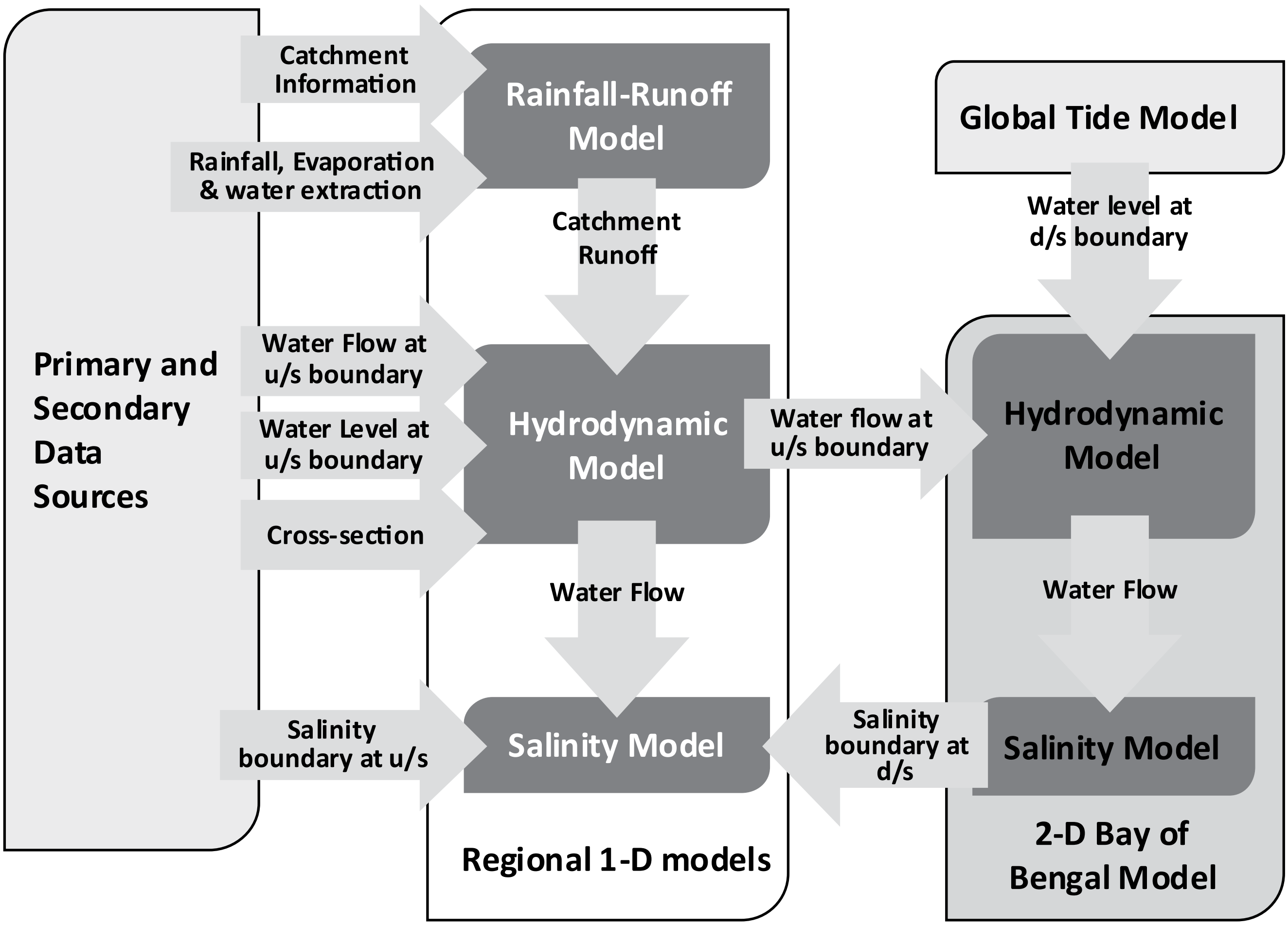


Fig. 5. Flow chart of the salinity model for the southwest coastal zone of Bangladesh.

6. Salinity and fresh water availability under different scenarios

Salinity levels in the southwest coastal zone show a distinct seasonal variation due to variation of upstream flow from monsoon to dry season. Average salinity concentrations are higher in the dry season than in the monsoon season due to lack of freshwater flow from upstream. Salinity generally builds up during October to early/late May. During May, salinity levels drop sharply due to increased upstream flow and rainfall. Salinity levels are highest during the latter part of the dry season, usually from March to May.

The effect of transboundary flow on salinity was assessed in combination with other drivers of change under different scenarios. Three levels of transboundary flow were used: the minimum (Fig. 6), average and maximum daily flows during the dry season in the Ganges River at Hardinge over a period from 1996 to 2013 (i.e. since the implementation of the Ganges Water Treaty). Decreased flow in the Ganges River with the construction of the Farraka Barrage (completed in 1975) resulted in large increases in river salinity downstream. For example, prior to 1975 salinity was below 1 ppt at Khulna and the river water was used for drinking, agriculture and industrial purposes. At present, river water salinity at Khulna increases to more than 15 ppt during the dry season and is unsuitable for most purposes.

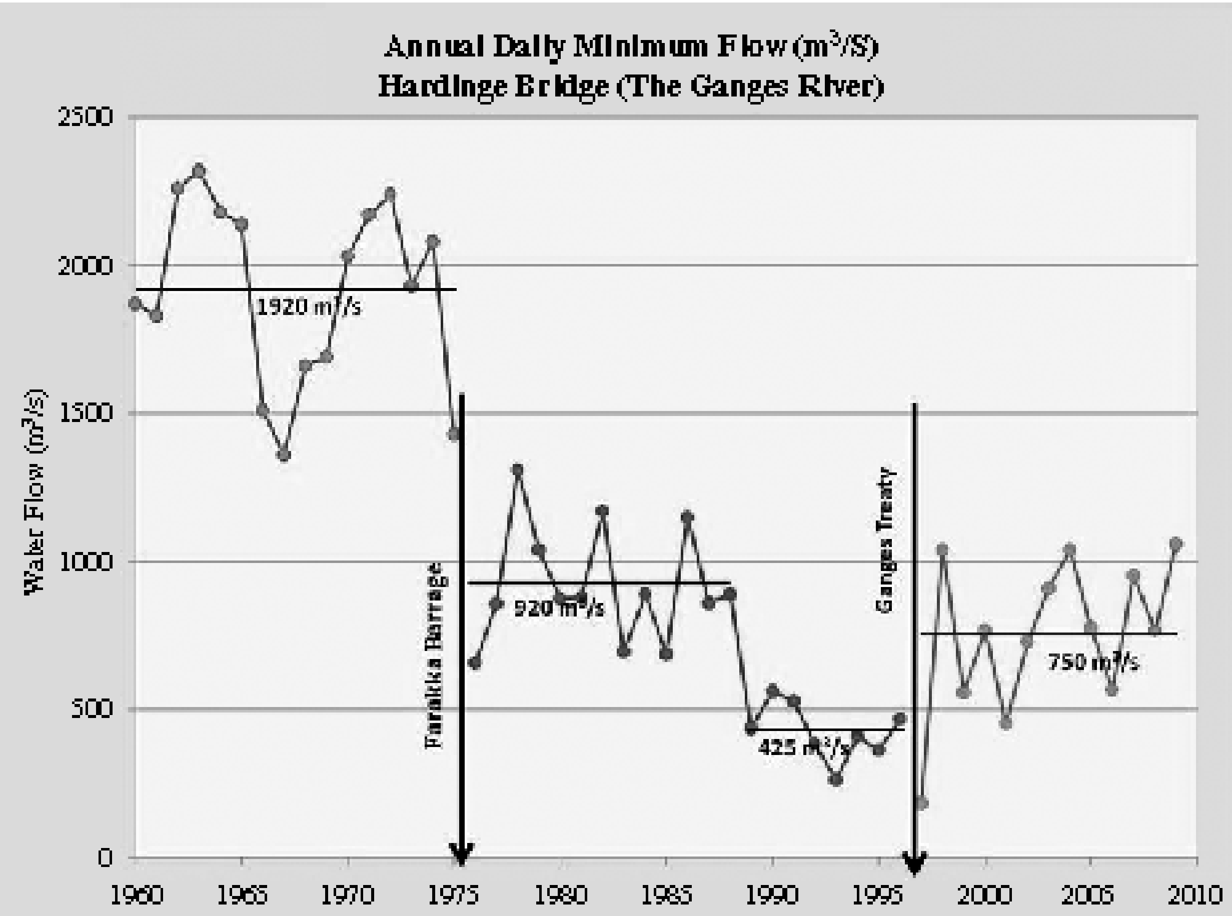


Fig. 6. Average minimum daily flow (average of daily minimum flow for the period January to May in the Ganges River at Hardinge Bridge from 1960 to 2009).

To examine the change in salinity and its spatial variation under each scenario, the calibrated and validated salinity model was used to prepare maps of surface water salinity for baseline conditions (2012). The map for March 2012 (Fig. 7) shows that there is fresh water in the river systems of Narial, Jessore and Gopalganj Districts in the northwest, and throughout most of Barisal Division.

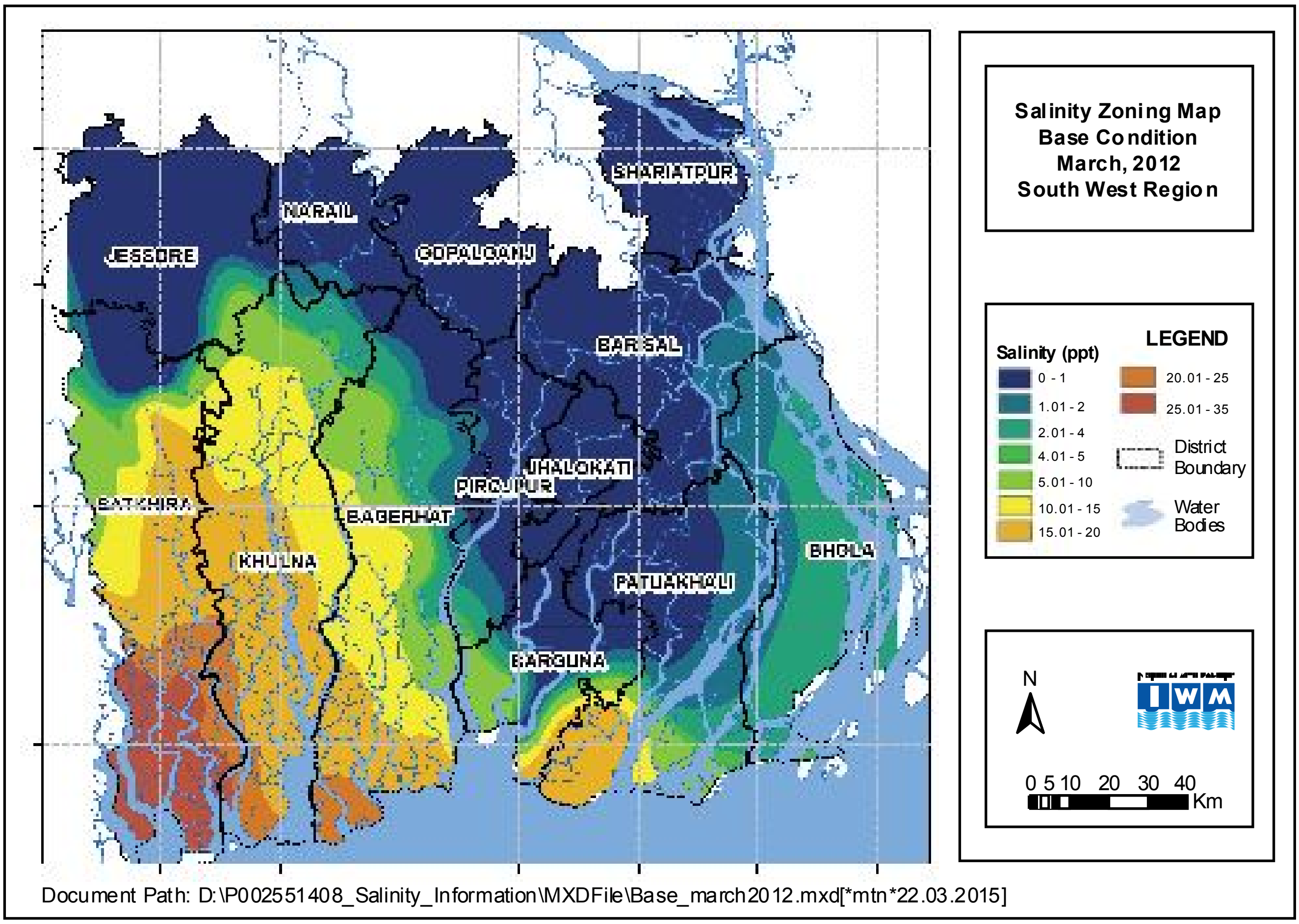


Fig. 7. Map of surface water salinity distribution for the baseline condition of March 2012.

Simulations of scenarios I to III were carried out to examine the combined effects of change in transboundary flow and sea level rise along with population growth and land use change. In the model population growth is considered as extraction of domestic water and urban water for major cities. Land use change is taken as additional water extraction for irrigation for future cropping systems. Under all scenarios except scenario IV the area exposed to freshwater and irrigation water decreases because of sea level rise and decreased transboundary flow in the Ganges. Under scenario-I, the freshwater area (0-1 ppt) is predicted to decrease by 19.3% and the irrigated area by 13.5% (Table 3). In the case of maximum transboundary flow with the same sea level rise, the area suitable for irrigation is 9% less than baseline. However, in January to March a larger area would be exposed to salinity than in April as salinity intrusion would affect a larger area.

However under these scenarios salinity in the rivers in Barguna, Patuakhali and Jhalokathi Districts does not exceed 2 ppt, which implies continued availability of river water suitable for irrigation in these regions. Thus, considerable water will be available for irrigation in much of Barisal Division in 2030 under the A1B climate change scenario with 22 cm sea level rise (Fig. 8). However, part of Narial, Jessore and Gopalganj are likely to become saline, despite the fact that under the base condition river water in these areas is fresh (Fig. 7).

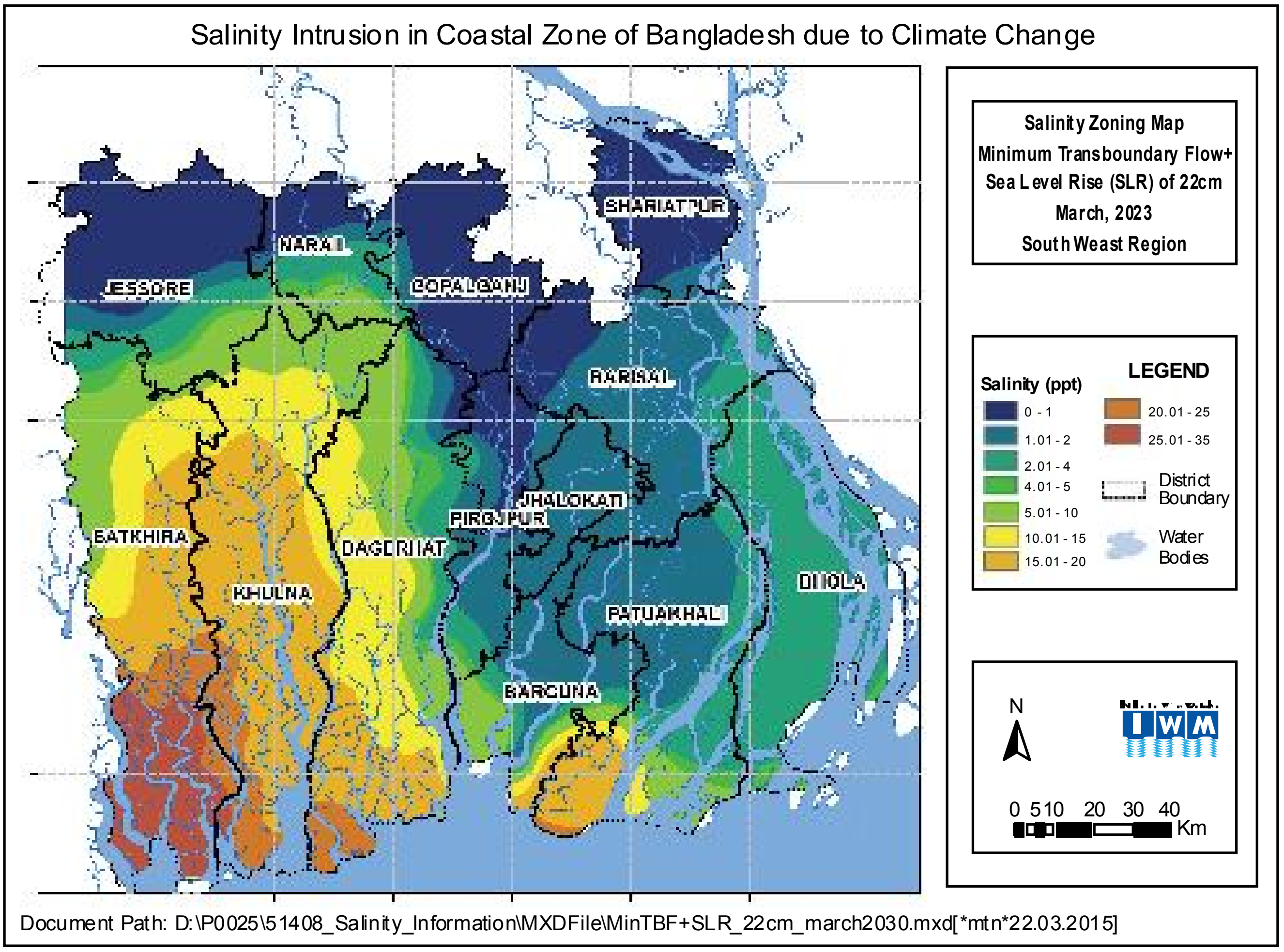


Fig. 8. Spatial distribution of salinity in the southwest coastal region with 22 cm sea level rise and minimum trans-boundary flow through the Ganges River.

Table 3. Effect of climate change (including precipitation, temperature change and sea level rise) and transboundary flow on freshwater availability (flow, m^3/s) in the southwest region of Bangladesh during April

Salinity level (ppt)	Base Condition (2012)	Scenario, 2030					
		Scenrio-I: MinTBF + CC+population+land use change		Scenario-II. Average TBF + CC+population+land use change		Scenario-III:MaxTBF + CC+population+land use change	
		Area (sq. km)	Change of Area over base condition	Area (sq. km)	Change of Area over reference condition	Area (sq. km)	Change of Area over reference condition
0-1 (Potable water)	19,575	15,792	-19.3%	16,738	-14.4%	17,255	-12%
0-2 (Suitable for irrigation)	21,261	18,377	-13.5%	18,909	-11%	19,387	-9%
0-5 (suitable for specific fish species)	26,066	23,517	-9.7%	23,892	-8%	24,722	-5%
>5 (Suitable for shrimp)	12,919	15,403	+19%	15,029	+16%	14,199	+10%

Note: -ve sign refers to a decrease in area and +ve sign refers to an increase in area over the 2012 baseline condition

Simulation results show that the freshwater zone (0-1 ppt) in Barguna, Patuakhali and Jhalokathi Districts is likely to be lost due to sea level rise of 52 cm in the year 2050. This increase in river water salinity is likely to impact freshwater aquaculture, drinking water supply and agriculture.

Installation of the Ganges barrage to divert flow through the Gorai River and other distributaries of the Ganges River is predicted to result in substantial seaward movement of the dry season salinity fronts. This would result in an additional 2660 km2 of land being exposed to less than 2 ppt river water salinity in comparison with the base case, i.e. a larger area would have access to irrigation compared to the present condition. However, with sea level rise of 22 cm, this additional area would decrease to 886 km2. Thus, the Ganges barrage would bring considerable benefits, even under 22 cm SLR.

7. Conclusions

An innovative methodology was established for selecting and ranking of external drivers of change involving farmers, fishers, researchers, academics and representatives of planning and implementing agencies. The key drivers were considered to be transboundary flow in the Ganges, population growth, land use change and climate change. The likely impacts of these changes were considered to be increased salinity, loss of fresh water fish habitat and rice production during the dry season, and damage to ecosystems.

Reduction in transboundary flow reduces the area where river water is suitable for irrigation (0-2 ppt salinity) and is most felt in the Gorai dependent area. Currently, there is abundant fresh water for irrigation in much of Barisal Division throughout the dry season. Under moderate climate change (scenario A1B) and with 22 cm sea level rise in 2030, salinity does not exceed 2 ppt in Barguna, Patuakhali and Jhalokathi Districts, ensuring continued availability of river water suitable for irrigation throughout the year. However, this region is likely to become more saline (2-4 ppt) with 52 cm sea level rise in 2050, damaging fish habitat and sources of irrigation water.

Regional cooperation is crucial for transboundary flow sharing, which is in turn necessary for salinity control and sustenance of river system ecosystem services in the face of a changing climate. Adaptation measures like the proposed Ganges and Brahmaputra barrages are important for fresh water security under climate change. New salt tolerant cropping technology will also be needed.

Acknowledgements

This paper presents findings from G4 ‘Assessment of the impact of anticipated external drivers of change on water resources of the coastal zone’, a project of the CGIAR Challenge Program on Water and Food.

References

Akhter, S. 2012. Impact of Climate Change on Saltwater Intrusion in the Coastal Area of Bangladesh; Paper presented in the Eighth International Conference on Coastal and Port Engineering in Developing Countries, IIT Madras Chennai, 20-24 February, 2012.

Carpenter, S. R., Bennett, E.M. and Peterson, G.S. 2006. Editorial: Special Feature on Scenarios for Ecosystem Services. Ecology and Society 11(2), 32. Available at http://www.ecologyandsociety.org/vol11/iss2/art32/ (last accessed 15 March 2015).

Dasgupta, S., Kamal, F.A., Khan, Z.H., Choudhury, S. and Nishat, A. 2014, River Salinity and Climate Change: Evidence from Coastal Bangladesh. Policy and Research Working Paper no. WPS 6817. Volume 1. The World Bank.

Mainuddin, M., Kirby, M., Chowdhury, R.A.R., Sanjida, L., Sarker, M.H. and Shah-Newaz, S.M. 2014. Bangladesh integrated water resources assessment supplementary report: land use, crop production and irrigation demand. CSIRO: Water for a Healthy Country Flagship, Australia.

Khan, Z.H., Kamal, F.A., Khan, N.A.A, Khan, S.H. and Khan, M.S.A. 2015. Present surface water resources of the Ganges coastal one in Bangladesh. These proceedings.

Climate change impacts on crop production and water requirement in southern Barisal, Bangladesh

M. Maniruzzaman[1], J.C. Biswas[1], M.A.I. Khan[1], G.W. Sarker[1], S.S. Haque[1], J.K. Biswas[1], M.H. Sarker[2], M.A. Rashid[2], N.U. Sekhar[3], A. Nemes[3], S. Xenarios[3] and J. Deelstra[3]

[1] Bangladesh Rice Research Institute, Bangladesh, mzamaniwm@yahoo.com, jatishb@yahoo.com, ashikjp@gmail.com, gwsarker@yahoo.com, shamiulbrri@gmail.com, biswas.jiban@gmail.com
[2] Center for Environmental and Geographical Information Services, Bangladesh, mhsarker@cegisbd.com, arashid@cegisbd.com
[3] The Norwegian Institute for Agricultural and Environmental Research, Norway, Nagothu.UdaySekhar@bioforsk.no, Attila.Nemes@bioforsk.no, Stefanos.Xenarios@bioforsk.no, Johannes.Deelstra@bioforsk.no

Abstract

Crop production in Bangladesh's southern Barisal Division is vulnerable because of increasing erratic rainfall, cyclones, tidal surge and salinity intrusion. Climate change and resultant sea level rise will exacerbate the situation. The effects of global climate change on climate in three *upazilas* of Patuakhali and Barguna Districts in southern Barisal were determined by downscaling, and used to assess the impacts of climate change on surface water resource availability, rainfed crop yields and net irrigation requirement. Mean annual temperature was predicted to increase by 1 to 30 C in the 21st century under IPCC (Intergovernmental Panel on Climate Change) scenario A1B, and by 0.6 to 2.5°C under scenario A2, compared to the baseline of 1971 to 2010. Annual rainfall was usually predicted to decrease in both scenarios throughout most of the 21st century, by 2 to 11%. The exceptions were 4% increases from 2011 to 2040 using scenario A1B in two of the three upazilas, and by 1 to 6% in all three upazilas from 2071 to 2100. A 12 to 30% reduction in river flows was predicted during the pre-monsoon period using the SWAT (Soil and Water Assessment Tool) model, while monsoon season and total annual water flows were predicted to increase during the 21st century. The DRAS (drought assessment) model predicted a 3 to 7% yield increase of rainfed T. Aus throughout most of the 21st century. On the other hand, rainfed *T. Aman* yield was predicted to decrease by 2 to 19% due to decreased rainfall and increased temperature. Irrigation water requirement to meet evaporative demand was predicted to decrease for *T. Aus* and to increase for *T. Aman* under the A1B and A2 scenarios. Concerted efforts by regional research and extension organizations are needed for the development and promotion of strategies for adaptation of cropping systems to climate change in southern Barisal.

Key message: Climate change is predicted to increase grain yield of pre-monsoon rainfed aus crops by 3 to 7% throughout most of the 21st century, and to decrease yield of monsoon rainfed aman crops by 2 to 19%, in southern Barisal, Bangladesh, in the absence of interventions.

Keywords: Climate change, SWAT model, DRAS model, fresh water

1. Introduction

The coastal areas of Bangladesh can broadly be divided into three distinct regions—eastern, central and western—based on morphological features. The PDO–ICZMP (2003a) classified the coastal areas of Bangladesh under two broad categories: interior coast and exterior coast. Out of 19 coastal districts (147 *upazilas*) a total of 48 *upazilas* in 12 districts (23,900 km2) are exposed to the sea and/or lower estuaries and defined as the exposed coast, and the remaining 99 *upazilas* are termed interior coast with a total area of 47,200 km^2 (PDO-ICZMP 2003b) (Figure 1).

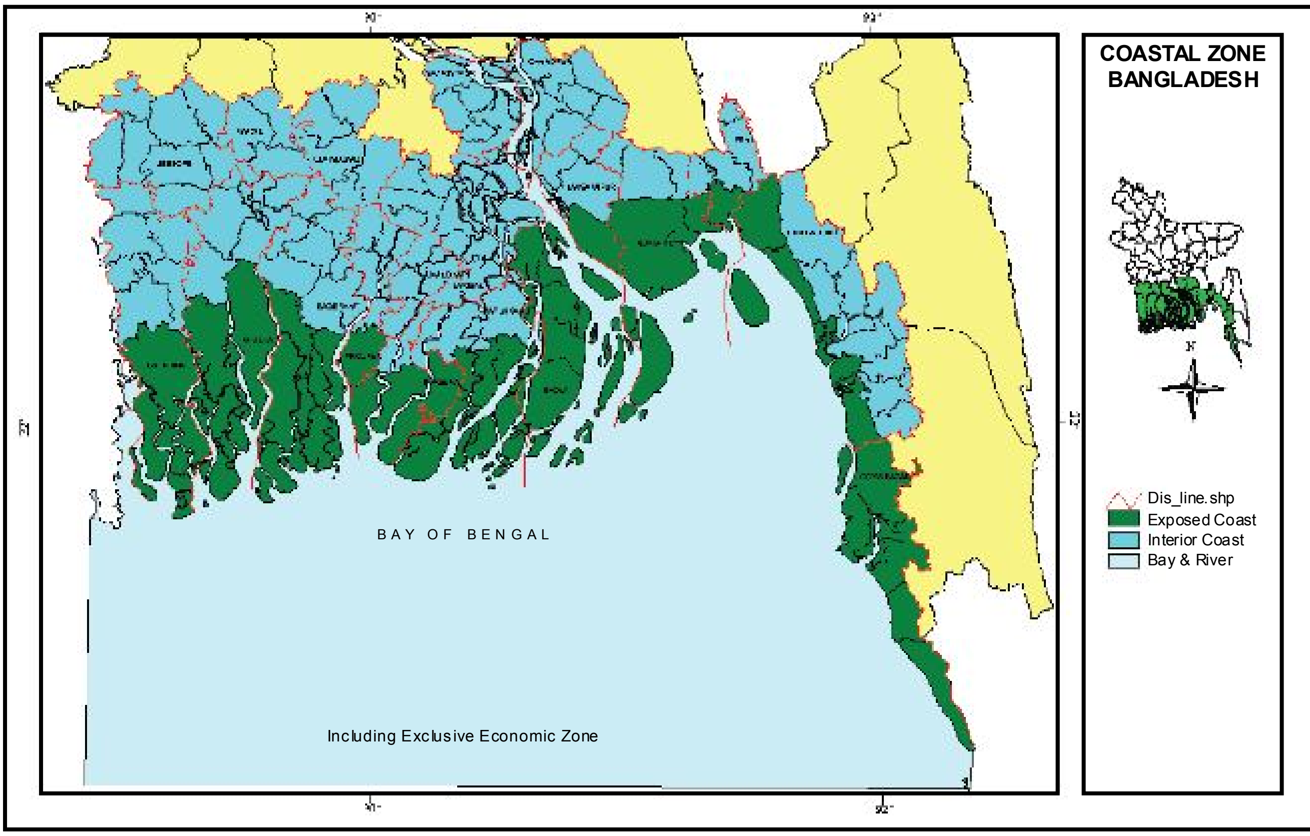


Fig. 1. Coastal regions in Bangladesh (source: BOBLME 2011).

The coastal zone of Bangladesh has many rivers and distributaries and complex ecology, and is strongly affected by cyclones, flooding, tidal surges and salinity. The coastline is 734 km long and the coastal zone has a population of about 50 million people, nearly one-third of the total population of the country (Miyan 2009). The majority of the people in the coastal zone are dependent on primary production (agriculture and aquaculture), and in particular on rice production, for their food security and livelihoods.

The suitability of crops and cropping systems for any region depends on climate, soils and water availability. The climate of the coastal zone is subtropical monsoon, with average annual rainfall of about 2,000 mm, most of which falls from June to October. The rainy season is followed by a cool and dry winter from December to February, and a hot summer in April to June during which there are occasional pre-monsoon rains. During winter and summer, salinity of the river water and soil increases, and availability of fresh water for irrigation is limited in many regions. Therefore, the main crop is aman rice grown during the rainy season over most of the coastal zone. Very limited areas of irrigated rice (boro) are grown during the dry season/early summer in the more northern parts of the coastal zone, and limited areas of aus rice are grown during summer/early rainy season (aus) in the south-central coastal zone. Both the aman and aus crops are predominantly rainfed.

Global warming is increasing the risk of drought and sea level rise in Bangladesh. The IPCC Report 5 (2013) indicated that temperature is likely to increase by 1.8 to 3.4°C at the end of the 21st century along with sea level rise of 0.26 to 0.82 m. Sea level rise will shift the coastal periphery inland and could reduce the land area by 17% (Dewan and Nizamuddin 1998; SRDI 1997). A sea level rise of 32 cm by 2050 is also predicted to increase the salt-affected area to 10,600 km2, and to 14,500 km^2 with 88 cm sea level rise at the end of this century (Figure 2, CEGIS 2006). The frequency of cyclones, severe flooding and drought is also expected to increase in coming years.

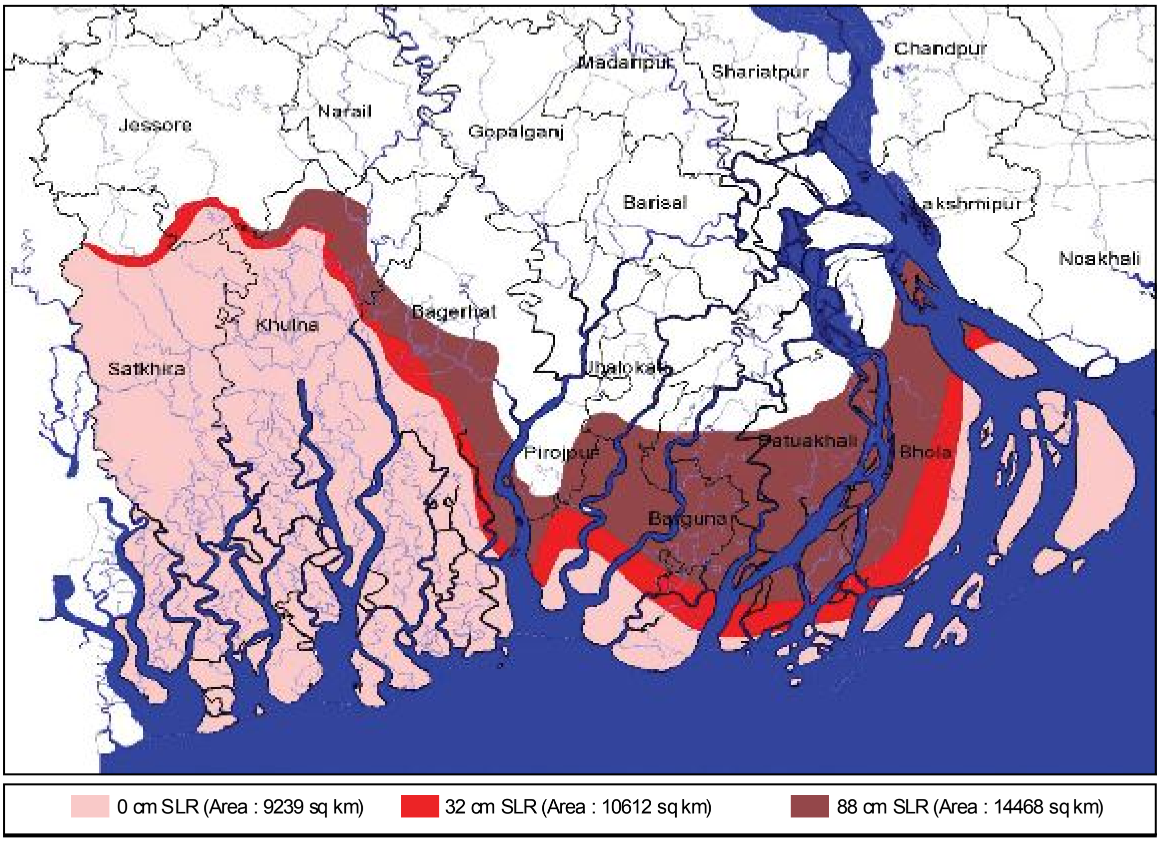


Fig. 2. Change in the salt-affected area due to sea level rise of 32 cm in 2050 and of 88 cm at the end of the 21st century (source: Center for Environmental and Geographic Information Services (CEGIS), Dhaka, Bangladesh).

Any variations in seasonal monsoon rainfall, temperature and cyclonic storms could significantly influence rice production and food security. To meet such challenges, analysis of the impacts of change on crop production and identification of potential adaptation strategies are needed. Therefore, a study was undertaken to estimate the impacts of global warming on the climate at three locations in the south-central coastal zone, and on the availability of surface water resources (river flows). The results were then used to determine the impacts of global warming on rice yields and crop water requirements.

2. Methodology

2.1 Site details

The study sites were three upazilas in southern Barisal Division - Amtali and Patharghata Upazilas of Barguna District and Kalapara Upazila of Patuakhali District (Figure 3). All upazilas are within polders. Soil properties were determined based on 30 samples per upazila collected after harvest of the aman crop. Soil properties varied widely. Most of the soils are acidic to neutral with generally satisfactory organic matter content, but with widespread deficiencies of nitrogen and phosphorus (Table 2). Soil salinity in the upazilas ranged from low to high. Soil salinity (electrical conductivity of saturation 1:5 soil:water extract, EC1:5) ranged from 1.5 -11.5 dS/m. High soil salinity impairs crop performance at some locations, especially in the dry season.

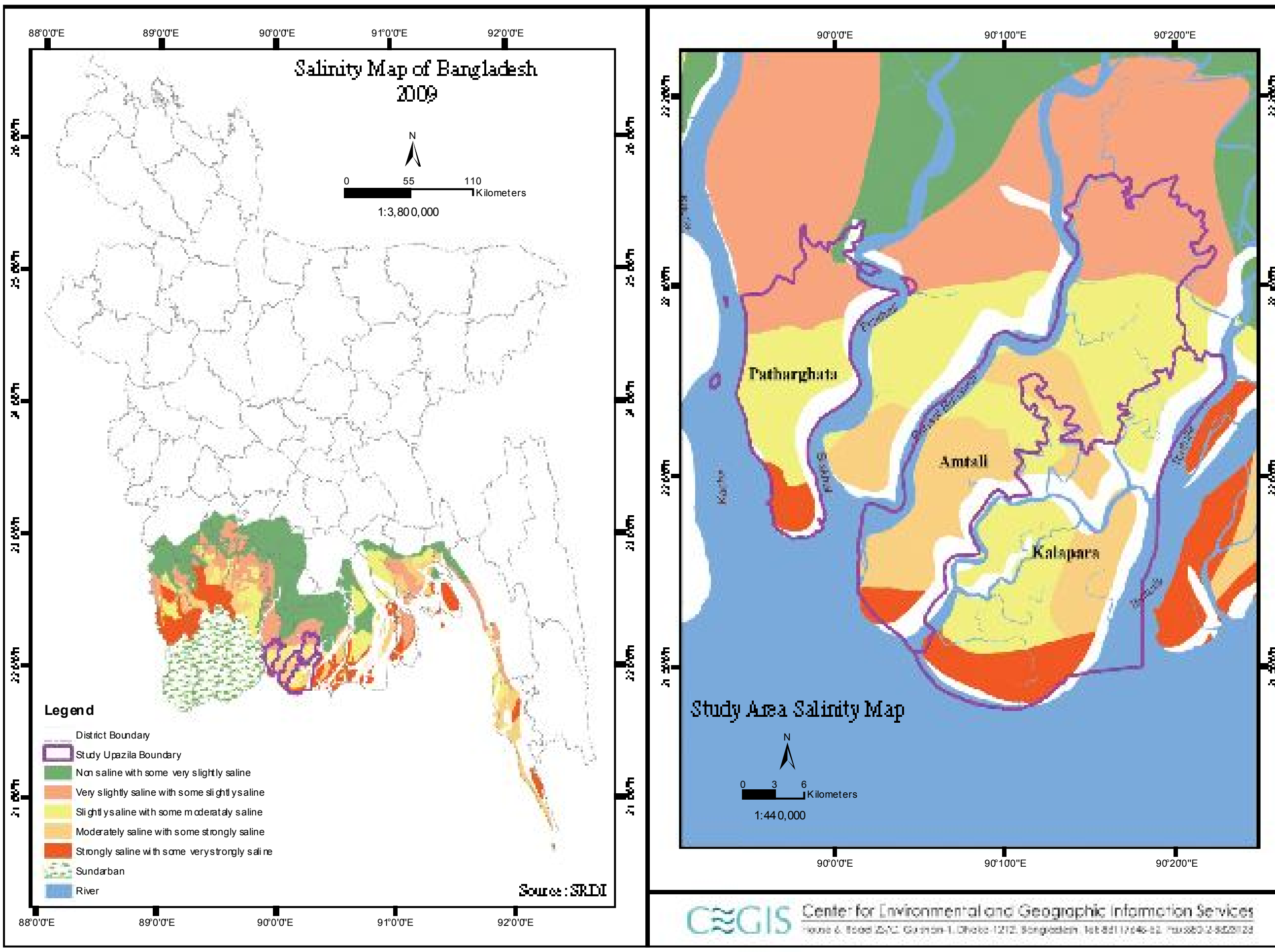


Fig. 3. Location and salinity of the study upazilas (purple boundaries) in southern Barisal, Bangladesh.

Table 2. Soil chemical properties of the study sites (range, median value in parentheses)

***Upazila* (n=30 per *upazila*)**	**EC1:5 (dS/m)**	**pH**	**OM**	**Total N**	**Mg**	**K**	**P**	**B**	**Zn**
			%		**Meq/100 g soil**		**μ/g**		
Amtali	1.44-6.85 (3.50)	4.3-7.1 (5.18)	0.93-2.63 (1.73)	0.05-0.14 (0.09)	5.09-8.08 (6.62)	0.21-0.72 (0.30)	0.42-5.76 (2.67)	0.22-1.10 (0.80)	0.54-1.60 (1.11)
Kalapara	1.66-5.86 (3.21)	4.7-5.4 (4.97)	0.76-2.16 (1.55)	0.04-0.12 (0.09)	4.97-7.99 (5.83)	0.20-0.34 (0.31)	0.85-8.76 (3.97)	0.50-0.95 (0.71)	0.69-1.28 (0.99)
Patharghata	1.91-11.51 (6.93)	4.5-7.2 (6.17)	0.83-4.17 (2.25)	0.05-0.24 (0.13)	3.32-6.56 (5.20)	0.20-0.34 (0.31)	1.27-11.78 (6.55)	0.33-0.98 (0.71)	0.52-2.77 (1.23)
Critical values	-	-	-	0.12	0.50	0.12	8.00	0.20	0.60

2.2 Climate change scenarios

Future climate and water resource scenarios were developed by downscaling the predictions of global climate change models to the upazila level. The downscaled predictions were used as inputs for prediction of water resource availability using hydrological modeling, and for prediction of crop irrigation requirement and yield using a crop model.

2.2.1 Climate change

The process of assessing future likely climate change for the region involved several steps including: i) review of existing model-based climate scenarios, ii) evaluation of climate model outputs and scenarios for Bangladesh, iii) assessment of the limitations of climate models and downscaling in the context of Bangladesh, iv) identification of currently adopted models, v) selection of climate models for use in this study, vi) downscaling of climate model results to upazila level, and vii) generation of climate scenarios. Two IPCC (2013) future climate scenarios were selected for the study: A1B (balanced emphasis on all energy sources) and A2 (self-reliant nations, continuously increasing population and regionally-oriented economic development). A dynamic downscaling process using the PRECIS (Providing Regional Climates for Impact Studies) regional climate model (Jones et al. 2004) by the Institute of Water and Flood Management from 1981 to 2100 was used to generate future climate data for the upazilas. The predicted rainfall pattern by 2050 was determined based on Rahman et al. (2012).

2.2.2 Hydrological modeling

Fresh surface water availability was estimated based on inflows (from rainfall and rivers) to the study area generated using the SWAT hydrological model (Neitsch et al. 2009; Arnold et al. 1998; Arnold et al. 2009a, b). The SWAT model is a physically based, continuous simulation model developed for watershed assessment of short and long-term hydrology and water quality. It is a widely used catchment-scale model that can predict the impacts of land management practices (human activities) and climate change over time on water, sediment, nutrient and pesticide yields with reasonable accuracy in large, ungauged river basins (Santhi et al. 2001). The model was calibrated and validated on daily and monthly scales for Amtali, Kalapara and Patharghata Upazilas (Figures 4a, b) using observed climate data (daily precipitation, maximum and minimum air temperature, wind speed, relative humidity and solar radiation) and hydrological data (watershed boundaries, river network, land use, flow rates). This part of the study area is situated in the coastal region and there are no observed discharge data to calibrate the model. For that reason, the model was calibrated against the monthly observed groundwater level at Patharghata station (Id BAG 005) for the period of 1986 to 1990 and validated for the period of 1981 to 1985. The model was also validated against the observed groundwater level at Amtali station (Id BAG002) for the period of 1981 to 1985. The Nash-Sutcliffe Efficiency (NSE) value for the calibration period was 0.54, which is in the range of "adequate" (Rossi et al. 2008). The values of mean relative bias (PBIAS), RSR (ratio of the root mean square error to the deviation) and coefficient of determination (R^2) were 14.15, 0.67 and 0.73, respectively, indicating satisfactory predictive capability of the calibrated model against the calibration data set. The NSE values for the validation period were 0.27 and 0.36 for Patharghata and Amtali station, respectively, and the correlation coefficients were 0.56 and 0.67, respectively. These results are acceptable, considering the simplicity of the SWAT soil water model with respect to other models (CEGIS, 2013). The calibrated and validated SWAT model was run for baseline conditions to simulate the temporal and spatial distribution of surface water yields in the study areas. The model was then run using future climate predictions to estimate the impacts of climate change on fresh water availability.

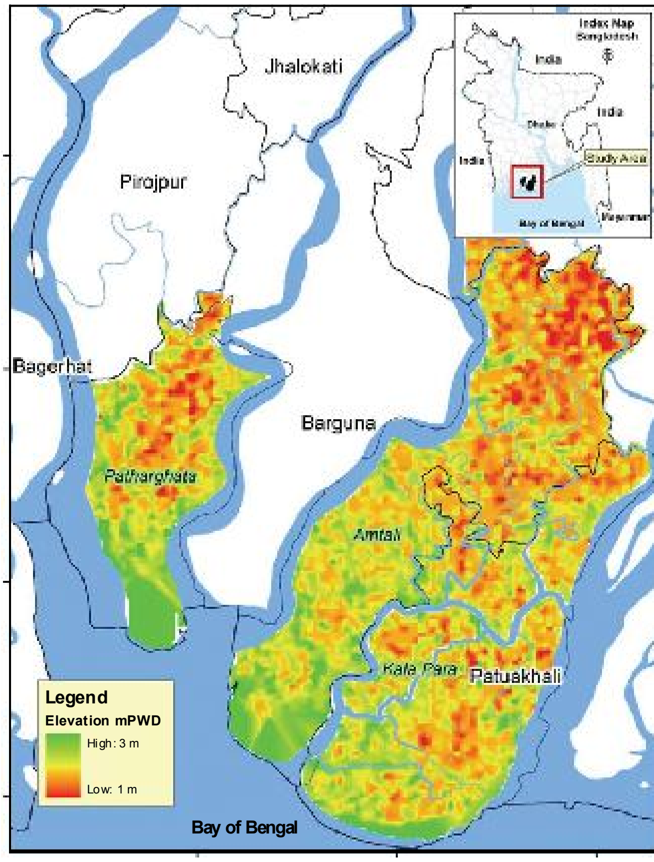


Fig. 4a. Base map of the study area.

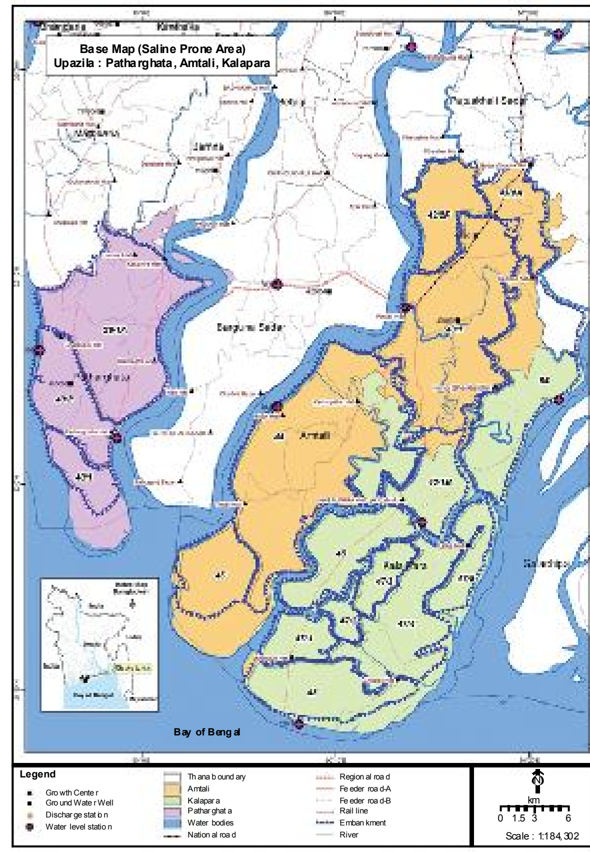


Fig. 4b. Land elevation of the study area.

2.2.3 Irrigation requirement and crop yield

Net irrigation requirement and crop yield reduction as a result of water deficit were estimated using the Drought Assessment (DRAS) model (Figure 5) (Hossain et al. 2008). This was done separately for pre-monsoon (aus), monsoon (aman) and winter rice (boro) crops in the study areas under baseline and A1B and A2 climate change scenarios.

The DRAS model uses three types of data: i) climate data, ii) soil data, and (iii) crop and management data. Thirty years (1981-2010) of climate data from the Bangladesh Meteorological Department for Khepupara in Patuakhali District were used. Potential evaporation (ETo) was calculated using ETo Calculator Version 3.2 (Raes 2012). Decadal ETo was used to determine maximum ET of a crop and to calculate actual ET under an existing soil moisture regime.

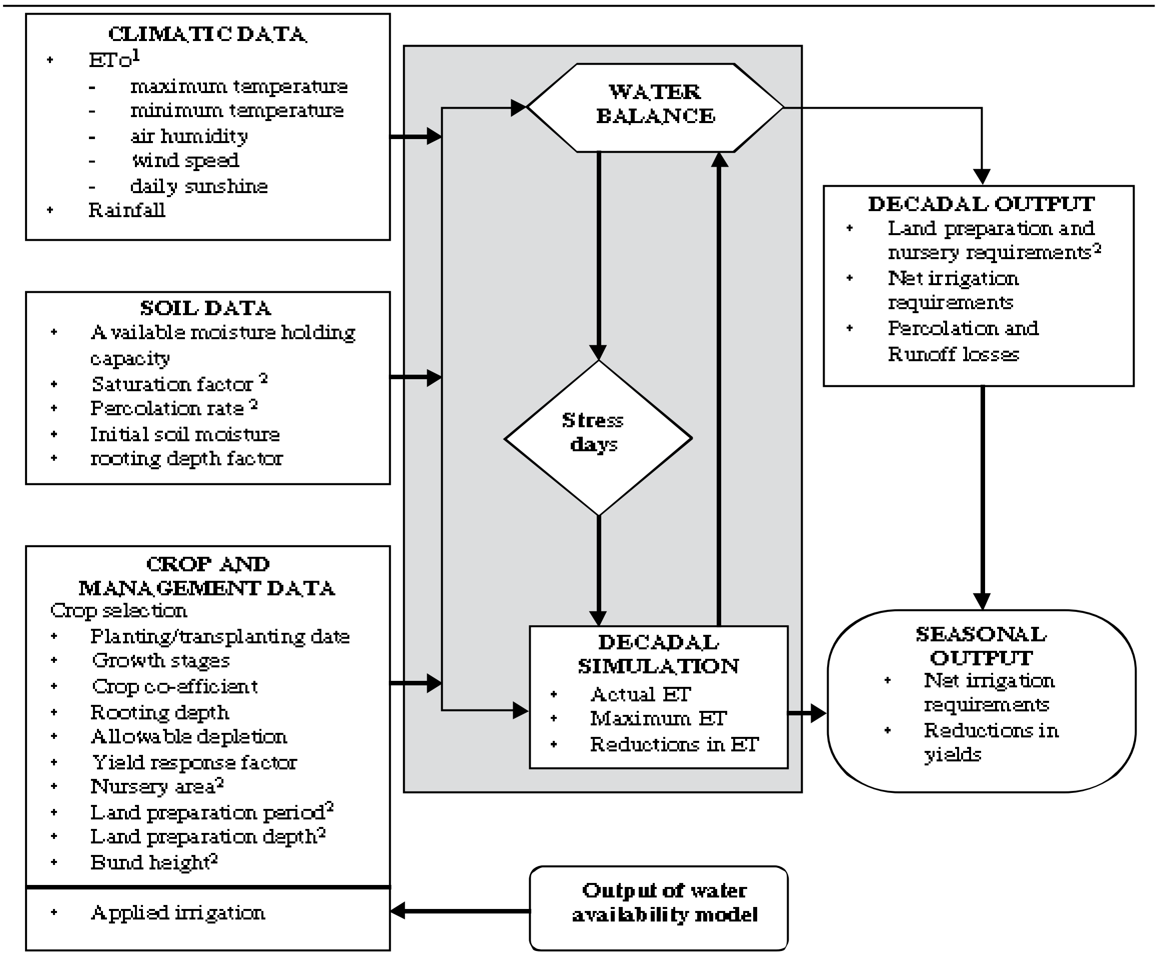


Fig. 5. Structure of the irrigation water demand and yield reduction model.

[1] Reference evapo-transpiration (ETo) is calculated separately by ETo Calculator Version 3.2 (Raes 2012) using climate data

[2] Parameters are applicable for transplanted rice crops

3. Results and discussion

3.1 Climate analysis

Mean annual temperature at Khepupara during 1971 to 2010 was around 26.2° C. Monthly mean minimum temperature was least in January (13.7° C) while monthly mean maximum temperature was highest in April and May (32.7° C). The highest recorded temperature was 38.1° C and the lowest was 8.5° C (CEGIS 2013).

Under both the A1B and A2 climate change scenarios, annual mean temperature of the study region is predicted to be higher during each of the 30-year periods from 2011 to 2040, 2041 to 2070 and 2071 to 2100 than during the base period (1971 to 2010). Increases of 1 to 3° C are predicted under A1B, and of 0.6 to 2.5° C under A2 (Figures 6-8). However, the difference will vary depending on the time period, season and location.

Daily average maximum temperature from April to June during the baseline period was more than 32° C (Figure 9), above the critical values for flowering of wheat, pea, mustard and tomato (Table 3). With climate change, maximum temperature will be more than 35° C from March to May by 2050 (IPCC 2013), indicating unsuitability for cultivation of those crops unless heat-tolerant varieties are developed and disseminated, or the cropping window is changed so that flowering occurs at lower temperatures.

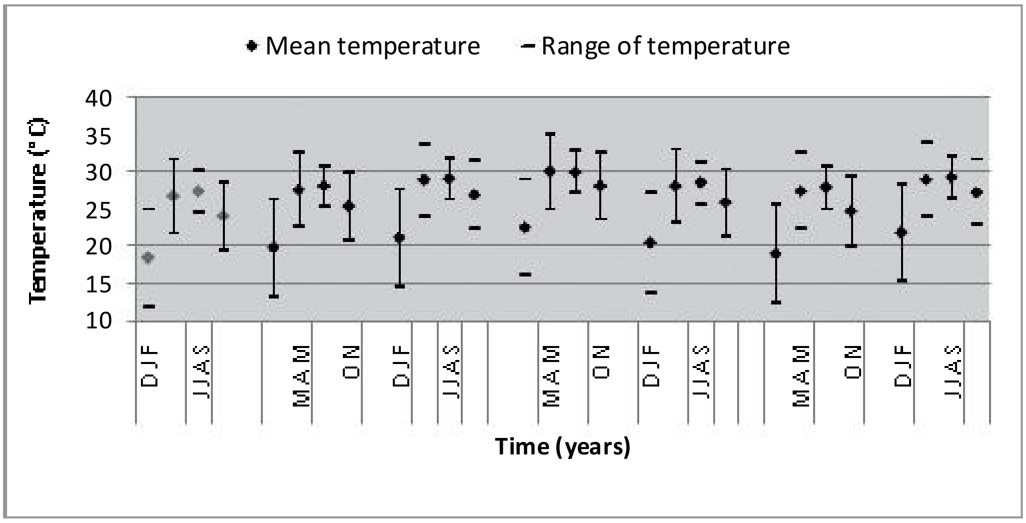


Fig. 6. Seasonal temperature variation in Amtali Upazila under baseline and future climate scenarios.

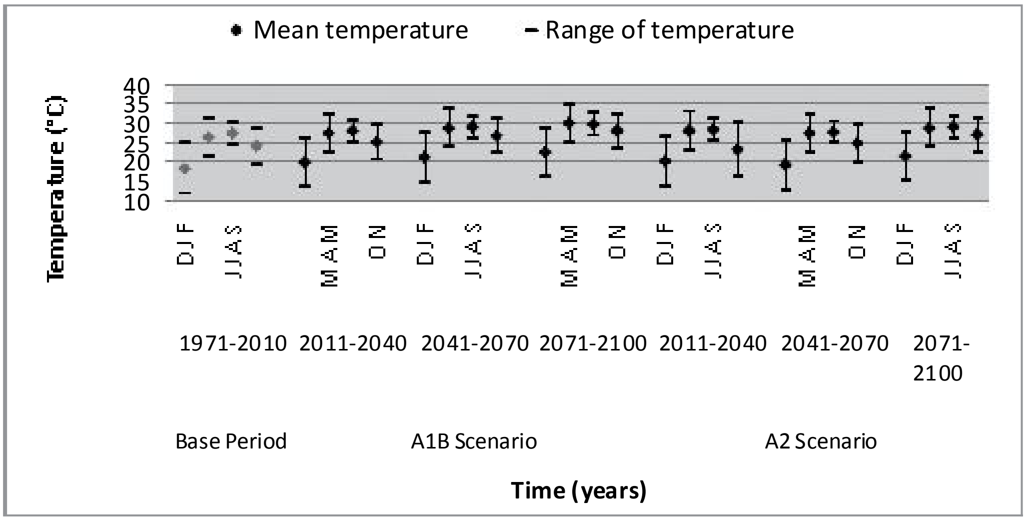


Fig. 7. Seasonal temperature variation in Kalapara Upazila under baseline and future climate scenarios.

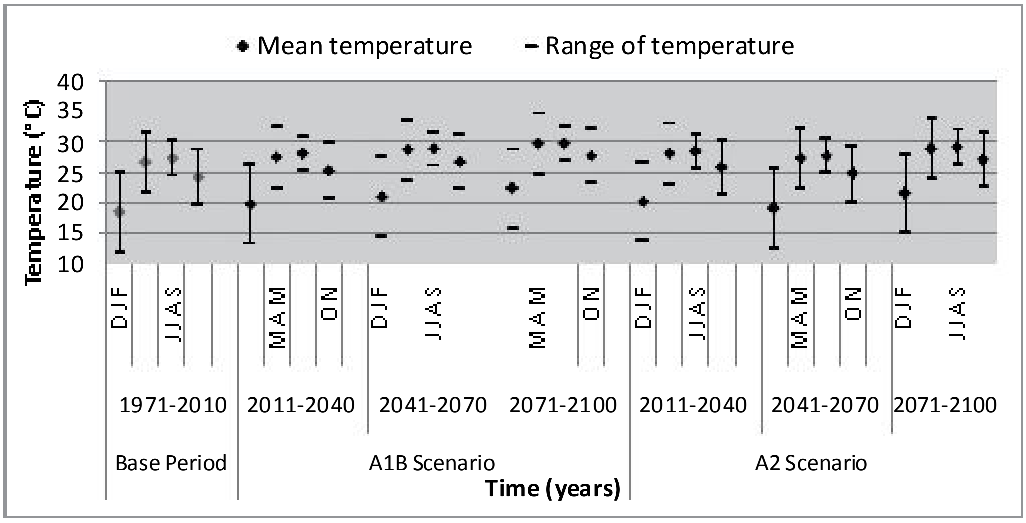


Fig. 8. Seasonal temperature variation in Parthaghata Upazila under baseline and future climate scenarios.

Table 3. Critical temperature for sterility at flowering stage in selected field crops

Name of crop	Critical temperature for sterility (°C)	Reference
Rice (Oryza sativa L.)	35	BRRI 2011
Wheat (Tritichum aestivum L.)	30	Saini and Aspinal 1982
Chickpea (Cicer arietinum L.)	35	Devasirvatham et al. 2012
Pea (Pisum sativum)	30	McDonald and Paulsen 1997
Groundnut (Arachis hypogaea L.)	35	Prasad et al. 1999
Mustard (Brassica juncea L.)	27	Chauhan et al. 2013
Mung bean (Vigna radiata L.)	40	Tickoo et al. 19996
Tomato (Lycopersicon esculentum L.)	32	Peet et al. 1998

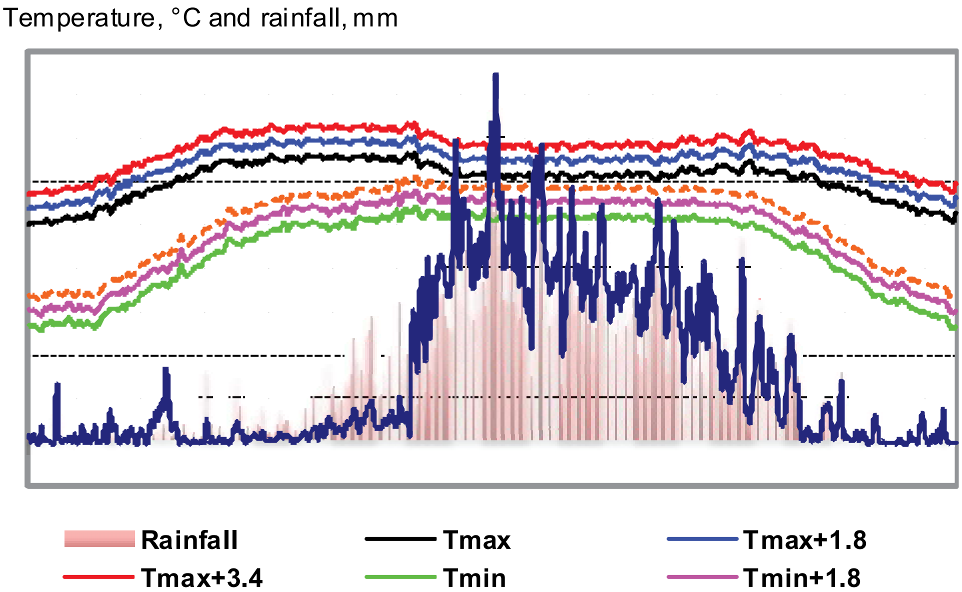


Fig. 9. Mean daily average maximum and minimum temperatures and rainfall (1983-2012 at Khepupara), and the effects of temperature increases of 1.8 and 3.4°C and 3% precipitation increase.

The predicted effects of climate change on rainfall are variable over time and across scenarios and upazilas. In Amtali, annual mean precipitation is expected to be 3% higher in 2011 to 2040 than the baseline under A1B scenario, but to be 3% lower from 2041 to 2100. In the A2 scenario, expected mean annual precipitation will be 9 to 11% lower from 2041 to 2070 than during the base period (Figure 10). In Kalapara Upazila the overall trend will be similar to that in Amtali Upazila. However, annual mean precipitation in Patharghata Upazila is predicted to decline in all three future periods in both scenarios except for A1B from 2071 to 2100. The predicted decrease from the base period is highest (about 11%) from 2041 to 2070 under A1B. Predictions of the effects of climate change on rainfall are inconsistent. Hussain (2011) reported increased rainfall in various regions of Bangladesh, including Barisal, during March through November in both 2050 and 2070 based on the Geophysical Fluid Dynamics Laboratory Transient (GFDL-TR) Global circulation model, but decreased rainfall in the same period based on the Hadley Center (HadCM2) Global circulation model. Rahman et al. (2012) reported increased rainfall by 107% in the dry season (December to February) using the Regional Climate Model version 3 (RegCM3), but Hussain (2011) predicted variable results in the dry season. Increased winter rainfall could hamper establishment of non-rice winter crops in southern Bangladesh due to excessive soil moisture and delayed recession of flood water. However, such a scenario would reduce irrigation cost for boro rice cultivation.

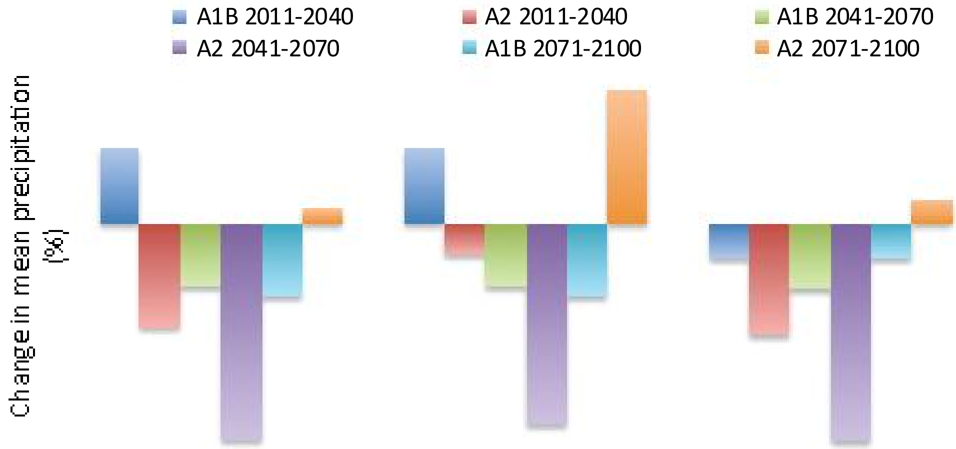


Fig. 10. Percentage change in annual mean precipitation in Amtali, Kalapara and Patharghata *Upazilas* considering A1B and A2 scenarios.

3.2 Predicted water availability

There are many natural canals (*khals*) crisscrossing Barisal region, which give the opportunity to irrigate using surface water. Tidal river water flows into the canals twice a day, with peak tides during the full and dark moons. As a consequence, surface water availability for crop production is sufficient in Barisal region if properly managed. However, after the middle of February, river water salinity increases due to increasing salinity (Miah 2010). The increase in salinity varies with location and is higher towards the coast – in much of Barisal the river water is of low salinity throughout the year (Khan et al., these proceedings), but this is not the case in the southern-most regions of Barisal. The problem of waterlogging during the rainy season is also increasing in some locations due to siltation of the khals, which also serve as drainage outlets.

The SWAT model was used to assess surface water availability under the A1B and A2 scenarios for the 2011 to 2040, 2041 to 2070 and 2071 to 2100 periods. Water availability trends are similar for all three study upazilas, so only the results of Patharghata are presented here. Annual water availability is predicted to decrease for both scenarios throughout the 21st century, except for A1B in 2011 to 2040 and A2 in 2071 to 2100 (Figure 11), however, the impact on availability within seasons varies. The reduction in water availability will be highest (12 to 30%) during the pre-monsoon period. Water availability will be reduced by 2 to 20% and 3 to 15% during the post-monsoon period and dry season, respectively. During the monsoon (Jun-Sep), predicted percentage changes in water availability are generally small. Predicted changes in total annual freshwater availability are also small for scenario A1B, while availability is predicted to be 10% lower in scenario A2 in 2040 to 2070, but 7% higher in 2070 to 2100.

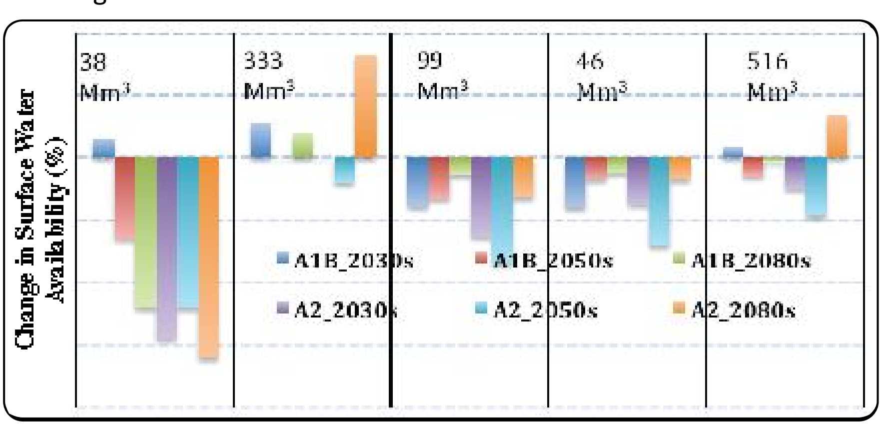


Fig. 11. Change in seasonal and annual surface water availability for A1B and A2 climate change scenarios of Patharghata *Upazila*, Barguna District. Values in the upper part of the figure are surface water availability during the base period (1981-2010).

Note: 2020s = 2010-2040; 2050s = 2040-2070; 2080s = 2070-2100

3.3 Predicted grain yield and water requirement

Grain yield of rainfed T. Aus is predicted to be 3 to 7% higher in all scenarios for most of the 21st century, apart from 2070 to 2100 in scenario A1B (Table 3). The yield is associated with increased rainfall by up to 15% under A1B and 12% under A2 scenarios throughout the 21st century in the T. Aus growing season. In contrast, yield of rainfed T. Aman rice yield is predicted to be 2 to 19% lower under the two scenarios throughout the 21st century, and this is associated with a decrease in rainfall of up to 2% under A1B and 10% under A2 scenarios together with an increase in evaporation rate of up to 12% under A1B and 8% under A2 scenarios during the T. Aman growing period.

Table 3. Yield of rainfed rice under different climate change scenarios in the study region

Crop name	% yield increase (+) or decrease (-) from base scenario					
	2010-2040		2040-2070		2070-2100	
	A1B	A2	A1B	A2	A1B	A2
T. Aus	+(6 to 7)	+(6 to 7)	+(3 to 4)	+(6 to 7)	+(0 to 1)	+(6 to 7)
T. Aman	-(8 to 11)	-(5 to 7)	-(3 to 10)	-(13 to 19)	-(4 to 12)	-(2 to 8)

The irrigation water demand of T. Aus is predicted to decrease by 8 to 111 mm compared to the base period under both the A1B and A2 scenarios, with the biggest difference for the 2011 to 2040 period (Table 4) due to increased rainfall in the T. Aus growing season. The effect of climate change on irrigation water demand of T. Aman is smaller (increases of 7 to 49 mm) due to decreased rainfall and increased evaporation rate. Throughout the 21st century there is a large surplus of surface water available for both the T. Aus and T. Aman crops. This implies that improving infrastructure for irrigation could mitigate seasonal droughts. In contrast to the situation for T. Aus and T. Aman, there is always a large surface water deficit for boro rice cultivation in the study sites. The effect of climate change on irrigation demand for boro is variable – small increases with scenario A1B, and slightly larger decreases with scenario A2 – and effects on surface water availability are very small.

Table 4. Comparison of irrigation water demand and surface water availability (SWA, mm) at Amtali Upazila, Barguna District

Scenarios	Year	*T. Aus*		*T. Aman*		*Boro*		Surplus/Deficit		
		Demand	SWA	Demand	SWA	Demand	SWA	T. Aus	T. Aman	Boro
	Base	117	833	97	473	881	58	716	376	-823
A1B	2020s	39	950	118	486	898	55	911	368	-843
	2050s	74	802	146	469	890	55	728	323	-835
	2080s	109	823	116	475	919	51	714	359	-868
A2	2020s	6	772	107	388	824	65	766	281	-759
	2050s	24	762	120	402	820	51	738	282	-769
	2080s	31	903	104	508	859	48	872	404	-811

Note: Base year = 1981-2010; SWA = Surface Water Availability; 2020s = 2010-2040; 2050s = 2040-2070; 2080s = 2070-2100

Estimated net irrigation water requirement (NIR) for T. Aus, T. Aman and boro crops is 100 to 120 mm, 80 to 125 mm and 830 to 880 mm, respectively, in the base period (Table 5). Irrigation water requirement is predicted to decrease under both scenarios for T. Aus, with reductions usually in the range of 60 to 100 mm. In contrast, Rahman et al. (2012) reported increased irrigation water requirements for T. Aus cultivation. There were generally small increases in NIR for T. Aman under both the scenarios. However, NIR would still be low because of high rainfall during the aman crop (Rahman et al. 2012). The predicted effect of climate change on NIR for boro is generally small but highly variable across scenarios and time periods during the 21st century.

Table 5. Net irrigation requirement (NIR) and effect of climate change on NIR in the study region

Crop Name	**Base year**	**Change of NIR (mm)**					
	(1981-2010)	**2010-2040**		**2040-2070**		**2070-2100**	
		A1B	**A2**	**A1B**	**A2**	**A1B**	**A2**
T. Aus	100-120	-(60 to 80)	-(90 to 110)	-(25 to 40)	-(80 to 90)	-(3 to 8)	-(70 to 90)
T. Aman	80-125	+(20 to 30)	+(10 to 30)	+(50 to 70)	+(20 to 40)	+(20 to 25)	+(10 to 30)
Boro	830-880	+(10 to 20)	-(40 to 60)	+(10 to 30)	-(40 to 60)	+(35 to 40)	-(10 to 30)

Note: (+) increased and (-) decreased in comparison with the base year

4. Conclusions and recommendations

In southern Barisal Division, Bangladesh, temperatures are predicted to increase by 1 to 3° C under IPCC (2013) climate change scenario A1B, and by 0.6 to 2.5° C under scenario A2, during most of the 21st century, in comparison with the baseline of 1981 to 2010. In the future, daily maximum temperature of 35° C or more will prevail from March to May, with potential adverse effects on wheat and mustard during the flowering and grain filling periods. Annual mean precipitation is generally predicted to decrease, but predictions are variable across scenarios and time periods, with changes ranging from +3% to -11%. A small increase in the yield of rainfed T. Aus is predicted. However, grain yield of rainfed T. Aman is predicted to decrease. While availability of surface water is predicted to decrease during the pre-monsoon period, water availability would still be more than adequate for irrigation of both T. Aus and T. Aman rice. But there will continue to be insufficient surface water available for irrigation of boro. Net irrigation requirement is predicted to be lower for T. Aus and slightly higher for T. Aman under both the A1B and A2 scenarios from 2011 to 2040 and 2041 to 2070 compared with the baseline. The effects of climate change on NIR for boro are variable and relatively small (only a small fraction of NIR). Further studies are needed on the effects of climate change on fresh water availability taking salinity into account, on rainfed crop response taking into account soil salinity as well as soil moisture, and on potential adaptation strategies to increase crop production in the future climate.

Acknowledgements

The authors acknowledge the “Climate Change Impacts Vulnerability and Adaptation: Sustaining Rice Production in Bangladesh” project funded by the Ministry of Foreign Affairs, Norway through the Royal Norwegian Embassy, Dhaka for funding the research in collaboration with BRRI, CEGIS and Bioforsk.

References

Arnold J. G., R. Srinivasan, R. S. Muttiah and J. R. Williams. 1998. Large area hydrologic modeling and assessment: Part I. Model development. J. American Water Resources Assoc. 34(1): 73-89.

Arnold J. G., S. L. Neitsch, J. R. Kiniry and J. R. Williams. 2009a. Soil and Water Assessment Tool – Theoretical Documentation, Version 2009, Texas, USA.

Arnold J. G., J. R. Kiniry, R. Srinivasan, J. R. Williams, E. B. Haney and S. L. Neitsch. 2009b. Soil and Water Assessment Tool– Input/Output File Documentation, Version 2009, Texas, USA.

BOBLME (Bay of Bengal Large Marine Ecosystem Project). 2011. Country report on pollution in the BOBLME – Bangladesh. BOBLME-2011-Ecology-01

BRRI (Bangladesh Rice Research Institute). 2011. Modern Rice Cultivation, 16th Edition. Pub No 5. 72pp.

CEGIS 2006. Impacts of Sea Level Rise on Land-use Suitability and Adaptation Options. Final Report, Submitted to the Ministry of Environment and Forest, Government of Bangladesh and United Nations Development Programme (UNDP), Dhaka, Bangladesh

CEGIS 2013. Description of physical and environmental parameters. CEGIS, Dhaka.

CEGIS, 2013. Report on Water Availability Assessment using SWAT Model. CEGIS, Dhaka.

Chauhan, J. S., M. L. Meena, M. Saini, D.R. Meena, M. Singh, S. S. Meena, and K. H. Singh. 2013. Heat stress effects on morpho-physiological characters of Indian mustard (Brassica juncea L.). Directorate of Rapeseed-Mustard Research, Sewar, Bharatpur 321 303, Rajasthan, India. E-mail: js_chau @yahoo.com

Devasirvatham V., P. M. Gaur, N. Mallikarjuna, R. N. Tokachichu, R. M. Trethowan, and D. K. Y. Tan. 2012. Functional Plant Biol., 39(12): 1009-1018

Dewan A. M. and K. Nizamuddin. 1998. A geographical Analysis of Salinity Intrusion in the South-West Region of Bangladesh. In Geographical paper No. 17.

Hossain, M. A., M. A. Haque, M. A. Ibrahim, E. H. Chaoudhury and M. A. Rashid. 2008. Bangladesh J of Agril. Engg. 19(1&2): 19-26.

Hussain, S. G. 2011. Assessing impact of climate change on cereal production and food security in Bangladesh. Pages 459-476. In R. Lal et al (ed) Climate Change and Food Security in South Asia. Springer Science+Business Media B. V. 2011.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Summary for Policymakers. Contribution of the Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jones, R. G., M. Noguer, D. C. Hassell, D. Hudson, S. S. Wilson, G. J. Jenkins and J. F. B. Mitchell. 2004. Generating high resolution climate change scenarios using PRECIS, Met Office Hadley Centre, Exeter, UK, pp. 40.

McDonald, G. K. and G. M. Paulsen. 1997. High temperature effects on photosynthesis and water relations of grain legumes. Plant Soil, 196, 47–58.

Miah M. M. U. 2010. Final report of UNEP/APFED project. Field Testing of Innovative Farming Practices Related to Climate Change in the Vulnerable Areas of Bangladesh. BCAS and UNEP, Dhaka, Bangladesh. 140p.

Miyan. M. A. 2009. Monsoon in Bangladesh; Changes and Adaptation: Asian Monsoon Years AMY-6, Kunming China November 30-December 01, 2009

Mondal, M. K., S. P. Ritu, M. H. K. Choudhury, A. M. Chasi, P. K. Majumdar, M. M. Islam and S. K. Adhikari. 2004. Performance of high yielding varieties of transplanted Aman rie in southwest coastal region of Bangladesh. 19-27. Proc. worksho: coastal water management and uptake technologies. IRRI and PETRRA.

Neitsch S. L., J. G. Arnold, J. R. Kiniry, J. R. Williams. 2009. Soil and Water Assessment Tool Theoretical documentation, Version 2009, Texas, USA.

PDO-ICZMP. 2003a. Delineation of the Coastal Zone. Project Development Office for Integrated Coastal Zone Management Plan. December 2003.

PDO-ICZMP (Program Development Office for Integrated Coastal Zone Management Plan). 2003b. Coastal Zone Management– an Analysis of Different Policy Documents; WP009, Dhaka

Peet M. M., S. Sato, and R. G. Gardner. 1998. Comparing heat stress effects on male-fertile and male-sterile tomatoes. Plant, Cell & Environ., 21: 225–231.

Prasad, P. V., P. Q. Craufurd, and R. J. Summerfield. 1999. Fruit Number in Relation to Pollen Production and Viability in Groundnut Exposed to Short Episodes of Heat Stress. Annals Bot., 84: 381-386.

Raes, D. (2012) The ETo Calculator. Reference Manual Version 3.2. FAO, Rome, Italy

Rahman, M.M., M.N. Islam, A.U. Ahmed, and F. Georgi, 2012. Rainfall and temperature scenarios for Bangladesh for the middle of 21st century using RegCM. J. Earth Syst. Sci. 121(2): 287-295.

Rossi, C. G., Dybala, T. J., Moriasi, D. N., Arnold, J. G., Amonett, C. and Marek, T. 2008. Hydrologic calibration and validation of the soil and water assessment tool for the Leon River watershed. Soil Water Conserv. 6, 533–541.

Saini, H.S. and D. Aspinal. 1982. Abnormal sporogenesis in wheat (Triticum aestivum L.) induced by short periods of high temperature. Ann. Bot., 49: 835-846.

Santhi C., J. G. Arnold, J. R. Williams, W. A. Dugas, R. Srinivasan and L. M. Hauck. 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. J. American Water Resources Assoc. 37(5): 1169-1188.

SRDI. 1997.Agricultural ecology and salinity in coastal areas of Bangladesh. Soil Resources development Institute, Dhaka.

Tickoo, J. L., Gajraj, R. Matho, and C. Manji. 1996. Plant type in mungbean (Vigna radiata (L.) Wilczek). In: Proceedings of Recent Advances in Mungbean Research, A.N. Asthana and D.H. Kim (eds.), Indian Society of Pulses Research and Development, Indian Institute of Pulses Research, Kanpur, India, pp: 197-213.

Groundwater salinity zoning for development plans: A case study of four sub-districts in the southwestern coastal region of Bangladesh

M.R. Hasan, M. Shamsuddin, M.S. Masud and A.F.M.A. Hossain

Institute of Water Modelling, Bangladesh, mrh@iwmbd.org, smd@iwmbd.org, msm@iwmbd.org, afh@iwmbd.org

Abstract

The southwestern region of Bangladesh is part of the Ganges floodplain, with low relief and numerous rivers and channels linked with the Bay of Bengal. Surface water salinity is increasing due to reduced upstream water flow. As a result, dependence on groundwater has become vital. The risk of salinization of groundwater is greater in regions closer to the sea and the situation can be further aggravated by anthropogenic influences (global warming, changes in trans-boundary river flows). For optimal use of groundwater resources in the coastal area a salinity zoning map would be a useful tool to help identify how to meet drinking water requirements as well as boost agricultural production. Therefore, a pilot study was undertaken to identify groundwater salinity zones in four upazilas of Khulna and Satkhira Districts in the southwestern coastal region of Bangladesh. Groundwater samples were collected in April 2013 from 245 randomly selected tubewells including 130 shallow hand tubewells (SHTW, screening depths from 35 to 120 m) and 115 deep hand tubewells (DHTW, 150 to 340 m). Chloride (Cl^-) concentration of the groundwater was used to develop groundwater salinity maps. The maps were fine-tuned using the findings of qualitative surveys (focus group discussions and key informant interviews) with a range of stakeholders. Only 20% of the SHTW and 54% of the DHTW had fresh water suitable for drinking ($Cl^- < 600$ ppm), while 86% of the shallow tubewells and 74% of the deep tubewells had water suitable for irrigation of rice ($Cl^- < 2{,}000$ ppm). In Paikgacha, there was no fresh water ($Cl^- < 600$ ppm) in DHTWs and only 4% of SHTWs had fresh water.

Key message: Studies of groundwater quality across the coastal zone of Bangladesh are urgently needed. In a 92,000 ha pilot area in Khulna Division, only 20% of the study area had fresh water in the upper aquifer suitable for drinking, while the percentage suitable for drinking in the deep aquifer was 54%.

Keywords: chloride, shallow aquifer, deep aquifer, Khulna, Satkhira

1. Introduction

Bangladesh has 710 km of coastline and the lands of the coastal zone cover about 32% of the country (MoWR 2005). Islam (2001) classified the coastal lands of Bangladesh into three distinct regions, namely southeast, central and southwest. The southwest coastal region is part of the Ganges tidal floodplain with low relief and is crisscrossed by rivers, tidal marshes and swamps. Although groundwater is abundant in the region saline water intrusion into the upper aquifer system is increasing due to reduction of upstream freshwater flows, shrimp farming and over-abstraction of groundwater. The region has also been identified as one of the most vulnerable parts of the world due to increasing temperature and salinity and sea level rise caused by climate change (FAO 2008; Roy 2009).

In the southwest region, the main focus of research to date has been on irrigation, drainage, flood control and diversion of river flows for irrigation during the dry season. Very few studies have been undertaken on groundwater salinity. Groundwater can be abstracted from aquifers at various depths. During the last four decades, thousands of hand tubewells were installed all over the country including the coastal region. The tubewells in the coastal area were generally installed at depths between 150 m and 350 m. In the Khulna region, Haskoning and Iwaco (1981) found that the upper aquifer contains brackish to saline water and that the fresh-saline groundwater interface lies at a depth between 200 and 300 m below ground level. Saline pockets also occur in both shallow and deep aquifers due to the presence of paleo-brackish water that was entrapped in small areas during rapid regressive events that occurred between 12,000 and 10,000 years after a transgression period, which occurred between 18,000 and 12,000 years ago (Acharyya 1999).

In Bangladesh, the recommended chloride concentration (Cl-) in drinking water is 150 to 600 ppm (ECR 1997). However, higher values (up to 1000 ppm) are considered acceptable in problem areas including the coastal belt (DPHE 2006). For rice production, a chloride concentration of less than 2000 ppm is considered suitable (BARC 2013).

The Department of Public Health Engineering (DPHE) engaged the Institute of Water Modelling (IWM) to conduct a study on salt water intrusion into groundwater in a pilot area of the southwestern coastal region. This included the delineation of groundwater salinity zones through two approaches: hydro-chemical investigations and participatory rapid appraisal (PRA). While hydro-chemical investigation indicates actual salinity of the groundwater, sociological indicators are also useful in understanding the impacts of salinity.

The main objective of the study was to identify groundwater salinity zones for meeting drinking water requirements and for other domestic uses. The study also sought to delineate potential areas for agriculture and brackish water shrimp farming.

2. Methodology

2.1 Study area

The study area is in Khulna Division and the boundary of the study area mainly follows the Kazibacha (local name of the Rupsha) and Kobadak rivers on the southern, eastern and western sides. The study area covers four *upazilas* (sub-districts): Dumuria, Batiaghata and Paikgacha *Upazilas* of Khulna District and Tala *Upazila* of Satkhira District, with a total area of about 918 km^2 (91,800 ha) (Fig. 1). The northern part of the study area is congruent with the northern boundaries of the *upazilas*. Land use in the study area is dominated by agriculture. Rice (*T. Aman*) is the main crop grown in the area. Most of the lands remain fallow in the dry season as no crop can be grown due to salinity. According to WARPO (2000), about 0.37 million ha of arable land have been badly affected by salinity in the greater Khulna region. Bagda (shrimp, P. Monodon, grown under saline conditions) farming is practiced in parts of the study area. About 21,000, 7,500, 4,400 and 3,700 ha were under Bagda in Paikgacha, Dumuria, Batiaghata, and Tala Upazilas, respectively, in 2005 (CEGIS 2006).

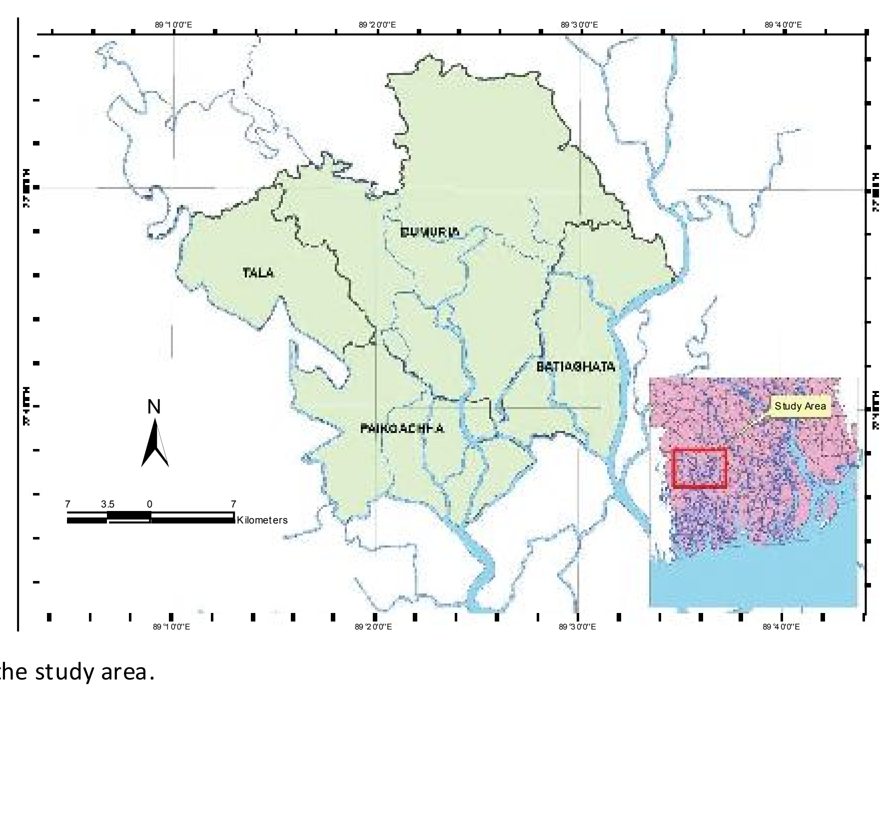


Fig. 1. Location of the study area.

2.2 Study design

The study involved hydro-chemical investigations and qualitative surveys, which were conducted in April 2013.

2.2.1 Hydro-chemical investigations

Groundwater samples were collected from 130 shallow hand tube wells (SHTW) and from 115 deep hand tube wells (DHTW) (Figure 2, Table 1). The SHTWs had screen depths varying from 35 to 120 m below ground level (bgl), and the DHTW had screens at 150 to 340 m bgl.

Groundwater pH, temperature, EC, total dissolved salts (TDS) and chloride concentration were determined at each tube well based on relationships with EC, determined using a field test kit (Hach Salinometer model EC5DL, a conductivity meter with a minimum detection level of 300 ppm). Water samples of eight wells were analyzed for EC and Cl- at laboratories of Bangladesh University of Engineering and Technology (BUET), Bangladesh Council of Scientific and Industrial Research, and DPHE. BUET laboratory results are considered to be the standard benchmark in Bangladesh. The results of the DPHE laboratory analyses and BUET were consistent, so the DPHE laboratory was selected for carrying out laboratory analyses of 12% of the samples for the development of relationships between EC and Cl- from EC, determined using the test kit.

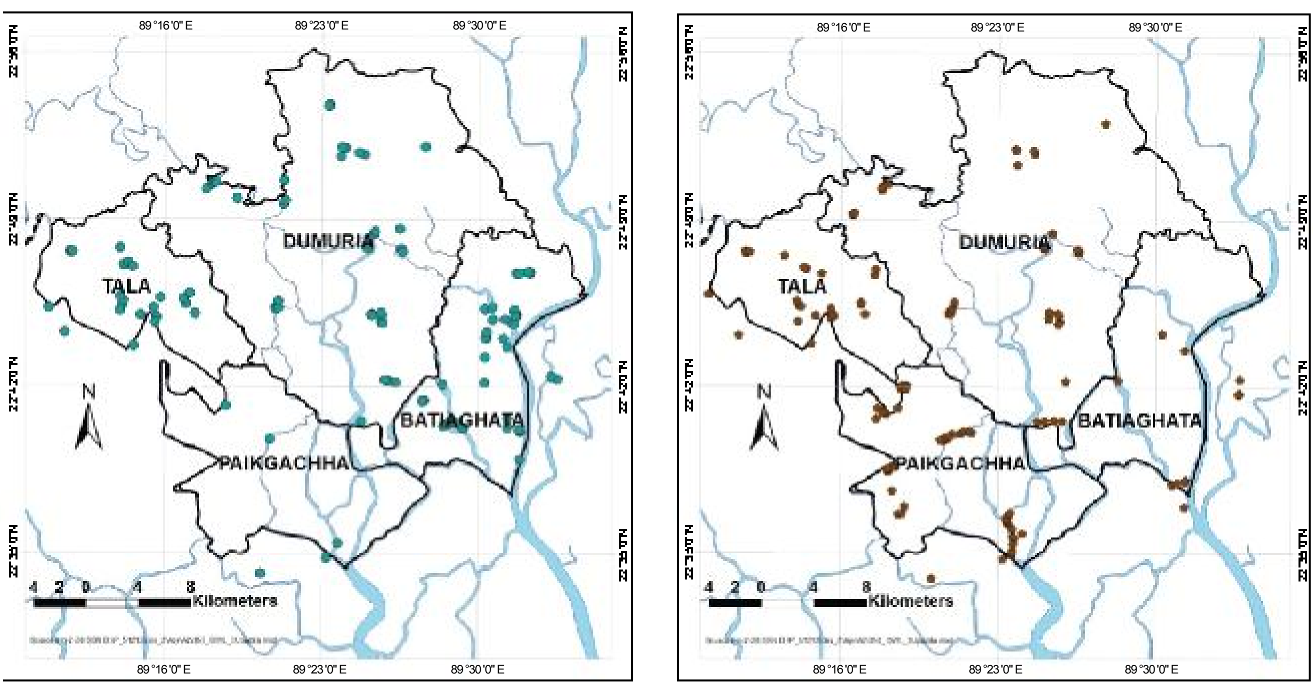


Fig. 2. Locations of ground water sampling sites: shallow aquifer (left) and deep aquifer (right).

Table 1. Distribution of the sampled tube wells by *upazila*

District	*Upazila*	No. of SHTW	No. of DHTW
Khulna	Dumuria	46	41
	Batiaghata	13	45
	Paikgacha	47	5
Satkhira	Tala	24	24
Total		**130**	**115**

2.2.2 Qualitative survey

A participatory rapid appraisal (PRA) including focus group discussions (FGD) and key informant interviews (KII) was carried out to collect qualitative information and users' perceptions and understanding about the tube wells and water quality. The FGDs were conducted in six unions with local level public representatives and representatives of a range of professional groups including farmers, businessmen, service holders, shopkeepers, teachers and housewives. Eight to twelve people participated in each of the FGD sessions. The KIIs were mainly held with staff of DPHE based in the study area.

To verify the results of the qualitative survey in relation to groundwater salinity, especially in areas reported to be less saline, field kit tests were carried out at most of the PRA locations. Samples were taken from at least three tube wells at each location. Before taking the water samples, sufficient water was pumped out to ensure that the sample was representative of the surrounding groundwater. The information from the qualitative social survey thus verified by field test kit was used to further inform the groundwater map delineation.

2.3 Mapping groundwater salinity zones

Both quantitative (i.e., hydro-chemical investigation) and qualitative (i.e., FGD, KII) data were used for delineating groundwater zones according to salinity. Salinity zone maps were generated based on Cl- concentration using ArcGIS 10.1 (inverse distance weight (IDW) method). Four groundwater salinity zones were delineated based on the suitability of the water for various purposes (Table 2). The qualitative information was superimposed on the salinity distribution map to improve the detail in delineating the groundwater salinity zones.

Table 2. Classes of groundwater salinity and their suitability for various uses

Classes (Cl-, ppm)	Usage and limitations
< 600	Very good quality water; suitable for drinking, domestic, irrigation
600 - 1000	Good waterl suitable for domestic uses and irrigation
1000 - 2000	Suitable for irrigation
> 2000	Saline-affected water

3. Results and discussion

3.1 Calibration of the field test kit

The relationship between EC measured using the field test kit and in the BUET laboratory was strong and there was a near perfect polynomial relationship (y = -0.00001* x2+1.061*x – 54.33, R2=0.999, where y is EC measured in the laboratory at BUET and x is EC measured using the field test kit) (Fig. 3a). There were also strong relationships between EC measured using the field test kit and chloride concentration in the water determined in both the BUET (R2=0.98) and DPHE (R2=0.96) laboratories. For EC > 4000 µS/cm the BUET equation was used, while for lower EC values the DPHE equation was used.

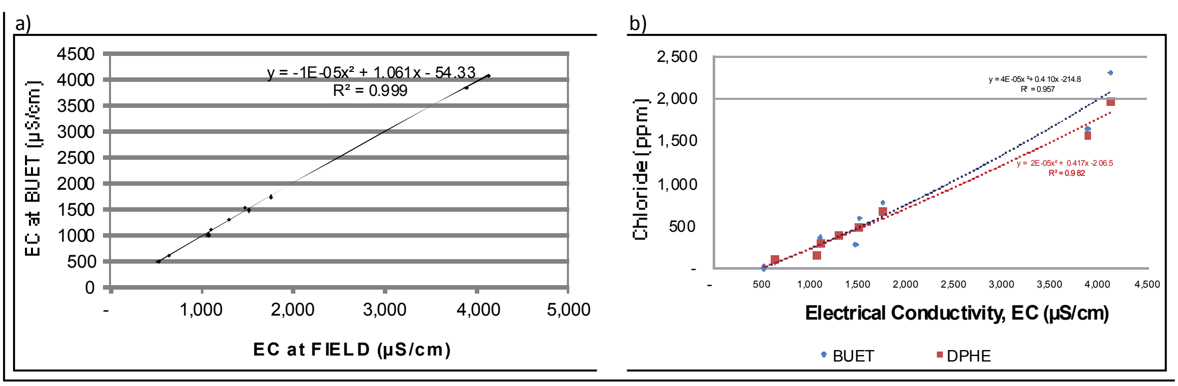


Fig. 3. Calibration of the field test kit against laboratory values from BUET and DPHE: a) field kit EC vs BUET- EC, and; b) field kit EC vs chloride concentration from BUET and DPHE.

3.2 Groundwater quality

Around 50% of the SHTWs had chloride concentrations exceeding 1,000 ppm (Table 3). However, in Tala Upazila, Cl- concentration of the SHTWs was below 600 ppm and thus suitable for drinking at all locations. In the shallow aquifer of Paikgacha Upazila, there were some areas with low Cl- concentration and other areas with very high values, indicating that in some parts of this upazila the shallow aquifer is suitable for drinking water while in others it is not. This variability may be due to the fact that, historically, fresh river water used to flow down the Kobadak River, recharging the shallow aquifers of adjacent areas and reducing their salinity. Throughout Paikgacha Upazila Cl- concentration of the deep aquifer exceeded 1,700 ppm and was generally unsuitable for irrigation.

Table 3. Range (median) of groundwater parameters in shallow and deep aquifers

Upazila	pH		EC (dS/m)		Cl^- (g/l)		TDS[1] (g/l)	
	SHTW	DHTW	SHTW	DHTW	SHTW	DHTW	SHTW	DHTW
Dumuria	7.2-8.2 (7.6)	7.5-8.6 (8.1)	0.6-6.1 (2.5)	1.8-4.3 (3.1)	0.3-2.1 (0.95)	0.3-5.8 (0.3)	0.3-3.0 (1.3)	0.3-6.7 (0.4)
Batiaghata	7.2-8.3 (7.6)	7.5-8.7 (8.3)	1.1-8.5 (2.7)	0.7-6.0 (1.1)	0.3-3.4 (0.98)	0.3-1.3 (0.3)	0.5-4.6 (1.4)	0.4-3.2 (0.6)
Paikgacha	7.1-7.8 (7.5)	7.4-8.3 (7.5)	0.6-12.9 (3.6)	0.6-8.6 (4.0)	0.3-12.9 (1.5)	1.7-3.5 (2.2)	0.3-17.0 (1.9)	2.1-4.7 (2.1)
Tala	7.2-7.7 (7.5)	7.3-8.7 (8.4)	0.5-1.6 (0.9)	0.6-7.6 (1.0)	0.3-0.5 (0.3)	0.3-2.9 (0.3)	0.3-0.8 (0.5)	0.3-4.1 (0.5)

[1] TDS = total dissolved salts; 1 g/l = 1,000 ppm

3.3 Findings of the qualitative surveys

Changes in groundwater salinity over time were not perceived by the people consulted during FGDs, and tube well drinking water quality was considered satisfactory by most (Table 4). Yet, at the same time, there was a strong perception that salinity was causing dysentery and diseases, and that salinity was increasing and affecting agriculture.

In contrast with the opinions of the FGD participants, key informants stated that groundwater salinity has increased over the past few decades (Table 5). In some places in the south, suitable water from a deep aquifer was not available. In these places people used SHTWs for domestic purposes. In the dry season most of the agricultural land could not be brought under cultivation due to high salinity of the available water sources. However, there was limited boro cultivation in areas where suitable groundwater was available. Shrimp farming was practiced throughout the area. In some fields, shrimp was raised in the dry months while paddy was grown in the wet season.

Table 4. Perceptions of people interviewed during FGDs on groundwater quality and related issues

Sl no.	Description	People's perceptions (% of people interviewed)
	Increment of salinity in groundwater	Almost 100% did not perceive any increase in salinity.
	Use of water for drinking	About 93% were comfortable drinking their tube well water.
	Source of irrigation water	Groundwater-24.7%; pond-36.8%; river/canal-38.5%
	Ownership of tube wells	Government-49%; NGO-1%; private-50%
	Impact on health	Almost 100% stated that they suffered from dysentery and skin diseases due to salinity.
	Impact of climate change (sea level rise, temperature and natural disasters)	About 91% stated that agriculture was affected by increasing salinity caused by sea level rise. More than 80% said that temperatures had been rising. About 26% stated that the frequency of cyclones had increased.

Table 5. Information on salinity of shallow and deep aquifers from the key informant interviews

	Upazila	Description
Shallow aquifer	Dumuria	Major portion does not have good drinking water except western areas (Maguraghona, Atlia, Sobhana unions), some portions of central and northern parts.
	Batiaghata	Only the central portion of Batiaghata union has a freshwater aquifer.
	Paikgacha	Paikgacha does not have fresh water for drinking, except for some scattered pockets in the northern, northwestern and southwestern parts of the upazila.
	Tala	The northeastern and southeastern parts of the study area do not have a good aquifer. The rest of the study area has fresh water
Deep aquifer	Dumuria	Most parts have fresh water except the southern part (Magurkhali and Sarafpur unions). Also some scattered areas of Maguraghona, Rudaghara and Atilia unions have saline aquifers.
	Batiaghata	Most of Batiaghata has fresh water with scattered pockets of salinity existing in the northern (Jalma union), southeastern (Gangarampur) and western parts (western half of Surkhali).
	Paikgacha	There are hardly any freshwater aquifers.
	Tala	Most of the northern part has a fresh water aquifer; there are scattered freshwater pockets in the southern part.

3.4 Groundwater salinity zoning maps

For the shallow aquifers, Cl- concentration exceeded 1,000 ppm in two-thirds of the tube wells, covering the eastern side of the study area from north to south (Table 6, Fig. 4). For deep aquifers, 54% of the tubewells had Cl-<600 ppm and salinity was highest (Cl->1,000 ppm) in the southern part. Twenty-six percent of the DHTWs were highly saline (Cl- >2000 ppm). Overall, the deep aquifer was less saline than the shallow aquifer. But in Paikgacha there was no fresh water (Cl- <600 ppm) in DHTWs, and only 4% of SHTWs had fresh water.

Table 6. Percent of SHTWs and DHTWs in different classes of salinity (expressed in Cl- concentration) in different *upazilas*.

Upazila	**600 ppm**		**600-1000 ppm**		**1000-2000 ppm**		**>2000 ppm**		**Total**
	SHTW	**DHTW**	**SHTW**	**DHTW**	**SHTW**	**DHTW**	**SHTW**	**DHTW**	**SHTW + DHTW**
Dumuria	6	37	11	3	28	1	5	9	50
Batiaghata	0	12	1	1	16	4	1	1	18
Paikgacha	4	0	0	1	7	5	8	13	19
Tala	10	5	0	4	3	1	0	3	13
Total	20	54	12	9	54	11	14	26	100

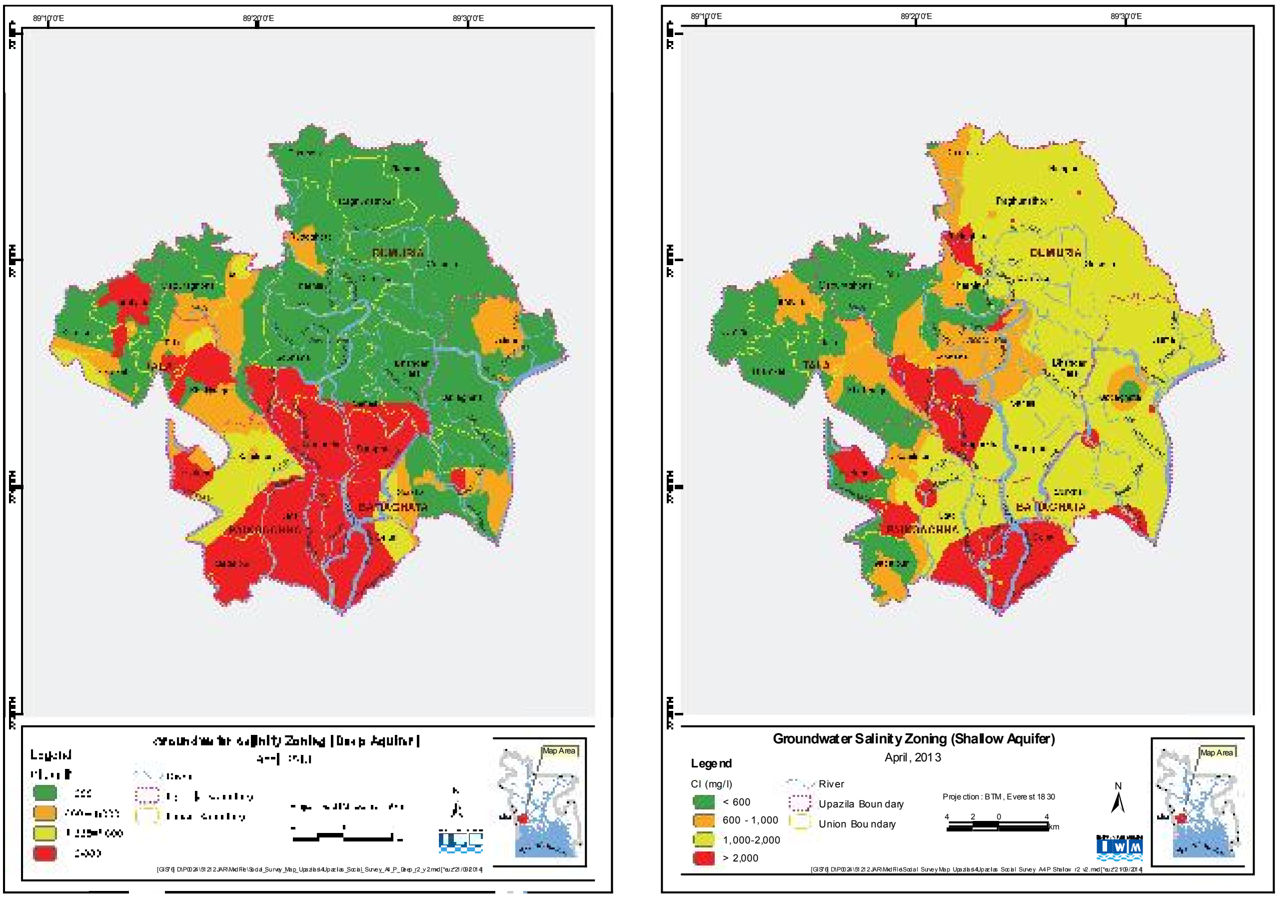


Fig. 4. Groundwater salinity map based on chloride concentration - shallow aquifer (left) and deep aquifer (right). Different colors designate different classes of chloride concentration: green<600 ppm; yellow 600-1000 ppm, orange 1000-2000 ppm and red>2000 ppm.

4. Conclusions and recommendations

This study revealed that the salinity of deep aquifers was less than that of shallow aquifers in most of the study area, except in Paikgacha Upazila. In general, Dumuria Upazila had better groundwater quality than the other upazilas. Only 20% of the study area had fresh water in the upper aquifer suitable for drinking, while the percentage suitable for drinking in the deep aquifer was 54%. About 14% of SHTWs and 26% of DHTWs in the study areas did not have water suitable for rice cultivation.

The study covered a limited area and was a short duration pilot. Similar studies are needed throughout the coastal zone to determine groundwater quality. A long-term groundwater monitoring strategy is also needed to identify changes in water quality over time. These studied are needed to inform planning and development activities.

Acknowledgements

The authors are highly grateful to Department of Public Health Engineering (DPHE) to engage the Institute of Water Modelling (IWM) to carry out the study. The authors would like to thank all the field staff of IWM at the Khulna Project office who provided data required for carrying out the study.

References

Acharyya, S.K., Chakraborty, P., Lahiri, S., Raymahashay, B.C., Guha, S., Bhowmik, A. 1999. Arsenic poisoning in the Ganges delta. Nature 401:545.

BARC. 2013. Suitable Agricultural Technology for Southwest Bangladesh. Bangladesh Agricultural Research Council, Ministry of Agriculture, Government of the People's Republic of Bangladesh. (In Bengali)

BGS and DPHE. 2001. Arsenic Contamination of Groundwater in Bangladesh. Kinniburgh, D.G. and Smedley, P. L. (Editors), Vol 2, Final Report, BGS Technical Report WC/00/19, British Geological Survey, Keyworth, United Kingdom.

CEGIS 2006. Impact of Sea Level Rise on Landuse Stability and Adaptation Options, BGD/96/007-Sustainable Environment Management Programme, Component 1.4.3. Ministry of Environment and Forest, Government of the People's Republic of Bangladesh.

DPHE 2006. Development of Deep Aquifer Database and Preliminary Deep Aquifer Map, Final Report. Ministry of LGRD and Cooperatives, Government of the People's Republic of Bangladesh.

ECR 1997. Environmental Conservation Rules, Bangladesh Gazette. Ministry of Environment and Forest, Government of the People's Republic of Bangladesh.

FAO 2008. Community Based Adaptation in Action: A case study from Bangladesh. Food and Agriculture Organization of UN, Rome.

Haskoning & Iwaco B.V.. 1981. Khulna Water Supply Project - Feasibility Study, Final Report, Vol 3. Department of Public Health Engineering, Dhaka, Bangladesh.

Islam, M.S. 2001. Sea-level Changes in Bangladesh: The Last Ten Thousand Years. Asiatic Society of Bangladesh.

MoWR 2005. Coastal Zone Policy (CZPo). Ministry of Water Resources (MoWR), Government of the People's Republic of Bangladesh.

Roy, K. 2009. Future Climate Change and Moisture Stress: Impact on Crop Agriculture in South-Western Bangladesh. vol: 1 issue:1 Unnayan Onnesion Khulna.

WARPO 2000. National Water Management Plan (NWMP), Draft Development Strategy, Volume-4, Annex-C, Land and Water Resources. Water Resources Planning Organization (WARPO), MoWR, Government of the People's Republic of Bangladesh.

Effect of groundwater use on groundwater salinity, piezometric level and boro rice yield in the Sundarbans of West Bengal

D. Burman[1], K.K. Mahanta[1], S.K. Sarangi[1], S. Mandal[1], B. Maji[1], U. K. Mandal[1], B.K. Bandyopadhyay[1], E. Humphreys[2] and D. K. Sharma[1]

[1] ICAR-Central Soil Salinity Research Institute, India, burman.d@gmail.com, mahantakk@gmail.com, sksarangicanning@gmail.com, subhasis2006@gmail.com, b.maji57@gmail.com, uttam_icar@yahoo.com, bimalbkb@gmail.com, dksharma@cssri.ernet.in

[2] International Rice Research Institute, Philippines, e.humphreys@irri.org

Abstract

Agriculture in the Sundarbans of India is mainly mono-cropped with kharif rice (aman) grown in the monsoon season. Scarcity of fresh surface water for irrigation during the post-monsoon period is the main constraint on growing boro (post monsoon/dry season) rice and other crops. Therefore, there is increasing exploitation of groundwater through shallow tube wells (STWs). At present, STWs are used to irrigate about 32% of the total irrigated area of approximately 55,300 ha in the Sundarbans. However, there is concern about the sustainability of current rates of groundwater use and its continued expansion. Therefore a series of surveys was conducted on the status of STWs in South 24 Parganas and North 24 Parganas districts from 2000 to 2014. The depth of STWs varied from 67 to 128 m below ground level (bgl). A study throughout 2003 showed that the piezometric pressure level was highest and salinity was least after the monsoon (November-December) and that piezometric level was least and salinity highest before the onset of the monsoon (May-June). The piezometric level and water quality recovered during the 2003 monsoon. Detailed study of STWs used for irrigating boro rice in 2003, 2009 and 2014 showed that the piezometric level decreased significantly from an average of 2.1 m bgl in January to 3.9 m bgl in May while the discharge rate decreased significantly from 10.8 to 7.2 ls-1. Over the same period, groundwater salinity increased significantly from an average of 2.0 to 3.7 dS m-1. Salinity (ECe) of the topsoil (0-15cm) in boro rice fields irrigated from STWs increased significantly from an average of 3.0 dS m-1 at sowing to 5.8 dS m-1 at harvest. The grain yield of boro rice increased significantly with increasing installation depth of STWs. STW depth accounted for 70% variation in grain yield and this was at least partly due to a significant decrease in water salinity with increasing STW depth. While the piezometric level and water quality recovered during the 2003 monsoon, whether this would be the case in more intensively irrigated areas is not known. The sustainable level of groundwater use needs to be determined across the region. Measures for more judicious use of groundwater are also needed to increase productivity of this precious resource.

Key message: There is an urgent need to better characterize the aquifers of the Indian Sundarbans and to develop a plan for the sustainable use of groundwater for irrigation.

Keywords: shallow tube well, soil salinity, coastal area, 24 Parganas, India

1. Introduction

The coastal region in the delta of the river Ganges in India and Bangladesh is known as the 'Sundarbans'. The Indian Sundarbans lies between 21032'and 21040' N and between 88005'and 89000' E. It comprises 102 islands, of which 54 are inhabited and spread across 19 blocks of the two southernmost districts of West Bengal, namely North 24 Parganas and South 24 Parganas. Out of 19 blocks, 13 are in South 24 Parganas and six are in North 24 Parganas. This region is one of the most disadvantaged and poverty stricken areas in India. Farmers are mostly very resource poor marginal and smallholder farmers with highly fragmented land holdings (Mandal et al. 2011). The productivity of the land is very low due to soil and water salinity.

Agriculture in the Indian Sundarbans is mainly mono-cropped with kharif (aman) rice grown in the monsoon season. Although the region receives high rainfall (about 1800 mm per annum), there is an acute shortage of irrigation water during the dry season as more than 80% of the rainfall occurs from July to September. Most of the croplands remain fallow during the post-monsoon period due to scarcity of fresh surface water for irrigation (Burman et al. 2013). Therefore, farmers in the Sundarbans resort to pumping groundwater using shallow tube wells (STWs) for growing crops (mostly boro rice) during the post-monsoon period. Boro is the preferred crop as its yield (3 t ha-1) is higher than that of rice grown during the monsoon season (2 t ha-1) or during the pre-monsoon rains (aus, 2.5 t ha-1).

In the coastal region of West Bengal, alluvium of Recent to Pleistocene ages and Tertiary sediments form aquifers that are in the general depth range of 70-360 m bgl and are mostly confined (CGWB 2014). Different aquifer systems (shallow to deep) are separated from each other by thick layers of clay. Each aquifer system comprises one or several interconnected aquifers. Both fresh and brackish/saline water-bearing aquifers occur, with fresh groundwater mostly found in the deeper aquifers (Ray and Shekhar 2009; Gayan2009; Misra and Nag 2009; CGWB 2014). Farmers in the Sundarbans pump ground water from shallow aquifers through STWs to grow boro rice, as extracting water from deeper aquifers is not economic. The number of STWs installed for irrigating boro rice has been increasing over time (Mahanta and Burman 2004). But some farmers report loss of boro rice yield due to the high salinity of irrigation water. Information on the status and use of groundwater through STWs in the Sundarbans is meager. Information on the dynamics, in time and space, of the quality and quantity of groundwater from STWs is needed to help understand the sustainability of the use of STWs for irrigation, and in particular for boro rice because of its high irrigation water requirement. The present paper deals with the expansion of STWs and the effects of groundwater pumping on water quality, piezometric level and productivity of boro rice in the Sundarbans of West Bengal.

2. Methods

Surveys were conducted on the status of STWs in 2000-01, 2002-03, 2008-09 and 2013-14 in 16 villages in Canning-I block and one village in Basanti block in South 24 Parganas District, and in one village in Sandeshkhali-I block and two villages in Sandeshkhali-II block in North 24 Parganas District. About 150 farmers were interviewed to collect information on the depth of installation of STWs, crops cultivated and yields, and on their perceptions of groundwater salinity. The survey team measured salinity of the groundwater and piezometric levels.

2.1 Study 1

During 2003, five STWs were selected in Dumki village for monthly determination of the piezometric level and salinity of the groundwater over a period of 12 months.

2.2 Study 2

In a separate study, the discharge rate, piezometric level and water salinity of 44 STWs in Dumki, Nikarighata, Chandkhali, Kathalberia, Simulhati, Daspara villages were measured at the beginning (January) and end (May) of the boro seasons in 2003, 2009 and 2014. The salinity of the topsoil (0-15cm) (EC of the saturation extract, ECe) in the farmers' fields irrigated from those STWs was also monitored during the boro season. Different STWs were monitored in different years.

2.3 Study 3

During 2014, 30 farmers' fields were selected in Dumki, Nikarighata, Chandkhali, Kathalberia, Simulhati, and Daspara villages where similar boro rice varieties (Lalminikit, WGL20471) were grown. The grain yield of boro rice and salinity of the surface soil (ECe, 0-15cm) at harvest were determined.

2.4 Monitoring

Water and soil salinities were measured using a conductivity meter and piezometric pressure level (depth below the soil surface) was determined using an electronic water level meter. The discharge rate of the STWs was measured by the coordinate method (Murty 1985).

3. Results and discussion

3.1 Status of STWs in the Sundarbans

The number of STWs in the Sundarbans roughly tripled from about 2,200 in 1994 to 7,656 in 2002 and has continued to increase, but at a slower rate, since then (Fig. 1). The area irrigated by this source roughly doubled from about 9,000 to 18,000 ha between 1994 and 2012. The slower rate of increase in STW installation in recent years was mainly due to increases in the costs of diesel and other inputs (Mahanta and Burman 2004), making the cultivation of boro rice less profitable. At present, about 32% of the total irrigated area of approximately 55,300 ha in the Sundarbans is irrigated using STWs (BAES 2012). On average, about 2.34 ha (17.4 bigha) are irrigated by each tube well.

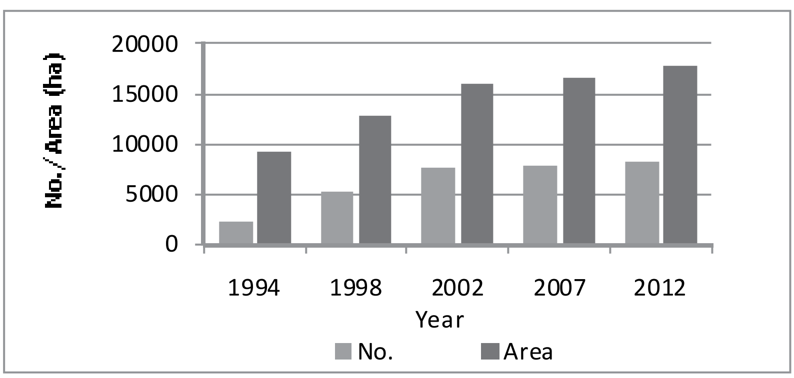


Fig.1. Number of STWs and area under STW irrigation during the last two decades in the Sundarbans of West Bengal (source: Bureau of Applied Economics and Statistics (BAES), Govt. of West Bengal, 1994, 1998, 2002 & 2012).

In the study area, the depth of the STWs varied from 67 to 128 m below ground level (bgl). The tube wells were installed in low, medium and high lands according to the land owned by the farmers and ability to irrigate the adjoining lands. All STWs were constructed using PVC pipe of diameter 7.6 cm, a strainer and a 5 horsepower diesel pump. Most strainers were made of PVC, some were bamboo, and a few were made from aluminum. The length of the strainers varied from 9.1 to 18.3 m with an average of 14.2 m.

3.2 Piezometric level, discharge rate, water and soil salinity

3.2.1 Study 1

The depth of the piezometric level and water salinity increased from January to May, just before the onset of the monsoon, which occurred in mid-June in 2003 (Fig. 2). The depth decreased steadily over the next few months to its lowest values in December. At the same time, salinity decreased sharply between May and June, and then more slowly to its lowest values in November and December (Fig. 3). The piezometric level and salinity in all STWs recovered to their original values at the start of the boro season (December). Total monthly rainfall in 2003 was similar to the long-term averages, except for unusually high rainfall in October (Fig. 4), which occurred after the piezometric levels and water salinity were measured in October.

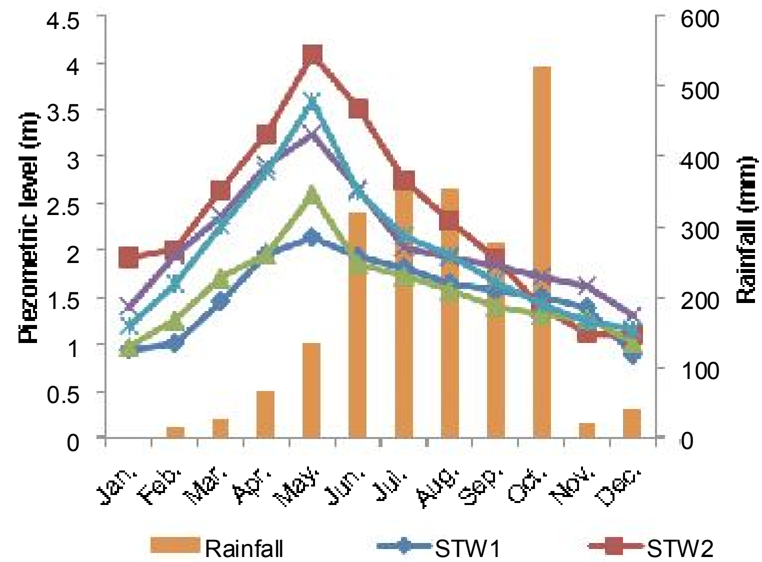


Fig. 2. Monthly rainfall in 2003 and monthly depth (below ground level) of the piezometric level in selected STWs in Dumki village.

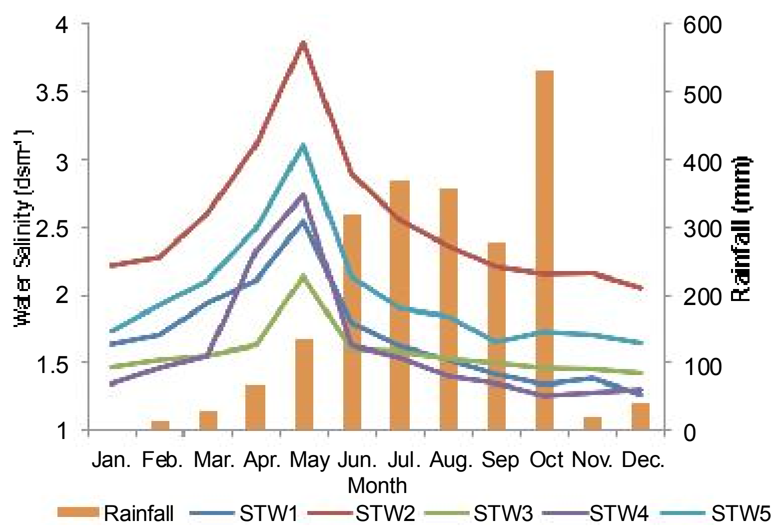


Fig. 3. Monthly rainfall in 2003 and monthly water salinity in selected STWs in Dumki Village.

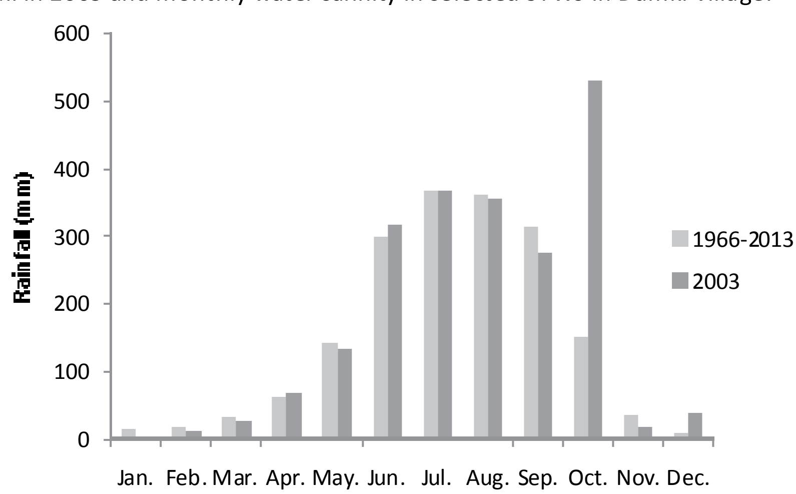


Fig. 4. Monthly rainfall in 2003 and average monthly rainfall from 1966-2013 at Dumki village.

3.2.2 Study 2

The 44 monitored STWs were installed at depths ranging from 73 to 116 m. The piezometric level and discharge rate decreased significantly ($P<0.01$) from January to May while salinity of the groundwater increased significantly during that period (Table 1). There was significant relationship ($P<0.05$) between piezometric level and discharge rate in both January and May, with piezometric level accounting for 36% of the variation in discharge rate in both months. The decrease in piezometric level and the decrease in discharge rate from January to May were also related significantly, however the decrease in piezometric level only accounted for 15% of the decrease in discharge rate. The increase in salinity of the groundwater suggests contamination of the aquifer from other sources (e.g. navigation canals, estuaries, saline aquifers) as a result of the decrease in pressure level.

The relationships between STW depth and initial (January) or final (May) water salinity were significant. STW depth accounted for 19% and 25% of the variation in initial and final water salinity, respectively, with higher salinity in shallower STWs. There was no relationship between STW depth and initial soil salinity, nor between initial and final soil salinity. However, there was a strong relationship ($p<0.01$) between initial water salinity and final soil salinity, with initial water salinity accounting for 41% of the variation in final soil salinity (Fig. 5). STW depth accounted for 42% of the variation in final soil salinity ($p<0.01$), reflecting the significant relationship between STW depth and initial water salinity, which was in turn related to final water salinity, reflecting the fact that irrigation with higher salinity water results in greater accumulation of salt in the topsoil due to evaporation. Similar observations were also reported by Burman et al. (2009) in the Sundarbans.

Table 1. Changes in the piezometric level, discharge rate, water salinity of STWs and soil salinity of rice fields during the boro season (data are for STWs monitored in 2003, 2009 and 2014; different STWs were monitored each year, total number of observations 44)

	Depth of STWs (m)	Depth of piezometric level (m bgl)		Discharge rate (ls^{-1})		Water Salinity (dSm^{-1})		Soil Salinity (ECe, dSm^{-1})	
		Jan	May	Jan	May	Jan	May	Jan	May
Range	73-116	1.3-4.1	2.1-6.5	7.8-14.2	3.0-9.5	1.3-3.9	2.5-5.4	2.0-3.9	2.6-11.3
Mean	94	2.1	3.9	10.8	7.2	2.0	3.7	3.0	5.8
SEm ±	2.18	0.1	0.2	0.3	0.3	0.1	0.1	0.1	0.1
Paired t test ($P<0.01$)		Significant		Significant		Significant		Significant	

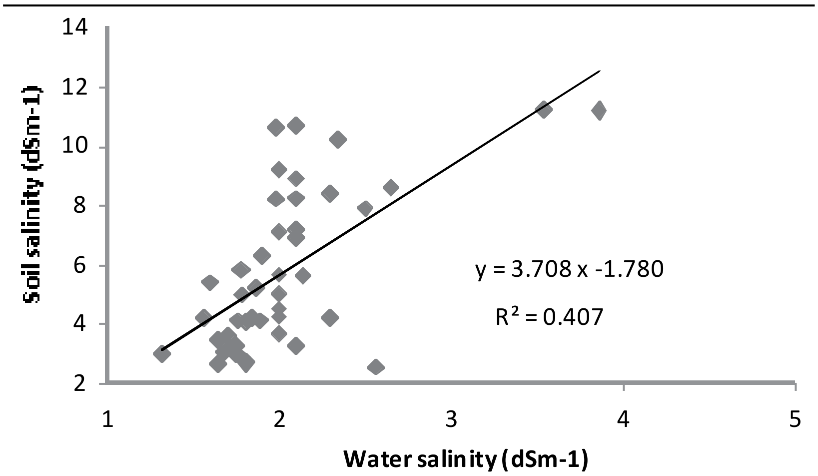


Fig. 5. Relationship between initial water salinty of STW and final soil salinity.

3.3 Effect of irrigation water on boro rice productivity

There was a significant ($p<0.01$) relationship between STW depth and grain yield of boro rice, with STW depth accounting for 70% of the variation in grain yield (Fig. 6). This was due to the relationships between STW depth and initial water salinity, between initial water salinity and final soil salinity, and between yield and final soil salinity (Fig. 7). Final soil salinity accounted for 74% of the variation in grain yield ($p<0.01$).

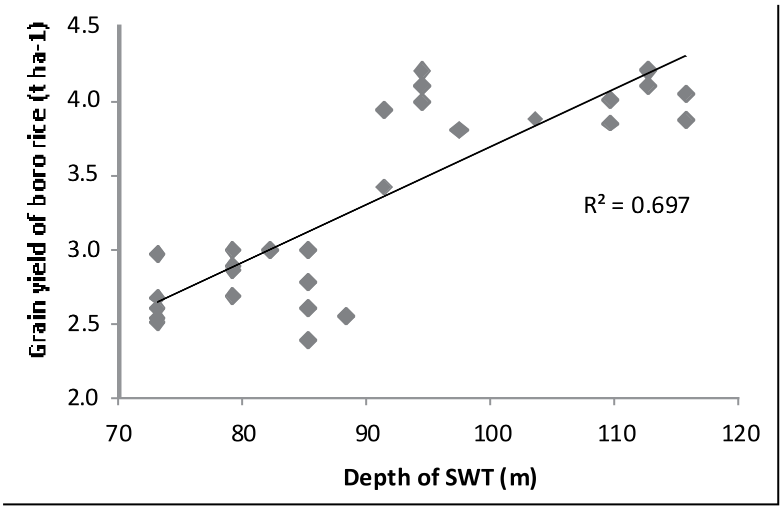


Fig. 6. Relationship between STW depth and grain yield of boro rice.

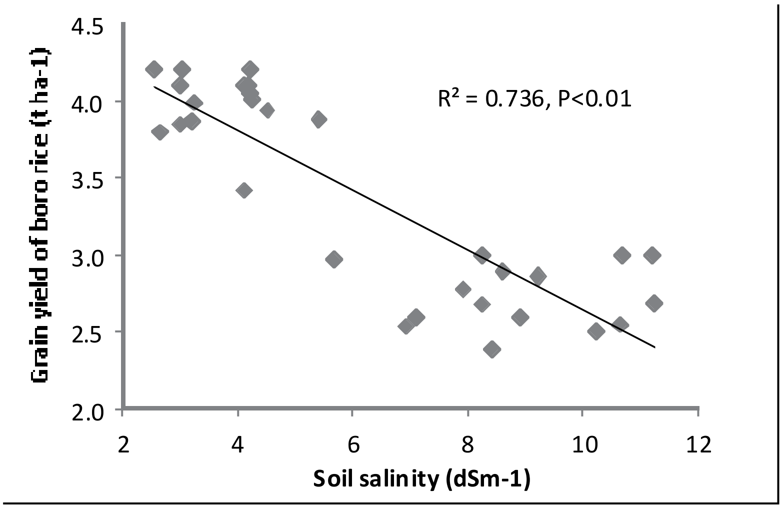


Fig. 7. Relationships between soil salinity at harvest and boro grain yield in farmers' fields irrigated through STWs.

4. Conclusions and recommendations

STWs are being used for irrigation of crops, mainly boro rice, in the salt affected Sundarbans in the coastal region of West Bengal, India. Decreases in piezometric level and discharge rate and increasing salinity of the irrigation water between the time of establishment and harvest of boro rice were observed. In 2003, the piezometric level and salinity of the STWs recovered during monsoon season in the study area. However, whether this would be the case in intensively irrigated areas with STWs and in all years is not known. Long-term studies of the status of the aquifers used for irrigation of agricultural crops, and of the deeper fresh aquifers, are needed to help determine the sustainable level of extraction.

Soil salinity increased during the boro season and rice yield was strongly and positively related to final soil salinity and strongly and negatively related to STW depth. Final soil salinity was inversely related to STW installation depth, at least partly due to the higher water salinity of the shallower STW.

There is an urgent need to better characterize the aquifers of the region and to develop a plan for the sustainable use of groundwater for irrigation. Strategies for increasing the productivity of ground water are also needed, including conjunctive use of ground water and surface water. Strategies for increasing the availability of fresh surface water are also needed, such as rainwater harvesting through surface storage structures. Harvested fresh water could be used in various ways, such as at critical crops stages (when sensitivity to salinity is greatest), and later in the season when STW salinity is highest. Crop practices to reduce irrigation requirement during the dry season are also needed, such as early establishment of boro rice and replacement of rice with crops with lower water requirement such as sunflower. The development of boro varieties with improved tolerance to salinity could also increase the productivity of groundwater in the region.

Acknowledgements

The authors acknowledge the financial and technical support to this research work by the Indian Council of Agricultural Research (ICAR) and the CGIAR Challenge Program on Water and Food (CPWF). Along with findings from research projects of ICAR-Central Soil Salinity Research Institute, this paper presents findings from 'G2 Productive, profitable and resilient agriculture and aquaculture systems', a project of CPWF.

References

BAES 2012.District Statistical Handbook, SOUTH/ NORTH 24-PARGANAS, Bureau of Applied Economics & Statistics, Department of Statistics & Programme Implementation, Government of West Bengal.

Burman, D., Bandyopadhyay, B.K., Mandal, Subhasis, Mandal, U.K., Mahanta, K.K., Sarangi, S.K., Maji, B., Rout, S., Bal, A.R., Gupta, S.K. and Sharma, D.K. 2013. Land shaping – A unique technology for improving productivity of coastal land. Technical Bulletin, CSSRI/Canning Town/Bulletin/ 2013/02, Central Soil Salinity Research Institute, Canning Town, South 24 Parganas, West Bengal.p.38.

Burman, D., Sarangi, S.K., Mandal, Subhasis and Bandyopadhyay, B.K. 2009. Water quality of tube-wells used for irrigation during rabi abd summer seasons in the coastal areas of Sundarbans, West Bengal. Journal of Indian Society of Coastal Agricultural Research 27(2): 76-79.

CGWB 2014. Report on status of ground water quality in coastal aquifers of India. Central Ground Water Board, Ministry of Water Resources, Government of India, Bhujal Bhawan, Faridabad, Haryana, India. p. 121.

Gayen, Anadi.2009. Sustainable ground water management options in the delta mouth area of Sundarban islands, West Bengal. Bhu-Jal News 24(1):79-84.

Mahanta, K.K. and Burman, D. 2004. Studies on the development and utility status of the shallow tubewells in the Sundarbans area. Journal of Indian Society of Coastal Agricultural Research 22: 124-25.

Mandal, Subhasis, Bandyopadhyay, B.K., Burman,D., Sarangi, S.K. and Mahanta, K.K. 2011. Baseline Report of the NAIP project on 'Strategies for Sustainable Management of Degraded Coastal Land and Water for Enhancing Livelihood Security of Farming Communities'. Central Soil Salinity Research Station, Regional Research Station, West Bengal, India. P.74.

Misra, A. K. and Nag, S. K. 2009. Aquifer characteristics in south 24-Parganas and Kolkata Municipal Corporation (KMC) area, West Bengal. Bhu-Jal News 24(1):28-36.

Murty, V.V.N. 1985. Land and water management engineering. New Delhi: Kalyani Publishers.

Ray, Abhijit and Shekhar, S. 2009. Ground water issues and development strategies in West Bengal. Bhu-Jal News 24(1): 2-17.

Reducing irrigation water requirement of dry season rice (boro) in coastal areas using timely seeding and short duration varieties

S.K. Sarangi[1], D. Burman1, S. Mandal[1], B. Maji[1], T.P. Tuong[2], E. Humphreys[2], B. K. Bandyopadhyay[1] and D. K. Sharma[1]

[1] ICAR-Central Soil Salinity Research Institute, India, sksarangicanning@gmail.com, burman.d@gmail.com, subhasis2006@gmail.com, b.maji57@gmail.com, bimalbkb@gmail.com, dineshksharma@rediffmail.com
[2] International Rice Research Institute, Philippines, e.humphreys@irri.org, t.tuong@irri.org

Abstract

Irrigated dry season rice (boro) can help to bridge the gap between production and consumption in eastern India. Due to scarcity of fresh surface water during the dry season, farmers resort to pumping ground water for irrigation. However this leads to the lowering of groundwater piezometric levels, increased pumping costs and saline water intrusion. Conservative use of irrigation water (IW) is essential to enable boro cultivation while sustaining the productivity of this fragile ecosystem. Therefore, research was conducted to test the hypotheses that early seeding and the use of short duration varieties would reduce IW requirements and increase the IW productivity (IWp) of boro rice. The experiment was conducted in the 2012–2013 and 2013–2014 boro seasons at Canning Town in West Bengal, India. Eight rice varieties including four from Bangladesh were sown during the first week (early seeding) and the last week (late seeding) of November. Each season, yields of early sown Binadhan-8, BRRI dhan47 and CSR 22 were similar (about 6 t ha^{-1}) and significantly higher than yields of the other varieties. With late seeding, Binadhan-8 produced significantly higher grain yield (5.9 t ha^{-1}) than all other varieties. Late seeding reduced grain yield of most varieties, more so in the case of longer duration varieties - by up to 24%. Irrigation water input increased with variety growth duration and was lowest with BRRI dhan55, followed by IR 10206-29-2-1-1 and BRRI dhan47. Average IW input with early seeding was 17% less than with late seeding, mainly due to lower irrigation requirements for land preparation. Irrigation water productivity with early seeding (41-45 kg grain $ha^{-1}cm^{-1}$) was 30% higher than with late seeding (31-35 kg grain $ha^{-1}cm^{-1}$) each year. With early seeding BRRI dhan47 had the highest IWp, while with late seeding Binadhan-8 had the highest. Two of the three varieties with highest yield and highest IWp came from Bangladesh, signifying the importance of cross-country germplasm exchange. There was an indication that early seeding resulted in higher yields and IWp, but this needs further verification.

Key message: Irrigation water input to boro crops in the coastal zone of west Bengal can be reduced while achieving yields in excess of 5 t ha^{-1} through the use of high yielding, short duration varieties, and possibly through earlier seeding.

Keywords: cropping intensification, eastern India, water management, water productivity

1. Introduction

The importance of rice as a staple food crop is known worldwide and Asian countries depend on rice as the major source of daily dietary requirements. It is the staple food of half the world's population and is grown by more than half the world's farmers (Fairhurst and Dobermann 2002). Rice is the most widely grown crop in India, which makes the country the second highest rice producer (close to 100 Mt per year) in the world. India needs to produce 120 Mt per year by 2030 to feed what will be by then its population of over one and a half billion (Adhya 2011). To meet the requirement, innovations are needed for higher production and sustained productivity.

One of the important strategies for increasing production is cropping intensification. In India, rice is mostly grown during three seasons, locally known as aus or autumn or pre-kharif (pre-monsoon), aman or kharif (monsoon), and boro or rabi or summer (post-monsoon or dry season). Among these three growing seasons, rice yield is highest during the boro season due to ample sunshine, controlled water management (irrigation) and higher efficiency of inputs like fertilizer and crop protection chemicals (Sarangi et al. 2014). But the area planted during boro is the least—around 4 Mha, in comparison to 38 Mha during kharif—mainly due to limited availability of irrigation water and suitable varieties. These constraints are particularly true for eastern India where surface water is affected by salinity during the dry season (Kukal et al. 2010; Bouman and Tuong 2001).

The source of water for dry season rice irrigation in eastern India is mainly pumping of groundwater through tube wells. Indiscriminate pumping of groundwater lowers the groundwater table during the dry season by an alarming magnitude, which has caused many tube well systems to go dry or deliver pulsating discharges during summer months (Goswami 2006). This situation results in increased pumping costs, salinity intrusion to the aquifers below rice growing land and build up of soil salinity in the top soil. In the future, groundwater utilization is likely to increase with expansion of irrigated agriculture and efforts to achieve national food production targets. Climate change is also likely to affect groundwater availability in terms of both quantity and quality (in particular coastal aquifers) due to changes in precipitation and evapo-transpiration (Pathak et al. 2014). Therefore, judicious use of irrigation water is essential to sustain boro rice production and to optimize the boro rice cultivated area. To reduce the irrigation water requirement of boro rice effective use of residual soil moisture after the kharif crop, optimum time of seeding and transplanting, and salt tolerant rice varieties are needed. Shorter duration boro varieties are also needed as rice requirements for irrigation water decrease with duration.

There is great scope for increasing rice production in the eastern coastal plains of India through the development and adoption of suitable varieties with site-specific crop and natural resource management (Saha et al. 2008). Planting date plays a crucial role in irrigation requirement and yield. Usually, farmers sow the seeds of the boro crop in the nursery from late November to the first week of December, about three weeks after the harvest of wet season rice. This planting date fails to tap the residual soil moisture in the topsoil of the paddy fields, which dries rapidly due to evaporation and recession of the groundwater table. Furthermore, the late sown rice crop is exposed to higher temperature and evaporation demand during the latter part of the crop growing period, from March to April (Fig. 1). The flowering and grain filling periods are exposed to warmer weather (heat stress), which increases spikelet sterility and shortens the grain filling period leading to lower yield (Castillo et al. 2006). Modelling studies for two boro rice varieties (BR3 and BR14) in Bangladesh indicated significant reduction (23 to 41%) in rice yield for delayed planting (Basak et al. 2010). Sterility percentage increased from 24 to 45% due to delayed planting (Mannan et al. 2012). Soil salinity also increases as the dry season progresses. Salt tolerant varieties can be used to maintain economic yield under moderate soil salinity and may need less irrigation water for leaching of salt than susceptible varieties.

Keeping these facts in view, this study was conducted to test the hypotheses that early seeding and the use of short duration varieties would reduce irrigation water (IW) requirement and increase the IW productivity (IWp) of boro rice.

2. Materials and methods

2.1 The study site

The experiment was conducted during the boro seasons of 2012-13 and 2013-14 at the ICAR-CSSRI Regional Research Station, Canning Town (Latitude: 22°15′N, Longitude: 88°40′ E; Altitude 3.0 m above MSL), West Bengal. The climate is tropical monsoon with average annual rainfall of 1802 mm, of which 89% occurs during the monsoon season (June-October). Rainfall during the boro season is not enough to meet the crop water requirement. Both maximum and minimum air temperatures, as well as potential evaporation, increase from January to April (Fig. 1) and the sky is usually cloudless with sufficient bright sunshine (6–7 h d^{-1}) for photosynthesis.

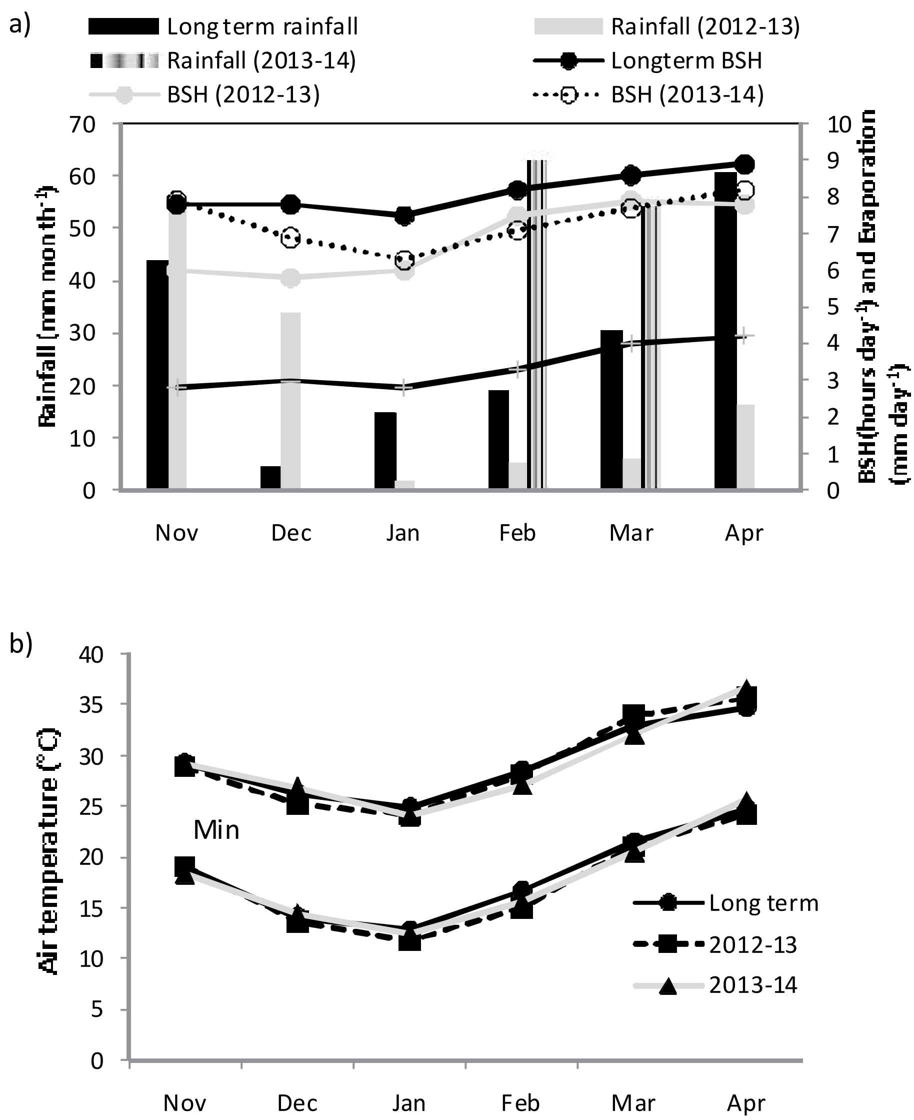


Fig. 1. Weather parameters during the crop growing months of the dry season: (a) rainfall, bright sunshine hours (BSH) and pan evaporation; and (b) maximum and minimum temperatures at ICAR-CSSRI RRS Canning Town. Long term data are for the period 1984-85 to 2013-14.

The experiment was conducted in two adjacent fields with very similar soil properties and groundwater table dynamics (Table 1, Fig. 2). The soil was a silty clay with a neutral pH, low organic carbon and available nitrogen, medium available phosphorus, and high available potassium (Table 1). Both fields were under paddy cultivation (one rainy season crop per year) for the three years prior to conducting this experiment.

Table 1. Initial physical and chemical properties of the topsoil (0-15 cm) at the experimental site. Area 1 and Area 2 refer to two fields (see section 2.2, experimental design).

Location	Clay	Sand	BD	N	P	K	Zn	pH	OC	ECe
	%		g cm-3		kg ha-1			ppm	%	dS m-1
Area 1	40	10	1.49	210	12.1	419	7.6	6.8	0.42	3.6
Area 2	44	10	1.52	227	11.1	378	7.8	7.1	0.46	4.2

The depth to the groundwater table (as observed in piezometers installed to a depth of 3 m) was similar in both experimental areas (Fig. 2). The water table was about 0.4 to 0.6 m below the soil surface in November each year, and the depth increased to about 1.2 m in April as the boro season progressed.

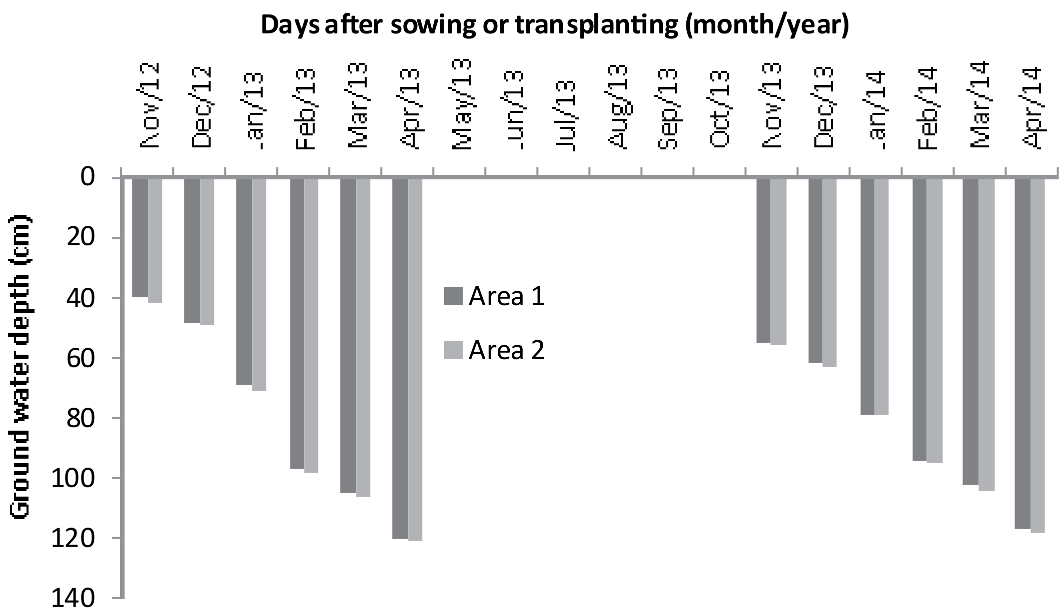


Fig. 2. Depth of groundwater in the study areas during the boro seasons of 2012-13 and 2013-14. Area 1 and Area 2 refer to two fields of the experiment (see section 2.2, experimental design). (For simplicity, data for May to October are not presented.)

2.2 Experimental design

The experiment was conducted in two adjacent fields with two seeding dates (early and late November), one seeding date per field. Eight varieties or lines were evaluated in each field.

Seeding dates:

Area 1: early November (6 Nov. 2012, 4 Nov 2013)
Area 2: late November (28 Nov. 2012, 24 Nov. 2013)

Varieties:
BRRI dhan47
BRRI dhan53
BRRI dhan55
Binadhan-8
CSR 34, CSR 22
IR 10206-29-2-1-1
CSRC (S) 50-2-1-1-4-B

All varieties tested were semi-dwarf high yielding salt tolerant varieties. Four varieties from Bangladesh were included, three of which are short duration (BRRI dhan47, BRRI dhan55 and Binadhan-8), with the other (BRRI dhan53) being medium short duration (www.knowledgebank-brri.org, www.bina.gov.bd). Three varieties/lines (CSR 22, CSR 34 and CSRC(S) 50-2-1-1-4-B) from India and one line from IRRI (IR 10206-29-2-1-1) were also included. These varieties were selected on the basis of previous evaluations done at CSSRI, RRS, Canning Town (Annual Report, CSSRI, 2011-12).

There were three replicates of each variety in a randomized block design within each field. Each variety plot measured 5 m x 19 m (gross area, including bunds). The plots were surrounded by 20 cm high x 50 cm wide bunds. The bunds were first built with dry soil, irrigation was applied for puddling, and the bunds were then plastered with mud to minimize lateral seepage. Irrigation for land soaking and puddling was applied 4 d before transplanting.

2.3 Management

Thirty day-old seedlings were transplanted at a spacing of 20 cm x 10 cm with one to two seedlings per hill. A fertilizer dose of 120:20:0 kg N:P2O5:K2O ha-1 was applied to each plot as urea, single super phosphate and muriate of potash, respectively. All of the P and K and 25% of the N were applied prior to leveling. Half of the N was broadcast 21 d after transplanting (DAT) and the remaining 25% was broadcast at 60 DAT. Hand weeding was done twice at 20 and 40 DAT to remove all weeds.

Chloropyriphos @ 2 ml l-1 water and tricyclazole @ 0.6 g l-1 water was used to control insects and diseases, respectively, as recommended. The plots were kept flooded (2.5-7.5 cm) throughout the season until about 20 d before harvest maturity.

2.4 Parameters monitored

2.4.1 Soil

Initial physico-chemical characteristics of the soil of the two fields were determined from top soil samples (0–15 cm) which were sun dried and sieved through a 2 mm sieve. Samples were then analyzed for texture, salinity, pH, organic carbon (Walkley and Black 1934), available nitrogen (Subbiah and Asija 1956), available phosphorus (Olsen et al. 1954) and available potassium (Hanway and Heidel 1952). Bulk density at 5-10 cm soil depth was determined on samples collected using a core sampler.

2.4.2 Water

The volume of irrigation water applied to each plot for puddling was measured from the discharge rate of the pump and the time of pumping. The depth of applied water was calculated by dividing volume by the plot area; the calculation assumes that lateral seepage was negligible as all plots were irrigated and puddled at the same time.

Water depth sticks with cm scales were installed in the middle and four corners of each plot after puddling. Irrigation was applied when water depth (as indicated by 3 out of the 5 water sticks) in the plot fell below 2.5 cm, to bring the water depth to 7.5 cm.

2.4.3 Crop duration

Crop duration was determined as the number of days from seeding to harvest. Harvesting was done when 80% of the grains turned straw colour.

2.4.4 Yield and yield components and irrigation water productivity

At harvest, grain yield was detemined on an area of 5 m x2 m in the middle of each plot. The grain was sun dried, weighed, moisture content was determined using a moisture meter, and grain yield was adjusted to a moisture content of 14%. Yield components (panicle density (no. m-2), number of spikelets panicle-1, spikelet fertility (%), 1000-grain weight) were also determined. The number of panicles was counted in three randomly selected areas of 1 m2 in each plot, and the average of three was used for statistical analysis. Ten panicles were randomly selected from each plot to count spikelets. These panicles were hand-threshed, filled (grains) and empty spikelets (chaff) were separated by submerging in water (floating spikelets considered empty), then the number of grains and empty spikelets was counted. Grain samples were adjusted to 14% moisture content to determine 1000-grain weight.

Irrigation water productivity (IWP) of each treatment was calculated by using the following formula:

IW_P (kg $ha^{-1}cm^{-1}$) = grain yield (kg ha^{-1})/volume of irrigation water applied (ha.cm)

All irrigation water, from land soaking and pudlling to the end of irrigation period, was included in the determination of IWP.

2.5 Statistical analysis

The results for each seeding date were analyzed separately. The effects of variety and year were determined by analysis of variance using the Statistical Tool for Agricultural Research (STAR) software developed by the International Rice Research Institute (http://bbi.irri.org). Treatment means were compared using the least significant difference (LSD) test and compared at P=0.05 level of significance (Gomez and Gomez 1984). When the interaction between variety and year was not significant, means were averaged across the two years. Lack of randomization of seeding date did not allow statistical analysis to be carried on the effects of seeding date.

3. Results and discussion

3.1. Crop duration, yield and yield components

There were no significant interactions between year and variety for either seeding date on duration, all yield components, and yield (Table 2). However, there were significant effects of variety and year on all these parameters for both seeding dates.

Table 2. Level of significance of the effects of year and variety and their interaction on crop duration and yield parameters for early and late sown boro

	Duration	Panicle m^{-2}	Spikelet $panicle^{-1}$	% fertility	1000-grain weight	Grain yield (t ha^{-1})
Effects	P>F	P>F	P>F	P>F	P>F	P>F
Early seeding (D1)						
Variety (V)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Year (Y)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
V x Y interaction	0.712	0.199	0.094	0.499	0.162	0.665
Late seeding (D2)						
Variety (V)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Year (Y)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
V x Y interaction	0.999	0.081	0.099	0.739	0.759	0.351

The duration of the varieties varied from 125 to 143 d with early seeding, and from 120 to 142 d with late seeding. The duration of each variety with late seeding was consistently 3 to 5 d shorter than that of the same variety with early seeding. In both sowing dates, BRRI dhan55, IR 10206-29-2-1-1, and Binadhan-8 had the shortest duration, while CSR 34 and CSR 22 had the longest duration.

Yields of CSR 22 and BRRI dhan47 did not differ significantly from that of Binadhan-8 in the first seeding, but were significantly lower than that of Binadhan-8 in the second seeding. On average, grain yield was 11% more with early seeding (mean 5.5 t ha-1) than late seeding (4.9 t ha-1). There was a general trend for delayed seeding to reduce grain yield of the longer duration varieties by more than the shorter duration varieties. Yield of BRRI dhan55 (duration 120-125 d) was not affected by seeding date, while the effect of seeding date on yield of Binadhan-8 (130-134 d) was small. Variety duration accounted for 56% of the effect of seeding date on yield (data not presented). The reduction in grain yield with late seeding was associated with reduced spikelet fertility, and to a very small degree with reduced panicle density (by 1%, but consistent across varieties) (Table 3). On average, spikelet fertility decreased from 84% in D1 to 77% in D2. This was probably due to higher temperature at flowering with late seeding each season. Flowering of the early seeding occurred in February while flowering of the late seeding occurred in March. The greater effect of late seeding on yield reduction with longer duration varieties is also probably due to flowering at higher temperatures.

The higher yield of Binadhan-8, CSR 22 and IR 10206-29-2-1-1 was associated with higher panicle density than most or all other varieties and more spikelets per panicle than some varieties. Bindhan-8 also had much higher grain weight than all other varieties except BRRI dhan47. BRRI dhan47 also had relatively high panicle density and significantly more spikelets per panicle than all other varieties.

The higher yield in 2013-14 was associated with unusually high rainfall in February and March 2014 (total about 120 mm, Fig. 1a) which probably reduced the salinity experienced by both the early and late sown crops.

3.2 Irrigation water (IW)

The interaction between variety and year was not significant for all IW parameters except IWP at late seeding. Therefore, mean data of the two years are presented for all parameters except the latter. There was a significant effect of variety on all parameters except the amount of irrigation water for land soaking and puddling (IWL) in both years, and a significant effect of year on all parameters except irrigation number.

The depth of irrigation water required for land preparation for the early seeding (22 cm) was much less than that for late seeding (38 cm) (Table 4). This is attributed to the higher water table depth (Fig. 2) and higher water content of the soil profile at the time of seeding. The amount of irrigation water for land preparation in 2012 was about 20 mm less than in 2013 for both crops. In 2012 there were 34 and 36 mm of rain between the times of harvest and transplanting of the early and late seeded crops, respectively, compared with no rain during this period in 2013, hence the higher irrigation input for land preparation in 2012. The irrigation input during the cropped period was 30 to 40 mm lower in 2013-14 than in 2012-13, and this was associated with the unusually high rainfall in February and March 2014 (Fig. 1a).

Table 3. Crop duration, yield and yield components of early and late sown boro varieties. Means are the average of three replicates over two years

	Duration	Panicle m^{-2}	Spikelet panicle^{-1}	% fertility	1000-grain weight	Grain yield (t ha^{-1})
Early seeding (D1)						
Variety Binadhan-8	134^{b}	490^{a}	121^{bc}	89.1^{a}	26.7^{b}	6.04^{a}
CSR 22	143^{a}	485^{a}	118^{c}	84.7^{c}	22.9^{f}	5.95^{a}
BRRI dhan47	135^{b}	455^{b}	139^{a}	83.9^{c}	27.5^{a}	5.89^{a}
IR 10206-29-2-1-1	134^{b}	483^{a}	126^{b}	81.4^{d}	23.9^{d}	5.57^{b}
BRRI dhan53	141^{a}	387^{c}	112^{d}	80.6^{de}	22.3^{g}	5.51^{b}
CSR 34	143^{a}	325^{e}	97^{f}	85.0^{bc}	23.1^{e}	5.25^{c}
BRRI dhan55	125^{c}	357^{d}	107^{e}	86.6^{b}	25.5^{c}	4.97^{d}
CSRC(S) 50-2-1-1-4-B	135^{b}	286^{f}	97^{f}	79.6^{e}	22.3^{g}	4.56^{e}
LSD (P=0.05)	1.49	5.3	3.1	1.08	0.07	0.12
Year						
2012-13	138^{a}	415^{a}	115^{a}	84.8^{a}	24.2^{b}	5.75^{a}
2013-14	134^{b}	401^{b}	114^{b}	83.0^{b}	24.3^{a}	5.19^{b}
LSD (P=0.05)	0.73	2.65	1.53	0.54	0.04	0.06
Mean	*136*	*408*	*115*	*83.9*	*24.24*	*5.47*
Late seeding (D2)						
Variety Binadhan-8	130^{d}	485^{a}	122^{c}	81.6^{a}	26.5^{b}	5.86^{a}
CSR 22	141^{a}	479^{ab}	119^{c}	73.9^{cd}	22.7^{f}	5.21^{c}
BRRI dhan47	132^{c}	451^{c}	140^{a}	79.0^{ab}	27.3^{a}	5.34^{b}
IR 10206-29-2-1-1	131^{cd}	477^{b}	126^{b}	76.3^{bc}	23.8^{d}	5.46^{b}
BRRI dhan53	137^{b}	383^{d}	113^{d}	73.7^{cd}	22.1^{g}	4.57^{e}
CSR 34	142^{a}	320^{f}	99^{f}	75.3^{c}	22.9^{e}	4.24^{f}
BRRI dhan55	120^{e}	352^{e}	107^{e}	81.7^{a}	25.3^{c}	4.92^{d}
CSRC(S) 50-2-1-1-4-B	132^{c}	282^{g}	98^{f}	71.5^{d}	22.1^{g}	3.79^{g}
LSD (P=0.05)	1.73	7.1	3.8	3.15	0.13	0.18
Year						
2012-13	134^{a}	410^{a}	116^{a}	77.31^{a}	24.0^{b}	5.22^{a}
2013-14	133^{b}	396^{b}	115^{b}	75.96^{b}	24.2^{a}	4.63^{b}
LSD (P=0.05)	0.62	2.51	1.35	1.10	0.05	0.06
Mean	*134*	*403*	*116*	*76.6*	*24.1*	*4.92*

Note: In the same seeding date, means with the same letter in a column are not significantly different at the 5% level by LSD. The interaction between year and variety was not significant for any parameters.

Table 4. Level of significance of the effects of year and variety and their interaction on number of irrigations (In), depth of irrigation for land soaking and puddling (IWL), depth of irrigation during crop period (IWC), total irrigation water (Total IW) and irrigation water productivity (IWP), for early and late sown boro

	I_n	IWL (cm)	IWC (cm)	Total IW (cm)	IW_P (kg $ha^{-1}cm^{-1}$)
Effects	P>F	P>F	P>F	P>F	P>F
Early seeding (D1)					
Variety (V)	<0.05	0.788	<0.05	<0.05	<0.05
Year (Y)	1.000	<0.05	<0.05	<0.05	<0.05
V and Y interaction	1.000	0.999	1.000	1.000	0.878
Late seeding (D2)					
Variety (V)	<0.05	0.708	<0.05	<0.05	<0.05
Year (Y)	1.000	<0.05	<0.05	<0.05	<0.05
V and Y interaction	1.939	0.944	0.941	0.998	<0.05

The number of irrigations increased with crop duration. About 17 irrigations were required for early sown CSR 22 and 34 (duration 141-143 d), whereas early sown IR 10206-29-2-1-1 and BRRI dhan47 (duration 131-135 d) needed only 13 irrigations. The number of irrigations under late seeding increased to 23 in the case of CSR 22 and CSR 34, and to 18 in the case of IR 10206-29-2-1-1and BRRI dhan47.

The amount of irrigation water applied between transplanting and harvest of the early seeding (107 cm) was approximately five times that needed for land preparation. The amount of irrigation water applied between transplanting and maturity (IWC) was similar for early (107 cm) and late (114 cm) seedings. There were small but significant differences in the amount of water applied during the cropped period to each variety , with differences of up to about 20 cm between varieties within both early and late seedings. Both IWC and total IW increased with crop duration, and were highest for CSR 22 (early seeding total 138 cm), followed by BRRI dhan53. Irrigation requirement was lowest in BRRI dhan55 followed by BRRI dhan47. BRRI dhan55 needed about 20 and 13 cm less irrigation water than CSR 22 under early and late seeding, respectively. On average, early seeding needed 17% less irrigation water than late seeding.

3.3 Irrigation water productivity (kg ha-1cm-1)

There was a consistent trend across years and seeding dates for highest IWP in Binadhan-8, BRRI dhan47 and IR 10206-29-2-1-1. This was due to both higher grain yield and lower irrigation water requirement during the crop growing period. The low IWP of BRRI dhan55 was due to lower grain yield which more than offset its lower irrigation water requirement.

Within variety, there was a consistent trend for higher IWP with early seeding (41-45 kg ha-1cm-1) than late seeding (31-35 kg ha-1cm-1) each year. This was mainly due to the larger amount of irrigation water required for land soaking and puddling and lower yield of the late seeding. Sarangi and Lenka (2000) observed that IWP in summer rice (variety: Lalat) in coastal areas of Odisha (India) could be increased from 38 kg grain ha-1 cm-1 with flooding throughout the growing period to 50 kg grainha-1cm-1of irrigation water by maintaining saturation from one week after transplanting to maturity in comparison with a ponded water depth of 3-5 cm.

Table 5. Number of irrigations from TP to maturity (In), depth of irrigation for land soaking and puddling (IWL), depth of irrigation during crop period (IWC)and total irrigation water (Total IW) used for boro rice crop at Canning Town, West Bengal, India (mean of 2012-13 and 2013-14)

Treatment	I_n	IWL (cm)	IWC (cm)	Total IW (cm)
Early seeding (D1)				
Variety Binadhan-8	14[b]	21.1	111[ab]	132[bc]
CSR 22	17[a]	21.9	116[a]	138[a]
BRRI dhan47	13[b]	21.4	102[c]	123[c]
IR 10206-29-2-1-1	13[b]	21.5	101[c]	123[d]
BRRI dhan53	16[a]	21.7	113[ab]	135[ab]
CSR 34	17[a]	22.3	112[ab]	134[bc]
BRRI dhan55	13[b]	20.9	97[c]	118[d]
CSRC(S) 50-2-1-1-4-B	16[a]	22.1	109[b]	131[c]
LSD (P=0.05)	1	NS[1]	4	3
Year				
2012-13	15	20.7[b]	109[a]	130[a]
2013-14	15	22.5[a]	106[b]	128[b]
LSD (P=0.05)	NS	0.9	2	1
Mean	*15*	*21.6*	*107*	*129*
Late seeding (D2)				
Variety Binadhan-8	19[c]	37.7	109[d]	147[d]
CSR 22	23[a]	38.1	120[b]	158[b]
BRRI dhan47	18[c]	37.4	107[d]	144[e]
IR 10206-29-2-1-1	18[c]	37.5	109[d]	146[de]
BRRI dhan53	21[b]	37.8	117[c]	155[c]
CSR 34	23[a]	38.0	124[a]	162[a]
BRRI dhan55	18[c]	36.7	107[d]	144[e]
CSRC(S) 50-2-1-1-4-B	21[b]	38.0	120[b]	158[b]
LSD (P=0.05)	1	NS	2	2
Year				
2012-13	20	36.4[b]	116[a]	153[a]
2013-14	20	38.9[a]	112[b]	151[b]
LSD (P=0.05)	NS	0.8	1	0.8
Mean	*20*	*37.7*	*114*	*152*

[1]NS= not significant

Note: In the same seeding date, means with the same letter in a column are not significantly different at the 5% level by LSD.

Table 6. Water productivity of rice varieties for early and late seeding (the interaction between year and variety was not significant for early seeding)

Variety	Early seeding (D1)	Late seeding (D2)	
	Mean	2012-13	2013-14
Binadhan-8	45.8[b]	41.7[a]	37.9[a]
BRRI dhan47	47.6[a]	38.9[b]	35.1[b]
BRRI dhan53	40.8[d]	33.1[d]	27.8[d]
BRRI dhan55	42.1[c]	35.9[c]	32.3[c]
CSR 22	43.1[c]	38.0[b]	31.2[c]
CSR 34	39.2[e]	31.1[d]	24.4[e]
CSRC(S) 50-2-1-1-4-B	34.9[f]	26.0[e]	22.9[f]
IR 10206-29-2-1-1	45.3[b]	39.2[b]	35.3[b]
Mean	*42.4*	*35.5*	*30.9*
LSD (P=0.05)	1.1		
LSD (P=0.05) for variety and year interaction 1.2			

Note: Means with the same letter in a column are not significantly different at the 5% level by LSD.

4. Conclusions and recommendations

The present study identified promising boro varieties for the coastal salt affected areas of West Bengal. The best varieties were Binadhan-8, BRRI dhan47 and CSR 22, which yielded > 5 t ha-1. Because of their short duration, Binadhan-8 and BRRI dhan47 used less irrigation water and had higher irrigation water productivity than CSR 22. Thus, two of the three varieties with highest yield and highest irrigation water productivity came from Bangladesh, signifying the importance of cross-country germplasm exchange.

The two season, non-replicated comparison between early seeding (during the first week of November) and late seeding (during the last week of November, farmers' practice) suggested that early seeding produced higher grain yield, required less irrigation water and thus had higher irrigation water productivity. The effects of seeding date, however, need to be confirmed by further research with adequate replication of date of seeding.

As availability of irrigation water is a constraint during the boro season, combining varieties with high yield and high irrigation water productivity with optimum seeding time can contribute to increasing rice production in coastal salt-affected areas.

Acknowledgments

This paper presents findings from G2 project on "Productive, profitable, and resilient agriculture and aquaculture systems", a project of the CGIAR Challenge Program on Water and Food. We also greatly acknowledge the support provided by the International Rice Research Institute (IRRI) and the Director, Central Soil Salinity Research Institute (CSSRI), Karnal in terms of providing necessary facilities to conduct the experiments at CSSRI, Regional Research Station, Canning Town.

References

Adhya, T. K. (2011). Vision 2030, Central Rice Research Institute, Cuttack, Odisha, India. www.crri.nic.in.

Annual Report (2011-2012). Central Soil Salinity Research Institute, Karnal, Haryana, India, p.115.

Basak, J.K., Ali, M..A., Islam, M.N. and Rashid, M.A. (2010). Assessment of the effect of climate change on boro rice production in Bangladesh using DSSAT model. Journal of Civil Engineering (IEB) 38(2):95-108.

Bouman, B.A.M. and Tuong, T.P. (2001). Field water management to save water and increase its productivity in irrigated lowland rice. Agricultural Water Management 49: 11-30.

Castillo, E.G., Tuong, T.P., Singh, U., Inubushi, K., Padilla, J., 2006. Drought response of dry-seeded rice to water stress timing and N-fertilizer rates and sources. Soil Science and Plant Nutrition 52: 496-508.

Fairhurst, T. H. Abd Dobermann, A. (2002). Rice in the global food supply. Better crops international, vol. 16, special supplement. www.ipni.net/publication.

Gomez, K.A., and A.A. Gomez. 1984. Statistical procedures for agricultural research. John Wiley and Sons, New York.

Goswami, S.B. (2006). Water balance and water productivity of summer rice as influenced by land situation in tube well commands. Indian Journal of Agricultural Sciences 76(1): 11-15.

Hanway, J.J., and H. Heidel. 1952. Soil analyses methods as used in Iowa State College Soil Testing Laboratory. Iowa Agric. 57:1-31.

http://bbi.irri.org. International Rice Research Institute, Manila, Philippines.

Kukal, S. S., Humphreys, E., Yadav, S. and Singh, Y. 2010. Irrigation water productivity of rice grown with resource conservation technologies. 19th World Congress of Soil Science, Soil Solutions for a Changing World 1 – 6 August 2010, Brisbane, Australia.

Mannan, M.A., Bhuiya, M.S.U., Akhand, M.I.U. and Rana, M.M. (2012). Influence of date of planting on the growth and yield of locally popular traditional aromatic rice varieties in boro season. Journal of Science Foundation 10(1): 20-28. DOI: http://dx.doi.org/10.3329/jsf.v10i1.16275.

Olsen, S.R., C.V. Cole, F.S. Watanabe,and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939:1-19, Gov. Printingoffice Washington D.C.

Pathak, H., Pramanik, P., Khanna, M. And Kumar, A. (2014). Climate change and water availability in Indian Agriculture: Impacts and adaptation. The IndianJournal of Agricultural Sciences 84(6): 671-679.

Saha, S., Singh, D.P., Sinhababu, D.P., Mahata, K.R., Behera, K.S., Pandy, M.P., 2008. Improved rice based production systems for higher and sustainable yield in eastern coastal plain in India. Journal of the Indian Society of Coastal Agricultural Research 26(2): 74-79.

Sarangi, S. K. and Lenka, D. (2000). Increasing water-use efficiency in summer rice (Oryza sativa) at Bhubaneswar. TheIndian Journal of Agricultural Sciences 70(11): 779-780.

Sarangi, S.K., Maji, B., Singh, S., Sharma, D.K., Burman, D., Mandal, S., Ismail, A.M., Haefele, S.M., 2014. Crop establishment and nutrient management for dry season (boro) rice in coastal areas. AgronomyJournal106 (6), 2013-2023. doi:10.2134/agronj14.0182.

Subbiah, B.V., and G.L. Asija. 1956. A rapid procedure for the determination of available nitrogen in soils. Current Science 25:259-60.

Walkley, A.J., and I.A. Black. 1934. Estimation of soil organic carbon by the chromic acid titration method. Soil Science 37:29-38.doi: 10.1097/00010694-193401000-00003.

Section 2

Coastal Environment

Bacteriological assessment of managed aquifer recharge (MAR) water in southwest coastal areas of Bangladesh

M. P. Kabir, M. A. Islam and M. A. Akber

Environmental Science Discipline, Khulna University, Bangladesh, mdpervezkabir@gmail.com, atikku_es@yahoo.com, shamim.05es@gmail.com

Abstract

Drinking water is scarce in the coastal areas of Bangladesh due to the unavailability of freshwater aquifers at suitable depths and high salinity of surface water. Households mainly depend on rainwater harvesting, pond sand filters and rain-fed ponds for drinking water. Thus, people in these areas often suffer from waterborne diseases. Recently the government and non-government organizations started promoting Managed Aquifer Recharge (MAR) in the coastal areas of Bangladesh to provide safe drinking water. This study was conducted to assess the bacteriological quality of MAR water. Five MARs were selected for the study and samples were taken from source pond, abstraction well (treated water) and household storage water. Samples were collected in two terms consecutively on June and August 2014 and were evaluated for indicator bacteria (*E. coli* and enterococci) and physico-chemical parameters (pH, electrical conductivity, turbidity and salinity). Although the MAR treatment reduces bacterial contamination, the treated water showed indicator bacterial contamination and an increase in salinity. For the source pond, abstraction well and household storage water the concentration of *E. coli* were 2570, 20 and 36cfu/100ml, respectively; concentrations of enterococci were 2400, 134 and 209cfu/100ml; and salinity concentrations were 0.86, 1.21 and 1.27 ppt, respectively. The study findings suggest that consumption of MAR water may pose a substantial risk to public health.

Key message: Application of Managed Aquifer Recharge (MAR) for rain-feed pond water treatment may reduce indicator bacterial concentration significantly, however point of use (in house) water treatment is required to ensure potability.

Keywords: drinking water, coastal area, MAR, indicator bacteria, salinity

1. Introduction

About 884 million people in the world, most of whom are from developing countries, do not get their drinking water from improved sources (WHO and UNICEF, 2010). Waterborne diseases are responsible for approximately 7 million deaths every year. Every eight seconds, a child dies from a waterborne disease, about 4 million in a year (Lalzad 2007). Access to safe drinking water is a fundamental human right and, like other developing countries, it is an important national goal of Bangladesh (Khan et al. 2008). In addition to risks from microbial contamination, the safety of drinking water in Bangladesh is also threatened by chemical contamination. The widespread fecal indicator bacteria and viral pathogens found in tube wells are known to be predictive of diarrheal disease in diverse populations around the world (Peter et al. 2012). Bangladesh is one of the most densely populated countries of the world; about 145 million people live in 145,000 km^2 area. Among the waterborne diseases diarrhea and cholera are still the major killers of infant and child mortality in this populous nation (Khan et al. 2008). The Bangladesh Bureau of Statistics and UNICEF estimated that children under five years of age suffer from three to five episode of diarrhea each year, each of which lasts for two to three days and sometimes more than two weeks (Arsenic Policy Support Unit 2006).

Scarcity of drinking water is acute in the coastal areas of Bangladesh as freshwater aquifers are not available at suitable depths and surface water is highly saline. WHO (2004) reported that in the southwest coastal area of Bangladesh (Khulna, Satkhira and Bagerhat Districts) the groundwater is unsuitable for human consumption due to high salinity (Harun and Kabir 2012). At present, the coastal population is mainly dependent on natural sources for drinking water, such as rainwater and pond water (Farhana 2011). Several studies (Kamruzzaman and Ahamed 2006; Karim 2010; Islam et al. 2011) showed that natural sources used as alternative sources of drinking water have microbial contamination. Rain-fed pond waters are heavily polluted due to unhygienic sanitation and eventually act as excellent carriers of water-borne pathogens (Karim 2010). Several studies (APSU 2005; Howard et al. 2006) in Bangladesh showed that rooftop harvested rainwater is of consistently high quality, free from arsenic and satisfies the physical and chemical water quality standard of Bangladesh. However, microbiological contamination was found to occur to a great extent, which may cause significant health hazards for rural people (Karim 2010). As a result, several water treatment technologies emerged in this region such as solar desalinization, reverse osmosis, pipe line water supply, and Managed Aquifer Recharge (MAR). MAR can restore groundwater levels and provide a barrier against seawater intrusion, and aquifers can be used as a reservoir facility for both seasonal and long term storage (Rahman et al. 2012). Now government and non-government organizations are promoting MAR to provide safe drinking water for the coastal people of Bangladesh. However, no detailed study on routine bacteriological assessment of MAR has been conducted for this area. It is therefore necessary to evaluate the effectiveness of MAR systems in producing safe drinking water by analyzing bacteriological contamination and salinity of the water from source to household storage.

2. Methodology

In the southwestern coastal region of Bangladesh, Dacope *Upazila* and Batiaghata *Upazila* in Khulna District and Mongla Upazila in Bagerhat District were selected as study areas. In these areas the problem of safe drinking water is likely to be severely acute, and many MARs have already been established as a supplementary drinking water source. A reconnaissance survey was conducted before site selection to understand the overall scenario of drinking water sources in this area. Five MAR sites were selected as sampling stations, out of which two sites were selected from Mongla, two from Dacop and one from Batiaghata. Water sampling and laboratory analysis was conducted in two terms between April and July 2014 to cover both dry and wet seasons. A total of 20 samples were collected during each sampling term where the number of samples from source pond, abstraction well (treated water) and household storage were 5, 5 and 10, respectively. For microbiological analysis, 500 ml water samples were aseptically collected in sterile Nalgene plastic bottles. All samples were placed in an insulated box filled with ice packs and transported to the Environmental Microbiology Laboratory of Khulna University for bacteriological analysis within 6 hours of sampling. We analyzed for two indicator organisms (*E. coli* and enterococci) and four physico-chemical parameters (pH, salinity, EC and turbidity). Proper quality assurance and control were adopted in water sampling, preservation and laboratory analysis according to the method of the American Public Health Association (APHA 1998). The indicator organisms were tested by membrane filtration technique. For *E. coli* enumeration the first petri dish was prepared with m-TEC Ager media. A 100 ml water sample was filtered through a 0.45μm membrane filter and then placed in the center of the petri dish. Then the dishes were closed, inverted, and incubated in 35±0.2^{o}C for 2 hours. After 2 ours the plates were sealed with zip-lock bags and placed on a rack in a 44.5±0.2^{o}C water bath for 24 hours. After 24 hours the plates were removed from the water bath. Then the absorbent pad was placed in a new petri dish, and the pad was saturated using urea substrate medium. Pale yellow, yellow-brown, yellow-green colonies are considered to be *E. coli*. Enumeration of enterococci is nearly similar to the enumeration of *E. coli.* For enterococci, the first petri dish was prepared by enterococcus agar media. A 100 ml water sample was filtered through a 0.45μm membrane filter and placed in the center of the petri dish and incubated at 35±0.2^{o}C for 48 hours. Dark red color colonies of enterococci were formed. The pH was measured by Hanna instrument (Hi 8424), salinity and electrical conductivity (EC) were measured by Hanna instrument (Hi 9635, microprocessor, Conductivity and TDS meter) and turbidity was measured by turbidity meter (HACH DR/820 portable spectrophotometer).

3. Results

3.1 Indicator bacterial contamination

Microbiological quality of the collected water sample is summarized in Table 1. *E. coli* and enterococci was present in 100% of the source pond water samples. However, *E. coli* and enterococci contamination was concentrated at the abstraction well and quantity of *E. coli* and enterococci slightly increased again at household storage.

Table 1. *E. coli* and enterococci concentration at source pond, abstraction well (treated water) and household storage water

Parameter	Source pond			Abstraction well (Treated water)			Household storage			Av. % reduction (source pond to abstraction well)
	Mean	Median	Range	Mean	Median	Range	Mean	Median	Range	
E. coli	2570	2300	1500-5400	20	8	0-80	36	40	0-130	99.65
Enterococci	2400	2900	300-4200	134	90	7-460	209	120	1-530	96.89

Maximum concentrations of *E. coli* and enterococci were found in the source pond water. About 37% of abstraction wellwater showed *E. coli* concentrations of 0 cfu/100ml while enterococci were found in all abstraction well water. At the abstraction well *E. coli* and enterococci concentrations ranged from 0-80 cfu/100ml and 7-460 cfu/100ml, respectively, and concentrations tended to increase from abstraction well to household storage water. *E. coli* and enterococci removal by MAR were 99.65% ($p < 0.01$) and 96.89% ($p < 0.05$), respectively (Table 1).

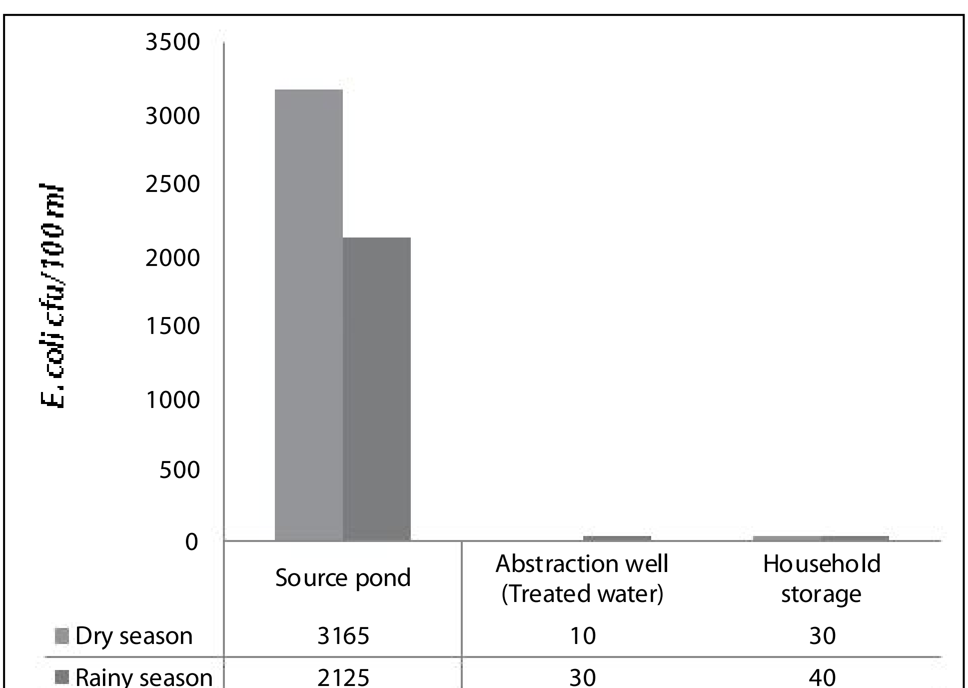


Fig. 1. Seasonal variation of *E. coli* concentration in source pond, abstraction well (treated water) and household storage water.

E. coli concentrations of source pond, abstraction well and household storage water in both dry and rainy season are shown in Figure 1. *E. coli* concentration of source pond water was higher during the dry season than the rainy season but at the abstraction well the result was considerably lower. During dry season *E. coli* removal by MAR was 99.69% ($p < 0.01$) whereas in rainy season it was 98.58% ($p < 0.05$). Both dry and rainy season *E. coli* concentrations increased from abstraction well to household storage water.

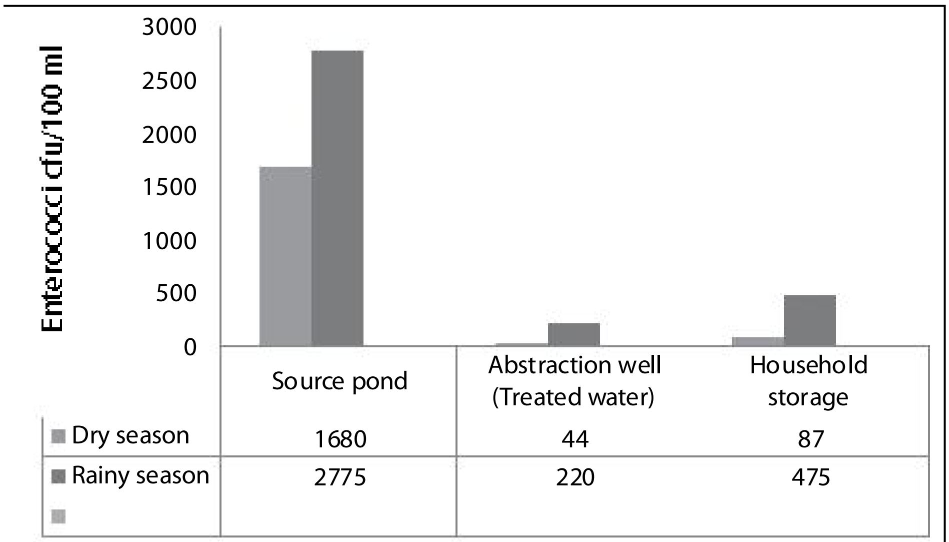


Fig. 2. Seasonal variation of enterococci concentration in source pond, abstraction well (treated water) and household storage water.

Figure 2 shows that the enterococci concentrations for both source pond and abstraction well water were higher during the rainy season, unlike *E. coli* concentrations. During the dry season enterococci decrease from source to abstraction well was 97.38% ($p < 0.05$), and in the rainy season it was 92.07% ($p < 0.05$). Like *E. coli*, enterococci concentrations increased from abstraction well to household storage water in both dry and rainy seasons.

3.2 Results of physico-chemical analysis

The results of the physico-chemical analyses of the water samples collected from source pond, abstraction well and household storage in both dry and rainy season are summarized in Table 2. Mean pH, EC and turbidity values for all options were within the guideline values of WHO (WHO 2004) but salinity is the prime concern, especially at the abstraction well.

Table 2. Concentrations of physico-chemical parameters during dry and rainy season at source pond, abstraction well (treated water) and household storage water

Parameter	Source pond				Abstraction well (Treated water)				Household storage			
	Dry season		Wet season		Dry season		Wet season		Dry season		Wet season	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
pH	7.35	7.1-7.88	7.9	7.65-8.34	7.32	6.8-7.84	7.33	7.08-7.87	7.54	7.0-7.67	8.5	8.31-8.7
EC (µS/cm)	2737	820-5520	923.7	375-1497	3526	1817-4940	1572	500-2040	330	1765-4575	1263	688-1838
Salinity (ppt)	1.35	0.40-2.74	0.37	.09-.64	1.73	0.90-2.45	0.67	0.15-0.90	1.63	0.88-2.27	0.55	0.25-0.85
Turbidity (NTU)	59.37	48.7-66.8	75.86	55.7-95.5	34.85	2.41-90.5	40.8	7.63-86.9	23.9	5.46-68	33.45	17.2-70.3

As shown in Table 2, mean pH values for all options are within the guideline values for drinking water of 6.5 to 8.5 (WHO 2004). During the dry season the mean ECs for all source pond and abstraction well water were above 1500 µS/cm, whereas during the rainy season mean EC values ranged from 923.7 to 1572 µS/cm. During the dry season, the mean salinity concentration for all source pond water was 1.35 ppt and for abstraction well water was 1.73 ppt; results indicate a 28% salinity increase from source pond to abstraction well. Overall salinity concentration decreased in the rainy season. In the rainy season, the mean salinity concentration for all source ponds was 0.37 ppt with salinity of 0.67 ppt at the abstraction well; results indicate an 81% increase in salinity from source pond to abstraction well. Source pond water showed the highest turbidity in the rainy season, whereas during the dry season the highest turbidity was observed at the abstraction well. In the dry season, the mean turbidity of source ponds and abstraction wells was 57.37 NTU and 34.85 NTU, respectively. Overall turbidity tends to increase in the rainy season. However, the mean turbidity of all source ponds and abstraction wells in the rainy season was 75.86 NTU and 40.8 NTU, respectively (Table 2).

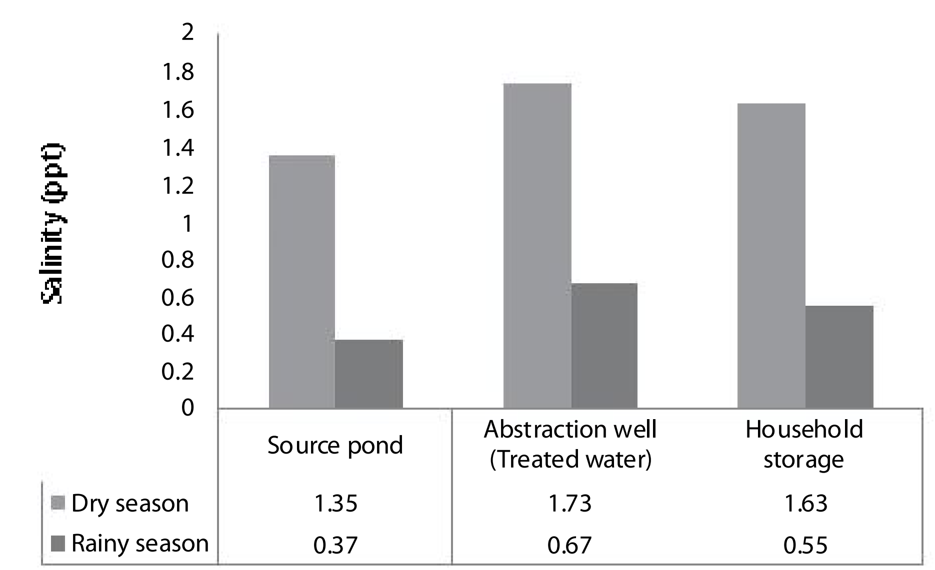


Fig. 3. Seasonal variation of salinity concentration in source pond, abstraction well (treated water) and household storage water.

Salinity levels of source pond, abstraction well and household storage water in both dry and rainy seasons are shown in Figure 3. The salinity of the source pond water was lower than the abstraction well. Salinity levels at the abstraction well were higher in both dry and rainy seasons, but tended to decline with household storage.

4. Discussion

The study suggests that source pond water experiences higher incidents of microbial contamination than abstraction well (treated water) and household storage water. Highest median *E. coli* and enterococci were found in source pond water, which may be attributed to contamination from surface runoff including agricultural, household and domestic runoff. It was observed that presence of embankments did not protect any of the ponds from contamination. Almost 100% of the source pond water samples showed *E. coli* and enterococci concentrations above WHO recommended guidelines (Table 1). At the abstraction well microbial contamination was relatively low. Mean *E. coli* and enterococci concentrations found at abstraction wells were 20 cfu/100ml and 134 cfu/100ml, respectively (Table 1); from source pond to abstraction well water about 99.65% ($p < 0.01$) of *E. coli* and 96.89% ($p < 0.05$) of enterococci were reduced. However, microbial quality of collected water samples deteriorated from abstraction well to household storage water. The increase in *E. coli* and enterococci may be attributed to poor hygienic and sanitary practices. Lack of hygienic practices, such as improper cleaning of storage pots before water collection, water collected by dipping of pot with unwashed hands and water stored in open containers are responsible for microbial contamination (Blum et al. 1990;

Tuttle et. al. 1995). During water collection from various sites we observed that water is collected in unwashed pots and stored in open containers. While 99.65% of *E. coli* and 96.89% of enterococci was removed by MAR (Table 2), salinity concentrations increased greatly. From source pond to abstraction well water, salinity increased by 28% during the dry season and 81% during the rainy season (Table 2). Salinity intake with water may be responsible for left ventricular hypertrophy, increasing the number of strokes and incidences of cardiovascular disease among coastal communities (Strazzullo et al. 2009).

The aim of MAR technology is to remove microbial contamination as well as decrease the salinity level of groundwater. This study found that MAR technology significantly reduces microbial contamination, but at the abstraction well *E. coli* and enterococci concentrations were above WHO drinking water guideline values. At the household consumption point different water treatment options like chlorination, alum treatment and halazone tablet treatment may be helpful for reducing microbial contamination. This study also found that salinity levels increased with MAR treatment.

References

American Public Health Association (APHA) 1998. Standard Methods for the Examination of Water and Waste water. 20th Edition, United Book Press, Inc., Baltimore, Maryland.

APSU 2005. *Progress with Provision of Arsenic Mitigation Options to the End of December 2004*. Dhaka: Arsenic Policy Support Unit.

APSU 2006. *Experiences from pilot projects to implement water safety plans in Bangladesh*. Dhaka: Arsenic Policy Support Unit.

Blum, D., Emeh, R.N., Huttly, S.R., Dosunmu-Ogunbi, O., Okeke, N., Ajala, M., Okoro, J.I., Akujobi, C., Kirkwood, B.R. and Feachem, R.G. 1990. The Imo State (Nigeria) Drinking Water Supply and Sanitation Project, 1. Description of the project, evaluation methods, and impact on intervening variables. *Tropical Medicine and Hygiene,* 84: 309-315.

Farhana, S. 2011. *Suitability of pond sand filters as safe drinking water solution in storm surge prone areas of Bangladesh: a case study of post-Aila situation in Shyamnagar, Satkhira district, Khulna.* MSc. Diss., BRAC University.

Harun, M. A. Y. A. and Kabir, G. M. M. 2012. Evaluating pond sand filter as sustainable drinking water supplier in the Southwest coastal region of Bangladesh. *Journal of the Applied Water Science*, 3:161–166.

Howard, G., Ahmed, M. F., Shamsuddin, A. F., Mahmud, S. G. and Deere, D. 2006. Risk assessment of arsenic mitigation options in Bangladesh. *Journal of Health, Population, and Nutrition*, 24(3), 346–355.

Islam, A.M.; Sakakibara, H.; Karim, M. .; Sekine, M. and Mahmud, Z.H. 2011. Bacteriological assessment of drinking water supply options in coastal areas of Bangladesh. *Journal of Water and Health* (09.2), 415 – 428.

Kamruzzaman, A. K. M. and Ahmed, F. 2006. Study of performance of existing pond sand filters in different parts of Bangladesh. *Proceedings of 32nd WEDC International Conference s*, 377–380.

Karim, M. R. 2010. Microbial contamination and associated health burden of rainwater harvesting in Bangladesh. *Journal of Water Science and Technology*, 61(8) 2129– 2135.

Khan,M. M. H., Kraemer,A. and Mori, M. 2008. *Drinking water crisis due to arsenic contamination in Bangladesh: public health consequences, mitigation strategies and sustainability*. University of Bielefeld, Germany and Sapporo Medical University, Japan.

Lalzad, A. 2007. *An Overview of the Global Water Problems and Solutions*. http://www.goftaman.com/daten/en/articles/An%20Overview%20of%20the%20Global%20Water%20Problems%20and%20Solutions.pdf

Peter S. K., Larry D. M., Alice L., Daniel E., Williams, Md. J., Alam, B. J., Mailloux, A. S., Ferguson, P. J., Culligan, M. L., Serre, M. E., Ahmed, K. M., Sayler, G. S. and Alexander, V. G. 2012. Unsealed tubewells lead to increased fecal contamination of drinking water. *Journal of Water Science*, 10(4): 565−577.

Rahman, M. A., Oberdorfer, P., Jin, Y., Pervin, M., and Holzbecher, E. 2012. Impact assessment of hydrologic and operational factors on the efficiency of managed aquifer recharge scheme. *Excerpt from the Proceedings of the 2012 COMSOL Conference*.

Strazzullo P., D'Elia L., Kandala, N.B. and Cappuccio, F.P. 2009. "Salt intake, stroke, and cardiovascular disease: meta-analysis of prospective studies". *BMJ* 339: b4567.

Tuttle, J., Rise, A.A., Chimba, R.M., Perera, C.U., Bean, N.H., Griffin, P.M. 1995. Antimicrobial-resistant epidemic Shigella dysenteriae type 1 in Zambia: modes of transmission. *Journal of Infectious Diseases,* 171(2): 371-375.

WHO 2004. *Occurrence of cyanobacterial toxins (microcystins) in surface waters of rural Bangladesh-Pilot Study*. Geneva: World Health Organization.
http://www.who.int/water_sanitation_health/emerging/wsh0406.pdf

WHO and UNICEF 2000. *Global Water Supply and Sanitation Assessment Report*. USA: World Health Organization. http://www.unicef.org/wash/files/gafull.pdf

Effects of controlling saline water intrusion in an empoldered area of Bangladesh

M. C. Rahman[1], T. H. Miah[2] and M. H. Rashid[2]

[1]Bangladesh Rice Research Institute, Bangladesh, siddiquer07@gmail.com
[2]Bangladesh Agricultural University, Bangladesh, tofazzal_miah@yahoo.com, mharunar@yahoo.com

Abstract

The study explores the effects of controlling saline water intrusion into coastal polder areas of Bangladesh. The study was conducted at the Dacope *Upazila* of Khulna District (Polder 31) using a predesigned and pretested interview schedule involving 200 farmers. Profitability and undiscounted benefit-cost ratios of rice and shrimp were calculated. Saline water has a significant impact on crop production in the study area and the two unions of Pankhali and Tildanga have a contrasting choice of crops and cropping patterns. Considering the impact of saline water on environment and rice production, the farmers of the Pankhali union decided to control saline water intrusion and follow a rice-cum-golda (freshwater prawn) cropping pattern. By contrast, the farmers of Tildanga practiced a rice-cum-bagda (brackishwater shrimp) pattern. Water salinity differed significantly between the two unions. Average monthly salinities throughout the year in Pankhali and Tildanga Unions were 7.85 and 12.34 with standard deviations of 7.39 and 8.85, respectively. Lands remained fallow in the *boro* (dry) season. The benefit-cost ratios of golda and bagda culture were 2.12 and 3.60, respectively. Farmers in Pankhali Union were able to compensate for lower benefits from golda farming with higher returns from T. *Aman* rice (BCR 1.76) and other benefits such as grazing land, drinking water, vegetables cultivation, *boro* farming, leasing arrangements and the higher price of golda. The people of Pankhali Union were actively controlling saline water inflow to the polder, whereas those of Tildanga Union preferred saline water because of better financial benefits from bagda farming. Poor farmers of Tildanga were thinking differently; they wanted to grow more rice and vegetables to escape from *Hurry* (a leasing system) and improve access to their land. According to farmers, the salinity of Pankhali Union is gradually declining due to changed water management and cropping practices. Farmers’ are interested in cultivating rice in the *boro* season and introducing salt tolerant rice varieties to improve productivity and food security. Separate water management policies are needed to facilitate increased productivity of farming at the two different areas.

Key messages: Controlling saline water intrusion into the empoldered area of coastal Bangladesh has an impact on rice productivity, salinity level, society and environment.

Keywords: water salinity, golda, bagda, T. *aman* rice

1. Introduction

Bangladesh has a large coastal area of 47,211 km^2 (32 percent of the country’s geographical area), where 35 million people (28 percent of the country’s total population) live in 6.85 million households. Of the country’s 64 districts, 19 are considered to be coastal districts (Rahman et al. 2013). The coastal area has been inhabited for centuries but is now suffering from various development pressures; salinity intrusion is a key problem particularly affecting rice cultivation. Bagda (brackishwater shrimp) farming creates an additional pressure on coastal areas of Bangladesh and has been associated with various negative social and ecological externalities. The situation has precipitated significant debate and controversies in recent years, resulting in a number of government initiatives to manage negative impacts including enacting laws governing land leasing, release of guidelines for site selection and operation of bagda farms, requiring consent of local farmers before setting up bagda farms, and the formation of Bagda Culture Steering Bodies at national, regional and local levels. These government regulations have been criticized on the grounds of their inadequacy, weak enforcement and non-sensitivity to environmental concerns (WorldFish Center 2009).

The effects on rice production are considered significant in coastal Bangladesh; the productivity of rice in the region is lower (3.0 ton/ha) than the potential yield (5.5 ton/ha) of modern varieties. Salinity has become a problem for livestock and forestry also, reducing options for diversification particularly by poorer farmers. Cultivation of rice-cum-golda (freshwater prawn) rather than rice-cum-bagda has become a suitable alternative in some areas, avoiding use of saline water and allowing rice culture. Widespread adoption of this method appears to be limited at present as larger farmers prefer shrimp culture with saline water, a practice that constrains options for less influential farmers.

Rice takes the monopoly position as a staple food of the country and salinity has significant impact on production of this staple. Recognizing this, people of the Pankhali Union of polder 31 in Khulna District banned the intrusion of saline water and brought more land under the cultivation of *T. Aman* rice, following a rice-cum-golda cropping pattern instead of rice-cum-bagda (Rahman et al. 2013). This study was designed to evaluate the effect of this initiative to control saline water intrusion into polders.

2. Methodology

Dacope *Upazila* of Khulna District was selected as the study area, with Pankhali and Tildanga Unions selected for in-depth study because they reflected contrasting cropping and salinity conditions. A stratified random sampling was used to select 200 (100 from each Union) farmers with two different cropping patterns (rice-cum-golda and rice-cum-bagda). Primary data were collected using a structured interview schedule. Both descriptive statistics and activity budgeting were used for data analysis. The productivity and profitability of rice and golda/bagda cropping was assessed using the following algebraic equation:

$$\pi = TR - TC$$

$$\pi = \sum Q_y.P_y + \sum Q_b.P_b - \sum_{i=1}^{n} (X_i.P_{xi}) - TFC$$

Where,

π	Net returns from production (Tk/ha);
Q_y	Total quantity of product (kg/ha);
P_y	Per unit prices of the product (Tk/kg);
Q_b	Total quantity of the concerned byproduct (kg/ha);
P	Per unit prices of the relevant byproduct (Tk/kg);
X_i	Quantity of the concerned i^{th} inputs;
P_{xi}	Per unit price of the relevant i^{th} inputs;
TFC	Total fixed cost involved in production;
i	1, 2, 3,…, n (number of inputs).

3. Result and discussion

3.1 Impacts of bagda farming in Tildunga Union

This section provides a qualitative description of the impacts of bagda farming in the Tildunga Union. A comparison of environment and farming systems is provided in Section 3.2.

3.1.1 Effect on forestry

A significant impact of salinity on presence and growth of trees was observed in Tildunga Union, with few indigenous fruit trees present. Older people reported a continuous reduction of indigenous trees in Tildunga, in contrast to the considerable development of indigenous trees in Pankhali Union. Reduction of indigenous trees and dominance of mangrove trees provides an indication of the impact of salinity on forestry. Mangrove trees (namely 'Gewa'- *Excoecaria agallocha* and 'Golpata'- *Nypa fruticans*) were notably more abundant in the Bagda *gher* areas.

Fig. 1. Development of mangrove trees in bagda *ghers*.

3.1.2 Unfavorable environment for crops and vegetables

Farmers wishing to grow rice and vegetables in Tildunga Union faced constraints associated with salinity in the water and soil. The effect of salinity on crops depends on the degree of salinity at critical stages of growth, but overall declines in productivity with exposure to salinity were reported. Only a small number of farmers grew some vegetables. Several aquatic plants and weeds were reported to be absent from now saline areas including *Durba, Baju, Chehur, Tankuni, Halencha, Malanshak, Kalmisak, Ambalisak, Kachuri Pana* and *Shapla.* Older people in particular reported such historical changes.

3.1.3 Scarcity of grazing land for livestock production

Saline water brought into *gher* areas for bagda farming in Tildunga Union has also resulted in a reduction in land for livestock grazing, limiting opportunities for livestock production among farmers in the area. The shrinkage of paddy area associated with expansion of bagda farming has also led to an acute shortage of rice straw, which resulted in negative impacts on the livelihoods of poorer families dependent on cattle rearing.

Fig. 2 No feed for livestock; the cow is grazing on algae in the *gher*.

3.1.4 Reduction in rice producing areas

Saline intrusion associated with bagda culture has left areas unsuitable for rice cultivation in Tildunga Union. Standing saline water in the polder damages rice crops and has an adverse effect on rice yields. Poor dyke construction by gher owners exacerbates the problem, leading to saline water leaking out or flooding adjoining rice fields. Poor rice farmers have less influence than richer and influential gher owners and as a consequence rice growing opportunities have become more restricted within the Union.

3.1.5 Shortage of drinking water

People of Tildunga Union area generally drink pond water that is also used for other homestead activities. Bagda cultivation has led to flooding of the area with saline water and contamination of pond water with salt. Local farmers have tried to resist construction of bagda ponds near freshwater ponds, leading to social tensions and clashes in Tildunga Union. Poorer people in particular faced acute problems with access to drinking water, with rainwater becoming the only source of water for drinking and other domestic uses. Depletion and salinization of freshwater supplies means women and children have to walk increasingly long distances to collect clean water.

Fig. 3. Women and children have been the greatest victims of bagda culture developments.

3.1.6 Impact of bagda on society

Bagda farming has significant impact on society. Increased income for bagda farmers increases the ability to save and further invest in other employment opportunities, leading to overall better socioeconomic conditions among bagda farmers. Small farmers within Tildunga Union suffer from improper leasing arrangements (known locally as '*Hurry*') that led to social conflict. In the *Hurry* system, large farmers lease the land of small farmers. Small farmers have no choice but to lease out the land for whatever money the rich farmers offer for it, with limited bargaining power. Large farmers use their control of canal water to their benefit, as there is no alternative irrigation system.

The overall impact of bagda farming is shown in the flow diagram below.

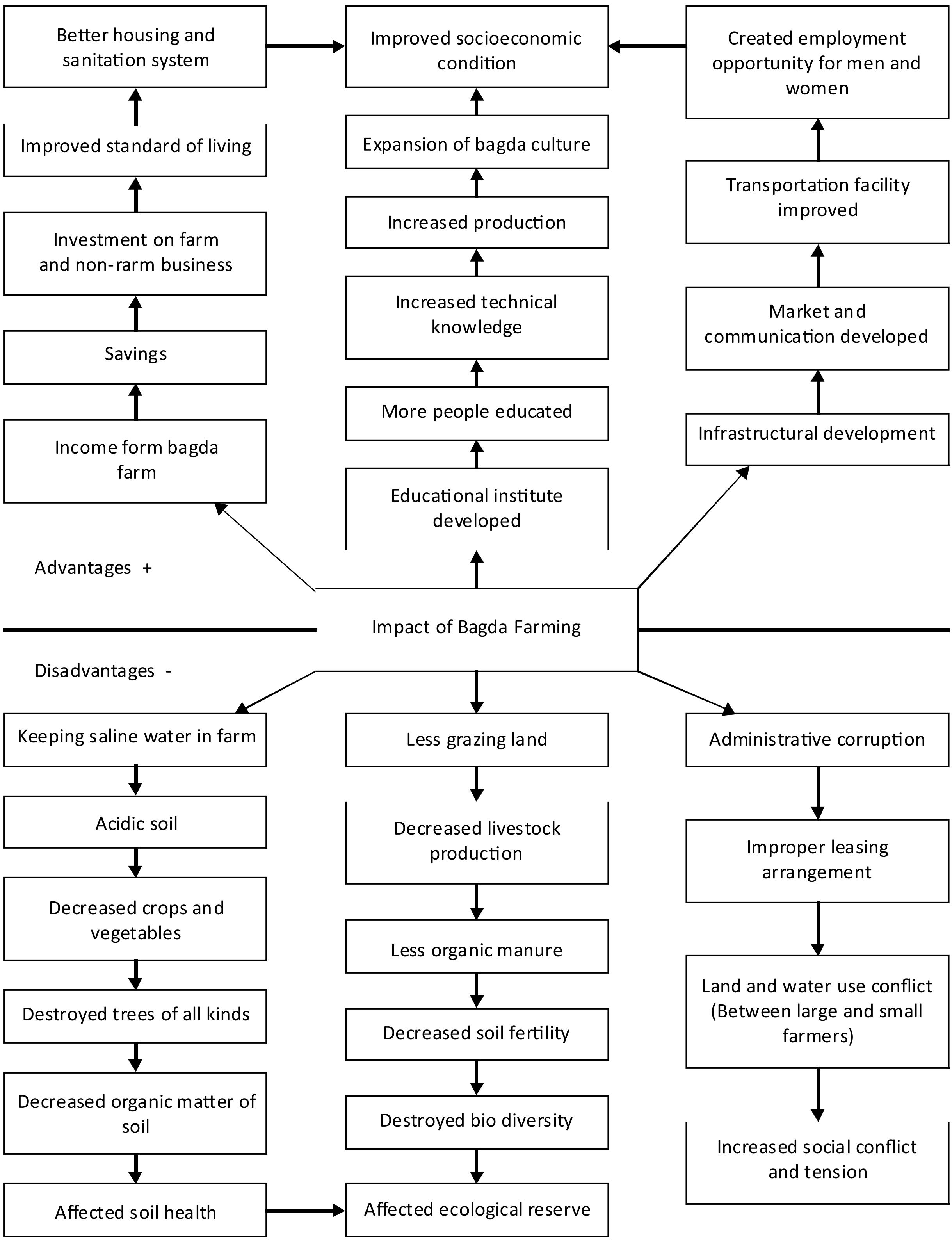


Fig. 4. Impact flow diagram of bagda farming.

3.2 Effect of controlling saline water intrusion in Pankhali Union

3.2.1 Water salinity of Pankhali and Tildanga Unions

Following the restriction of saline water intrusion in Pankhali Union, its water salinity levels changed significantly from those of Tildanga Union. Salinity varies from month to month, with lower salinity during the months of August to December and higher during the months March to June (Figure 5). The average salinity of Pankhali and Tildunga was 7.85 dS/m and 12.34 dS/m, respectively. The lowest salinity (0.50 dS/m) of Pankhali Union occurred during September and that of Tildanga (1.95) was during November. The highest water salinity occurred in Panlhali and Tildanga during the months of April (19.75 dS/m) and May (26.50 dS/m), respectively (Table 1).

Table 1. Comparative salinity of Pankhali and Tildanga unions

Area (union)	Monthly water salinity (dS/m)			
	Minimum	Maximum	Mean	Std. Deviation
Pankhali	0.50	19.75	7.85	7.39
Tildunga	1.95	26.50	12.34	8.85

Source: Soil Resource Development Institute (2012), author's calculation

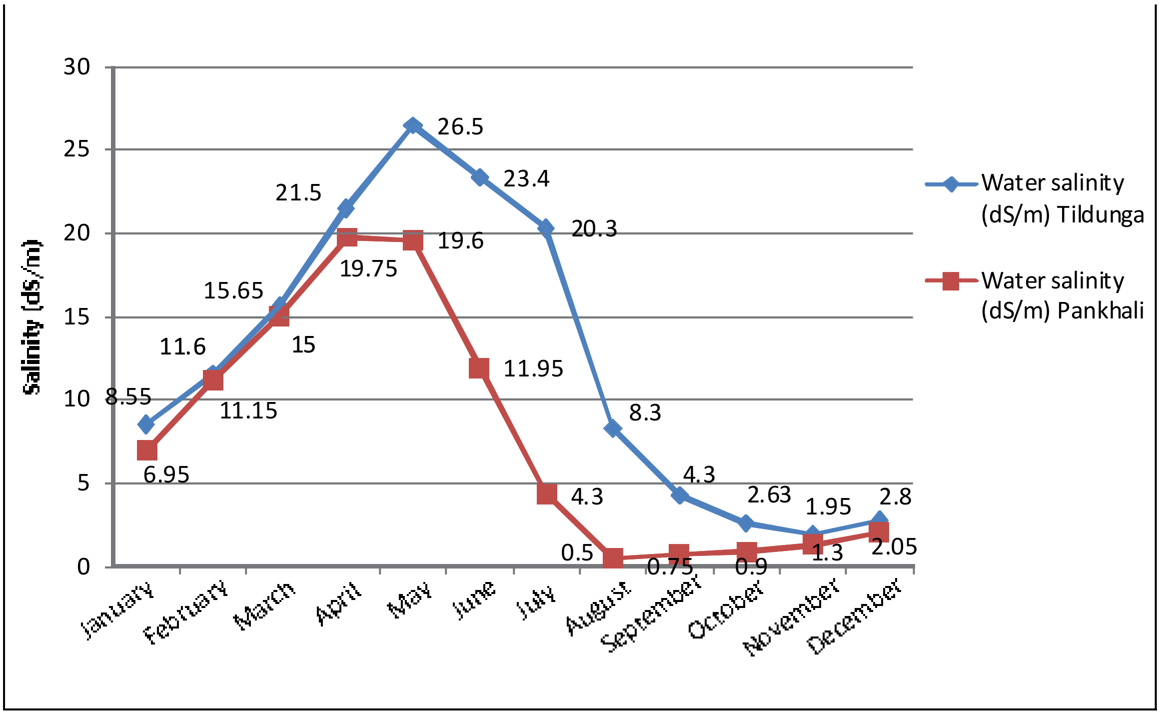


Fig. 5. Comparative salinity of Pankhali and Tildanga Unions (source: Soil Resource Development Institute (2012).

3.2.2 Productivity of T. aman rice and prawn/shrimp in Tildunga and Pankhali Unions

The productivity of rice also differed between the different salinity areas. The productivity of rice is marginally higher in the lower salinity areas than that of higher salinity areas. On average the productivity of rice in Pankhali Union was 3,098 kg/ha and 3,005 kg/ha in Tildunga Union (Table 2). This indicates that water salinity has some impact on the productivity of rice in the study area. However, the productivity of golda at Pankhali was higher than that of bagda at Tildanga.

Table 2. Productivity of rice and shrimp in Tildunga and Pankhali unions

Area	Mean productivity (kg/ha)	
	Rice	Shrimp (golda/bagda)
Pankhali Union	3098.20	254.94
Tildunga Union	3004.72	233.18

3.2.3 Comparative gross margion, net return and BCR of T. Aman rice and shrimp

Although the gross return from golda was higher in Pankhali Union than that of bagda in the Tildunga Union, the benefit cost ratio (BCR) of bagda (3.60) was higher than that of golda (2.12). The reason for this is the low investment cost of bagda (shrimp). The gross return and BCR of rice production, though low, was higher in Pankhali Union than Tildunga Union (Table 3), as salinity was lower in Pankhali Union.

Table 3. Comparative per hectare costs and return of T. Aman rice and shrimp farming

Items	Shrimp farming		T. Aman rice farming	
	Pankhali Union (mostly golda)	Tildunga Union (mostly bagda)	Pankhali Union	Tildunga Union
Gross returns (Tk/ha)	446,025.00	221205.00	58,237.00	47958.00
Variable costs (Tk/ha)	131,898.00	54458.00	25,736.00	31999.00
Gross margin (Tk/ha)	314,127.00	41592.00	32,501.00	15959.00
Fixed costs (Tk/ha)	78,547.00	7612.00	7,418.00	8033.00
Total costs (Tk/ha)	210,445.00	62070.00	33,154.00	40032.00
Net returns (Tk/ha)	235,580.00	159135.00	25,083.00	7926.00
BCR	2.12	3.60	1.76	1.20

Source: Field survey (2012).

4. Conclusion

Realizing the environmental, social and rice yield impacts of bagda cultivation with saline water, the people of Pankhali Union became interested in cultivating golda instead of bagda. The community has restricted the intrusion of saline water into the polder area. People of that area were happy enough as the system was beneficial for rice farming and resulted in better quality water for drinking. Small farmers reported that they had removed the curse of *Hurry*.

Although poor and small farmers benefited by restricting the entry of saline water, larger *gher* farmers were reported to be unhappy as it hampered bagda farming. Rice takes the monopoly position as the staple food item throughout the country and saline water intrusion for bagda culture hampered rice cultivation. The preference for bagda is clearly driven by significantly higher financial benefit (BCR was 3.60). Farmers in Tildunga Union were also thinking of introducing-salt tolerant rice varieties to solve the existing problem of culturing rice alongside bagda. The farmers of both areas want to be satisfied with the existing farming situation of rice-golda and rice-bagda. However, different water management policies should be adopted within the respective areas to facilitate better management of water for rice-golda and rice-bagda farming.

Acknowledgements

The author is grateful to the International Water Management Institute (IWMI), which led the 'G3: Water Governance and Community Based Management' project of the CGIAR Challenge Program on Water and Food's Ganges Basin Development Challenge, for granting a fellowship to undertake this research.

References

Rahman, M.C., M.A.B. Siddique, M.A. Salam, M.A. Islam, and M.S. Al-faisal. 2013. Assessment of technical efficiency of rice farmers in a selected empoldered area of Bangladesh. *European Journal of Agricultural Sciences 102,* no. 10. http://bellpress.org/Journals/index.php/EJAS/article/viewFile/959/199.

Rahman, M.C., M.A.B. Siddique, M.A. Salam, M.A. Islam, M.F. Kabir, and M.S. Mahamud. 2013. Farm level evaluation of *T. aman* rice cultivation in selected saline and non-saline areas of Bangladesh. *IOSR Journal of Agriculture and Veterinary Science (IOSR-JAVS) 91,* no. 4. http://www.iosrjournals.org/iosr-javs/papers/vol4-issue4/O0449198.pdf?id=6498.

SRDI. 2012. Survey report, '*Soil Resource Development Institute*', Brackish water station, Shatkhira, Bangladesh.

WorldFish Center and N.M. Ahsan. 2009. Community-related social issues in shrimp and prawn farming in Bangladesh. *WorldFish Center Bangladesh*, Dhaka.

Section 3

Water Governance

Indo-Bangladesh Ganges water interactions: From water sharing to collective water management

P. Saikia and B. Sharma

International Water Management Institute, India, p.saikia@cgiar.org, b.sharma@cgiar.org

Abstract

Sharing of Ganges water resources has been a long, contested issue between India and Bangladesh. It dates back to the pre-independence era when Bangladesh was part of Pakistan. The crux of the dispute is the water diversion and dry season allocation at Farakka Barrage in India. The problem is exacerbated by an historical background of mistrust and antagonism between the two countries along with bureaucratic inefficiency within each country.

The signing of the Indo-Bangladesh Ganges Water Treaty (GWT) in 1996, one of the landmark treaties in South Asia, gave a new dimension to relations between India and Bangladesh with the promise of ending the longstanding dispute over the operation of the Farakka Barrage. But to what degree the dispute has been settled remains a matter of contention. Despite the working agreement, controversies continue unabated on the inefficient implementation of the treaty, water diversion at the barrage and the low freshwater flow of the Ganges downstream of the barrage in both Bangladesh and West Bengal, India. This raises major questions on the current management practices, institutional capacity and policy initiatives of the Indo-Bangladesh Ganges water sharing arrangements.

This paper describes the current challenges faced by downstream areas due to inadequate freshwater flow in the dry season, including increased sedimentation, salinity intrusion, dying river streams, siltation of navigational channels, and river bank erosion in the lower Gangetic plains. The paper also reveals many inefficiencies in the institutional arrangements between India and Bangladesh over Ganges water sharing, and presents potential avenues for improving cooperation between the two countries to address the problem of inadequate dry season freshwater flow. This requires the development of a strong institutional framework to achieve an equitable win-win situation for both the upper and lower riparian populations. The paper concludes with suggested policy options and recommendations for consideration by the national policy makers of India and Bangladesh.

Key message: The Indo-Bangladesh transboundary complexities and challenges related to Ganges water management can be resolved through an effective, strong, sustainable and collaborative institutional arrangement.

Keywords: Ganges Water Treaty, Farakka Barrage, Joint River Commission, Gorai River, Hooghly-Bhagirathi River, Kolkata Port

1. Introduction

The Ganges basin covers an area of about 109 Mha and is shared by Nepal, India, Bangladesh and China (Fig. 1). The sharing and management of Ganges water resources between India and Bangladesh has not been an easy process. Despite a joint institutional arrangement and a working agreement through the Ganges Water Treaty (GWT) signed in 1996, the two countries have not been very successful in addressing the challenges of the downstream Ganges Dependent Areas (GDA), particularly in relation to meeting water needs during the dry season (Salehin et al. 2011).

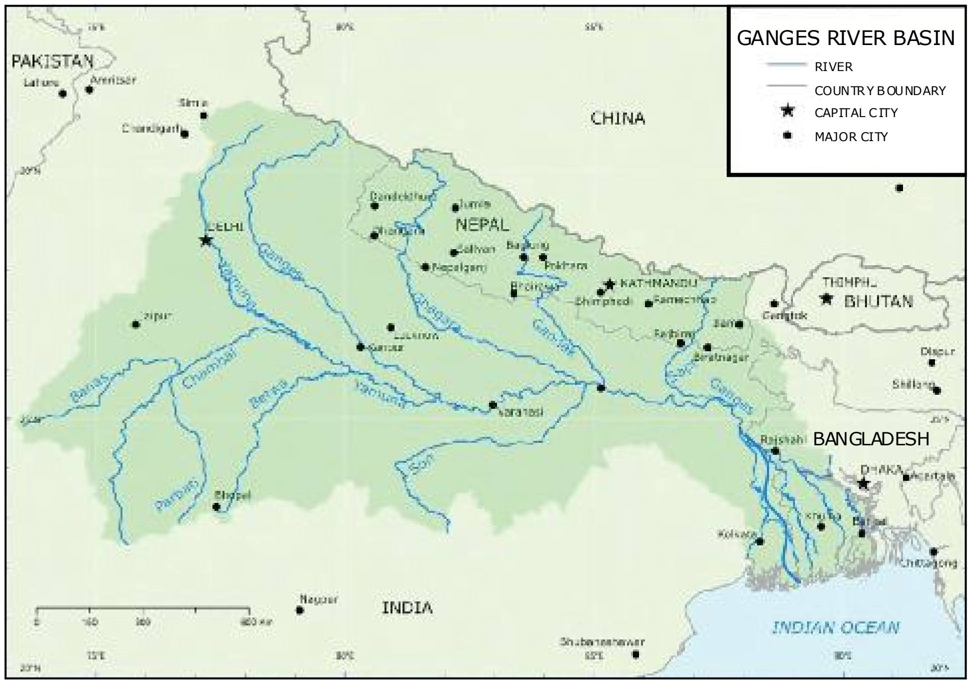


Fig. 1. Ganges River Basin (shaded green), showing the Ganges Dependent Area in India, Nepal and Bangladesh (source: WLE, CGIAR 2012).

The crux of the water sharing dispute is the construction of the Farraka Barrage (Fig. 2) and water diversion into the Hooghly-Bhagirathi River channel, and the resultant reduction in dry season flow to Bangladesh. Construction of the barrage dates back to the pre-independence era when Bangladesh was the eastern province of Pakistan. Concern over the navigability of Kolkata port in the state of West Bengal in India pushed Indian officials to take a unilateral decision to construct a barrage at Farakka in West Bengal (Fig. 3) to feed the navigational channels of the Bhagirathi River (Government of India 2004).

The Ganges splits into two channels about 40 km downstream of the Farakka barrage in Murshidabad District of West Bengal. The right arm is the Hooghly-Bhagirathi River system and the left arm enters Bangladesh through Chapi Nawabganj District of Bangladesh and flows into the Ganges/Padma River, the distributary of the Ganges in Bangladesh. Both the Hooghly-Bhagirathi and Ganges/Padma Rivers flow into the Bay of Bengal.

The Hooghly-Bhagirathi River channel, with a catchment area of 55,600 km^2, is one of the major distributaries of the Ganges in West Bengal. It is the only perennial river in the Gangetic plains of that state. Kolkata port is 299 km downstream of Farakka Barrage, and the navigational channel of the port is fed by the Hooghly-Bhagirathi River. The 2,225 m Farakka Barrage was constructed about 300 km north of Kolkata and about 16 km from the border with Bangladesh. A 38.38 km long feeder canal was constructed with a capacity of 1133 $m^3 s^{-1}$ (40,000 $ft^3 s^{-1}$) to divert water from the Ganges into the Hooghly-Bhagirathi River. The feeder canal offtake is located in the right bank of the river above the barrage, and outfalls into the Hooghly-Bhagirathi River about 40 km from Farakka Barrage.

This water diversion intervention only benefitted India and triggered conflict between India and Bangladesh. Experts in Bangladesh claimed that it reduced the flow of fresh water from the Ganges into Bangladesh and that this caused considerable hydrological, socio-economic and environmental changes in the GDA of Bangladesh, comprising roughly one-third of the country (Mirza and Hossain 2004; Khan 1996).

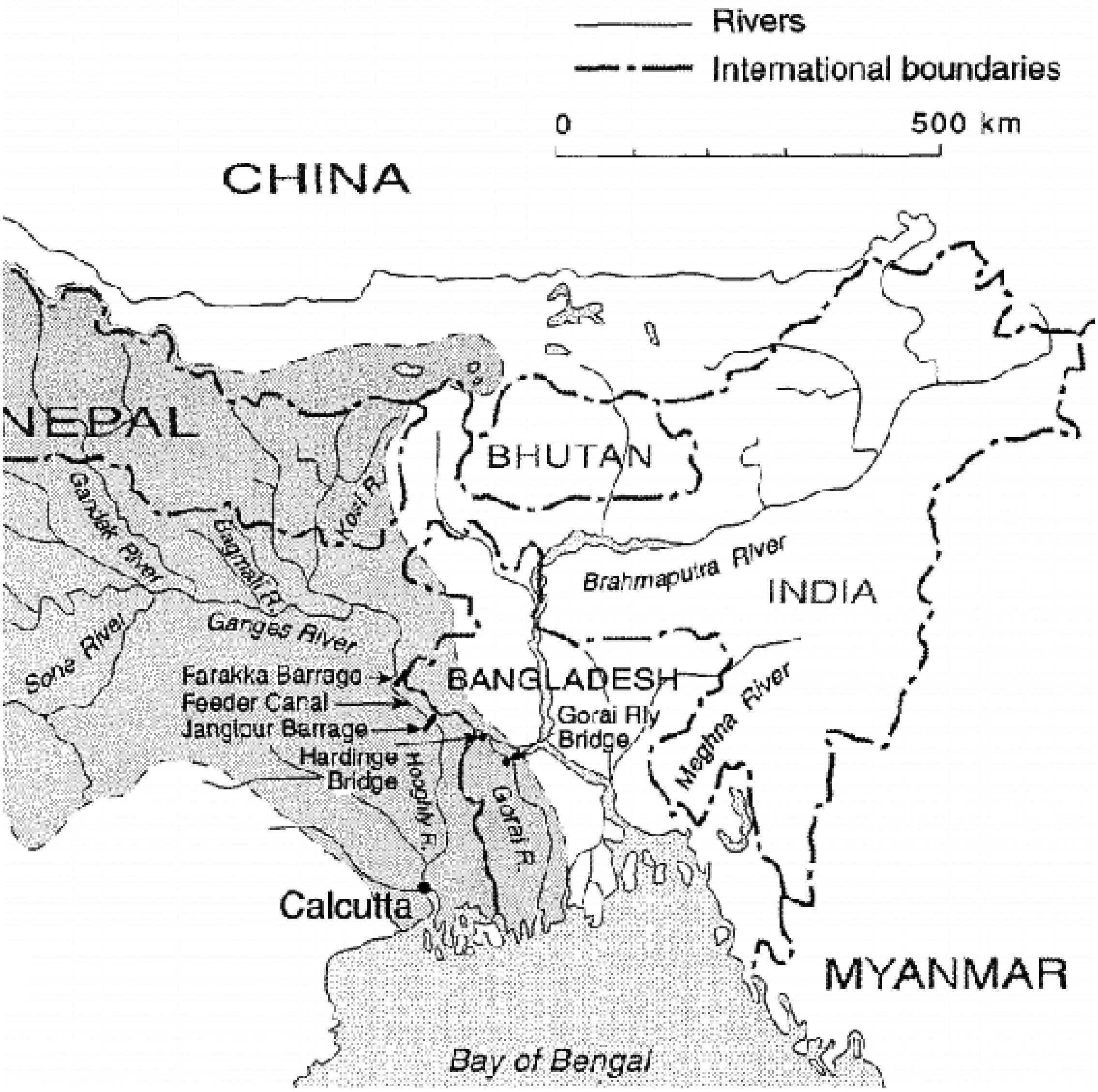


Fig. 2. Map showing the location of Farakka Barrage and the Gorai River (source: Mirza 1997).

There is also widespread concern in the region that national priorities, political disparities in relation to increasing human intervention in the river basin, and the impacts of climate change will further exacerbate the transboundary complexities between the two countries (Crow et al. 1995; Verghese 1997). A study under the National Communication (NATCOM) project of the Government of India concluded that climate change has already reduced flows in the dry season and increased flows during the wet season in river systems such as the Ganges, Krishna, Cauvery and Narmada (Gosain et al. 2006). Reduced dry season flows have resulted in severe droughts in some parts of the country, and increased flows during the wet season have enhanced intensity of floods in other parts (AK Gosain, Indian Institute of Technology, India, personal communication, 2013).

The projected general rise in temperature, temperature extremes and changes in precipitation are also likely to affect river and groundwater flows in the Ganges basin (Bharati et al. 2009). Together with climate change and increased climate variability, hydrological and morphological changes in the Ganges system will have major impacts on the water flow reaching Farakka Barrage, further challenging the transboundary arrangements between India and Bangladesh. Future flows reaching Farakka Barrage will also be modified by increased abstraction of river water for irrigation, industrialization and urbanization, and by the construction of hydropower schemes, flood control embankments and revetments in the upper reaches. Excessive exploitation of groundwater will also affect the flow dynamics of the river system (Bharati et al. 2011).

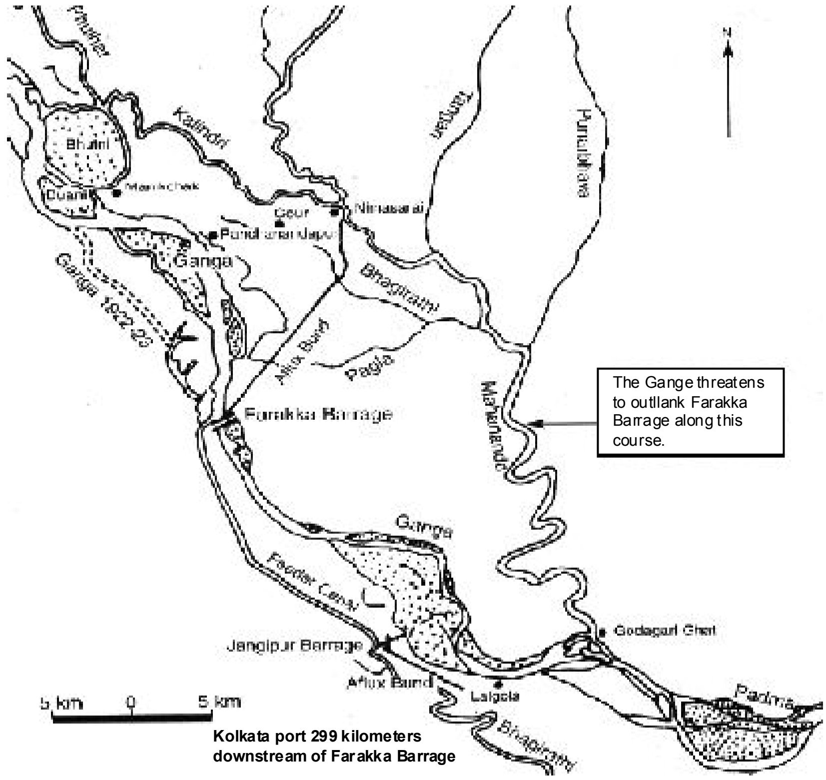


Fig. 3. Map showing Farakka Barrage, Farakka feeder canal and Bhagirathi River (source: Rudra 2004).

In addition to future loss of surface water and lowering of the groundwater table, the Ganges River basin faces problems of riverbed and coastal erosion, destruction of navigational routes, deteriorating water quality and saline water intrusion (Adel 2013). With increasing demand for surface water resources coupled with excessive groundwater withdrawal and contamination of aquifers, conflict may soon extend to rights on the shared groundwater resources.

Resolving the conflicts in water resources sharing between India and Bangladesh would contribute greatly to the development of the region, and help to conserve Ganges water resources and ecology. Among the first steps towards conflict resolution are understanding the complexities and the institutional setup of the Indo-Bangladesh transboundary water resources sharing treaty and how these impact on water resources of the coastal zone in Bangladesh and India.

The literature on transboundary flow has mostly focused on technical aspects and on the impacts of the Farakka Barrage. Research on institutional arrangements has been scarce. It is possible that that the extensive degradation of the Ganges and the serious conflicts in water sharing are not just the results of imprudent physical interventions but, more importantly, due to negligence in river basin management by all its riparian countries, inadequate information sharing, and lack of joint management and institutional capacity.

This paper aims to increase understanding of the causes of the water sharing conflicts and to identify viable approaches for Indo-Bangladesh transboundary cooperation on Ganges water sharing. The objectives of this paper are:

- To outline the historical background of the Indo-Bangladesh institutional arrangements over sharing of Ganges water, focusing on the Farakka Barrage dispute, implementation of the 1996 GWT, and the operation of the Indo-Bangladesh Joint River Commission (JRC)
- To identify the transboundary complexities between India and Bangladesh over the sharing of Ganges waters
- To identify the drivers of these transboundary complexities and how these transboundary issues impact on changes in water resources in coastal Bangladesh
- To explore and recommend avenues for cooperation over the Ganges River, not just for water sharing but towards a basin-wide resource management approach

2. Methods

The research methods included review of qualitative and quantitative data in the literature, secondary data analysis and interviews with key personnel involved in decision making about the transboundary flows. Discussions were also held with scientists, engineers, hydrologists, water experts and professionals from government agencies and academic institutes in both India and Bangladesh to get information and additional literature, and to get their views on Ganges water sharing and other current bilateral arrangements. The literature reviewed is listed by topic in Table 1.

3. Results and discussion

3.1 Common concerns over the low dry season flow of the Ganges in West Bengal and Bangladesh

The major concern for both India and Bangladesh is low freshwater flow during the dry season, which has resulted in increasing sedimentation, salinity intrusion, dying river streams, siltation of navigational channels and river bank erosion in the lower Gangetic plains (Salehin et al. 2011).

Table 1. Literature reviewed by topic

Topic	Citations
Transboundary flow of Ganges	Afroz and Rahman 2013; Bahadur 2004; Biswas 2011; Crow and Singh 1999;Crow et al. 1995; Joint River Commission (JRC) 1996; Khan 1996; Government of India 2004; Nishat 1996; Rahaman 2009; Rahaman 2006; Salman and Uprety 2011; Salman 1998; Pant 2002
Indo-Bangladesh Ganges water sharing dispute over Farakka Barrage	Government of India 2004; Mirza and Hossain 2004; Khan 1996; Crow et al. 1995; Verghese 1997; Rahaman 2006; Bahadur 2004; Iyer 2008
Indo-Bangladesh Ganges water sharing agreements and institutional arrangements	Rahaman 2009; Rahaman 2006; Salman and Uprety 2011; Crow and Singh 1999; Rahaman 2006; Upreti 1993; Bangladesh Water Development Board 2010; Government of Bangladesh 1977; Government of India 1972
The Indo-Bangladesh Joint River Commission (JRC)	Joint River Commission (JRC) 1996
1996 Ganges Water Treaty	Crow et al. 1995; Joint River Commission (JRC) 1996; Government of India 2004;Rahaman 2009; Rahaman 2006; Salman and Uprety 2011; Salman 1998)
Impact of inadequate freshwater flow in Ganges Dependent Area of Bangladesh and West Bengal	Salehin et al. 2011; Ahmad et al. 2001; Nishat 1996; Verghese 1997 Bandyopadhyay and Nandy 2011; Panda and Bandyopadhyay 2011; Adel 2013
Climate change impacts on hydrology of Ganges basin	Bharati et al. 2011; Bharati et al. 2009; Gosain et al. 2006
Hydrological and morphological changes of Ganges	Bangladesh Water Development Board 2010; Islam and Gnauck 2011; Rudra 2004; Sinha and Ghosh 2012; Panda and Bandyopadhyay 2011
Socio-economic impacts of Farakka Barrage, inadequate freshwater flow of Ganges	Bandyopadhyay and Nandy 2011; Banerjee 1999; Basu et al. 2****; Chakravarti 2004; Dutt 2004; Islam and Gnauck 2011; Maiti et al. 2014; Mirza and Hossain 2004; Mirza 1997; Panda and Bandyopadhyay 2011; Rudra, 2004; Sinha and Ghosh 2012; Sawin 2009);Government of West Bengal 2007
Institutional arrangements and in transboundary water cooperation	Mapendere 2007; Kappameier et al. 2012; Crow et al. 1995; Wolf et al. 2003; Wolf 1998; Wolf 1999; Schmeier 2010

3.1.1 Dying and disconnected river channels of the Ganges in Bangladesh

The Ganges River feeds the rivers in the western and southwestern regions of Bangladesh. With the rising population, the per capita availability of fresh water in Bangladesh will decrease rapidly (Ahmad et al. 2001), and this is also a major concern and challenge in meeting water demand in Bangladesh.

The reduced flows from the Ganges along with the construction of polders have resulted in silting up of stretches of these rivers and increased water salinity in the dry season. The construction of polders reduced tidal flooding of the lands (and associated deposition of silt), resulting in accumulation of silt in the river beds (Zahirul Khan, Institute of Water Modelling (IWM), Bangladesh, personal communication, 2013). As a result, many of the tributaries and distributaries of the Ganges/Padma are now becoming disconnected from the main stream due to the rise in sediment bars along the offtakes of these streams (Zahirul Khan, Institute of Water Modelling (IWM), Bangladesh, personal communication, 2013). Many distributaries and tributaries of the Ganges/Padma and the numerous (formerly) perennial water bodies (locally known as *pukur, baors, khals, beels, dinghies*) are almost dry during the low flow period.

Siltation has greatly affected the navigational channels in the GDA of Bangladesh (Nishat 1996). The 1989 Bangladesh Inland Water Transportation Authority study of classified waterways found that the length of the waterways varies from 3865 km in the dry season to 5968 km in the rainy season (Mishra and Hussain 2012).

The southwest coastal zone of Bangladesh (Fig. 4) depends on the Ganges for freshwater flow. However, the Gorai River (Fig. 2), the major distributary of the Ganges/Padma in Bangladesh, has been completely dry during the dry season since 1989 (Bangladesh Water Development Board 2010; BG Verghese, Centre for Policy Research, India, personal communication, 2013). Siltation has created a huge silt dam, about 5.5 m high and 30 km long in the river channel (Verghese, 1997). A vast network of rivers in the southwest region of Bangladesh is dependent on the Gorai (Afroz and Rahman, 2013). The reduced flow has led to increasing sedimentation and salinity intrusion into the estuaries of these rivers and reduced crop production in the region (Nabiul Islam, Senior Research Fellow, Bangladesh Institute of Development Studies, BIDS, personal communication, 2013).

To try and better manage the water scarcity problems and to augment the flow of the Gorai River, the government of Bangladesh has initiated various projects such as the Ganges Barrage project, the Gorai River Restoration project and water control schemes under the Bangladesh Water Development Board (BWDB), along with increased dredging activities at the inflow points. However, future activities and projects upstream of Farraka Barrage will also have a critical influence on downstream dry season flows. In the present scenario of decreasing freshwater flow at Farraka, the next ten years will pose major challenges for the Bangladesh government to manage the food, water and energy needs of its people. Having an effective arrangement with its riparian countries will be crucial (Ainun Nishat, personal communication, 2013).

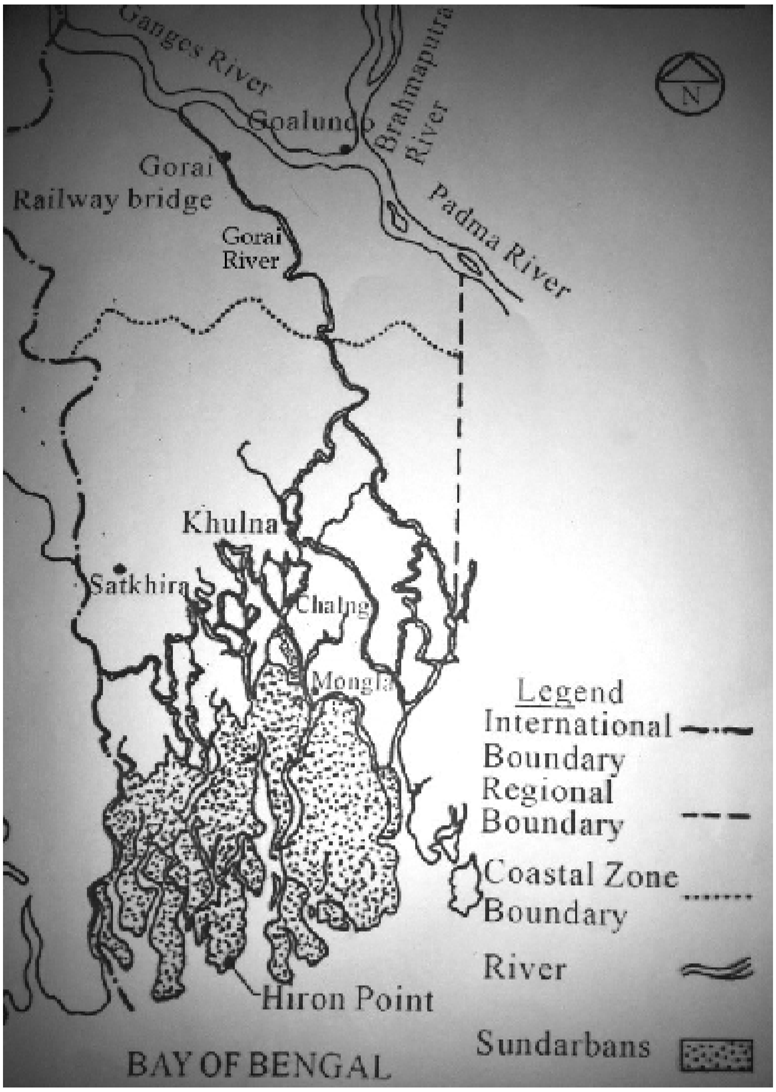


Fig. 4. Map showing the southwest coastal zone of Bangladesh (Khulna, Satkhira, etc.) fed by the Gorai River (source: Bangladesh Water Development Board 2010).

3.1.2 Dying Bhagirathi-Hooghly River system in India

Stress as a result of the low dry season flow of the Ganges is also felt in India, mostly in West Bengal. Decreased water flow into the Hooghly-Bhagirathi River has increased the salinity of the river downstream, with reverse flow high tide effects as far inland as Tribeni, 205 km from the sea in Hooghly District (Bandyopadhyay and Nandy 2011).

Increasing sedimentation, loose texture of the soil and varying discharge from the Farakka Barrage into the Hooghly-Bhagirathi River have led to meandering of the river channel and the formation of ox-bow lakes (Kolkata Port Trust, personal communication, 2013). The catchment areas of the western tributaries to the Hooghly-Bhagirathi River have been drastically modified during the last two centuries due to these major sediment induced cut-offs, reducing the length of the river (Panda and Bandyopadhyay 2011). The hydraulic regime of this area has also been modified as a result of depletion of forest cover, expansion of agriculture, indiscriminate exploitation of groundwater, expansion of road and railway networks, and the building of dams and barrages across the rivers. All these events combined to contribute to reduced flow and increasing sediment load in the Hooghly-Bhagirathi River. Dams built across some of the western tributaries also reduced the peak discharge of the Hooghly-Bhagirathi River which affected the ability to flush the sediment load into the sea (Chief Hydraulic Engineer, Hydraulic Department, Kolkata Port Trust, personal communication, 2013).

The morphological changes in the Hooghly-Bhagirathi River system (up to Hooghly Point) greatly influence the Hooghly estuary. The increasing sedimentation in the upper part of the river system is leading to sediment deposits in the estuarine part of the river system.

3.2 Lack of effective institutional arrangements

3.2.1 Indo-Bangladesh Ganges water sharing agreements

Several bilateral arrangements have been made in the past between the two countries over sharing of the Ganges water and management of downstream dry season flows. In July 1970 an agreement was signed between India and Bangladesh (then East Pakistan) in which it was agreed that the barrage would be the main point of water sharing between the two countries. However, there were no clear provisions on how the water would be shared.

On 29 March 1972, a friendship agreement ('Treaty of Friendship, Cooperation and Peace') was signed by the two countries. Under this treaty the Indo-Bangladesh Joint River Commission (JRC) was established to facilitate negotiation over sharing of the many common rivers (Government of India 1972). Following this, the two countries have made several attempts to find a suitable and equitable solution through several legal agreements over sharing of the Ganges water. But due to changing national politics (changes in governments in both countries) and ups and downs in the relationship between the governments of India and Bangladesh, the arrangements over water sharing were either ignored or overshadowed by other foreign policy issues. The negotiations repeatedly failed to make substantive progress during that phase (Crow and Singh 1999).

A breakthrough was achieved in 1975 with the signing of an agreement to temporarily operate the Farraka Barrage for 41 days. Under this agreement, varying discharges at Farakka Barrage were implemented in 10-day periods during April and May 1975 (Table 2). A joint team of experts from the two governments was formed to observe the flow of the Ganges at appropriate places in each country to monitor the effects of the various withdrawals at Farakka. This involved flow observations in the discharge canal and the Hooghly-Bhagirathi River, and the flows into Bangladesh.

Table 2: Flow in ten-day periods during April and May, 1975 at Farakka barrage (observations by the joint team based on which the agreement was signed).

Month	Ten-day period	Withdrawal ($m^3 s^{-1}$)
April,1975	21st to 30th	11,000
May, 1975	1st to 10th	12,000
	11th to 20th	15,000
	21st to 31st	16,000

Source: Salman and Uprety 2011

The 1975 agreement expired after two years, however India continued unilateral diversion of the Ganges flow beyond the stipulated period of the 1975 agreement. Bangladesh then brought the issue to the United Nations (UN). In 1976, the UN General Assembly adopted a consensus statement and directed both countries to negotiate and settle the issue. Under the direction of the UN General Assembly both countries signed a five-year agreement in 1977 (Salman and Uprety 2011). Under this agreement a Joint Committee was formed to monitor and implement the provisions of this new agreement and to examine the operation of the barrage. The Joint Committee was responsible for observing and recording daily flows at Farakka, in the feeder canal in India, and at Hardinge Bridge in Bangladesh, and to keep a record of the water shared at Farakka between the two countries. One of the provisions, in Article II(i) of the agreement, was that the sharing of the Ganges waters at Farakka from the 1 January to the 31 May every year would be based on 75% availability calculated from the recorded flows of the Ganges at Farakka from 1948 to 1973, with 60% of the flow for Bangladesh and 40% for

India (Rahaman 2006) (Table 3). Another provision, the "80 per cent guarantee clause", guaranteed Bangladesh a minimum of 80% of its share during each 10-day period, however low the flow of the Ganges may be. The provisions of the agreement were highly criticized by the Kolkata Port Authority as the required amount of water for the port was not met under this arrangement. Thus, with varying demands and individual national interest priorities, the two countries failed to come up with an equitable solution to sustain this agreement.

Table 3. Shares of dry season flow at Farakka ($ft^3 sec^{-1}$) according to the 1977 agreement

Period		Flow reaching Farakka[1]	Withdrawal by India at Farakka[2]	Minimum release to Bangladesh[3]
January	1-10	98,500	40,000	58,500
	11-20	89,750	38,500	51,250
	21-30	82,500	35,000	47,500
February	1-10	79,250	33,000	46,250
	11-20	74,000	31,500	42,500
	21-28/29	70,000	30,750	39,250
March	1-10	65,250	26,750	38,500
	11-20	63,500	25,500	38,000
	21-30	61,000	25,000	36,000
April	1-10	59,000	24,000	35,000
	11-20	55,500	20,750	34,750
	21-30	55,000	20,500	34,500
May	1-10	56,500	21,500	35,000
	11-20	59,250	24,000	35,250
	21-31	65,500	26,750	38,750

[1] Based on 75% availability

[2] Less if flow reaching Farakka is less than the 75% availability amount

[3] At least 80% of this amount if the flow reaching Farakka is less than the 75% availability amount – this "80% guarantee clause" was later removed

Note: 1 $ft^3 sec^{-1}$ = 0.028316847 m^3s^{-1}

Source: Upreti 1993

As a result of the failure to reach an equitable agreement, a short-term measure was agreed and a Memorandum of Understanding (MoU) was signed on 7 October 1982 on specified water use between January and May for two years (1983 and 1984). There was no arrangement for sharing the dry season flow in 1985. It was only on 22 November 1985 that another MoU was signed for sharing the dry season flow for three years, starting in 1986. The provisions of these two MoUs were similar to the 1977 agreement except that the 80% guarantee clause was removed. After the MoU expired no further legal agreements on management of the dry season flow at Farakka were made between the two countries for almost eight years (1989-1996).

Finally, with improved bilateral relations, the two countries negotiated and signed a 30-year Indo-Bangladesh Ganges Water Treaty (GWT) on 12 December 1996 (JRC 1996). This was one of the landmark water treaties in South Asia, the first time a formally termed 'treaty' was signed between India and Bangladesh over Ganges water sharing. The treaty also called for future cooperation between the two countries over its 53 common rivers and emphasized reaching water sharing agreements on all these rivers.

The GWT provided a formula for sharing the Ganges water at Farakka barrage during the dry season, operational between 1 January 1 and 31 May each year (Table 4, Rahman 2009). The GWT further states that the water sharing arrangement shall be reviewed at five-year intervals, or earlier if needed, by the requirement of either party.

Table 4. Formula for Farakka barrage water sharing during January–May, according to the Ganges Water Treaty, 1996

Flow at Farakka ($ft^3\ sec^{-1}$)	India's share	Bangladesh's share
< 70,000	50%	50%
70,000–75,000	Balance of flow	35,000 $ft^3\ sec^{-1}$
> 75,000	40,000 $ft^3\ sec^{-1}$	Balance of flow

Note: 1 $ft^3\ sec^{-1} = 0.028316847\ m^3s^{-1}$

Source: Joint River Commission (JRC) 1996

A Joint Committee was established under the treaty to monitor implementation of the treaty. The Joint Committee is responsible for observing and recording the daily flow at Farakka, along the feeder canal, below the barrage and at Hardinge Bridge, and for submitting reports and sharing of information. The Joint Committee is also responsible for reviewing the treaty every five years based on the field observations (Rahaman 2009).

3.2.2 Ineffectiveness of the institutional arrangements

Despite the signing of the GWT, the Indo-Bangladesh water sharing arrangements have not been successful. The two countries have not been able to reach agreement for augmentation of the dry season flow of the Ganges. A major weakness has been the lack of collective action and failure in the implementation of the institutional arrangements.

There has been considerable change in the flow of water reaching Farakka since the implementation of the GWT. The dry season flow at Farakka has seldom reached the historic average flow (during the period 1949-88) of 12,105 $m^3\ s^{-1}$ (Fig. 5).

It has been over 18 years since the signing of the GWT. During this period, the Joint Committee has not conducted any reviews of the implementation of the treaty. Nor has the committee studied the hydrological and morphological changes in the Ganges.

The operation and functioning of the Joint Committee remains unclear. Article IV of the GWT states that the Joint Committee is responsible for monitoring the Ganges flow. Articles V and VI state that the Joint Committee shall decide its own procedures and methods of functioning and shall submit an annual report to the two governments (Ganges Water Treaty 1996).

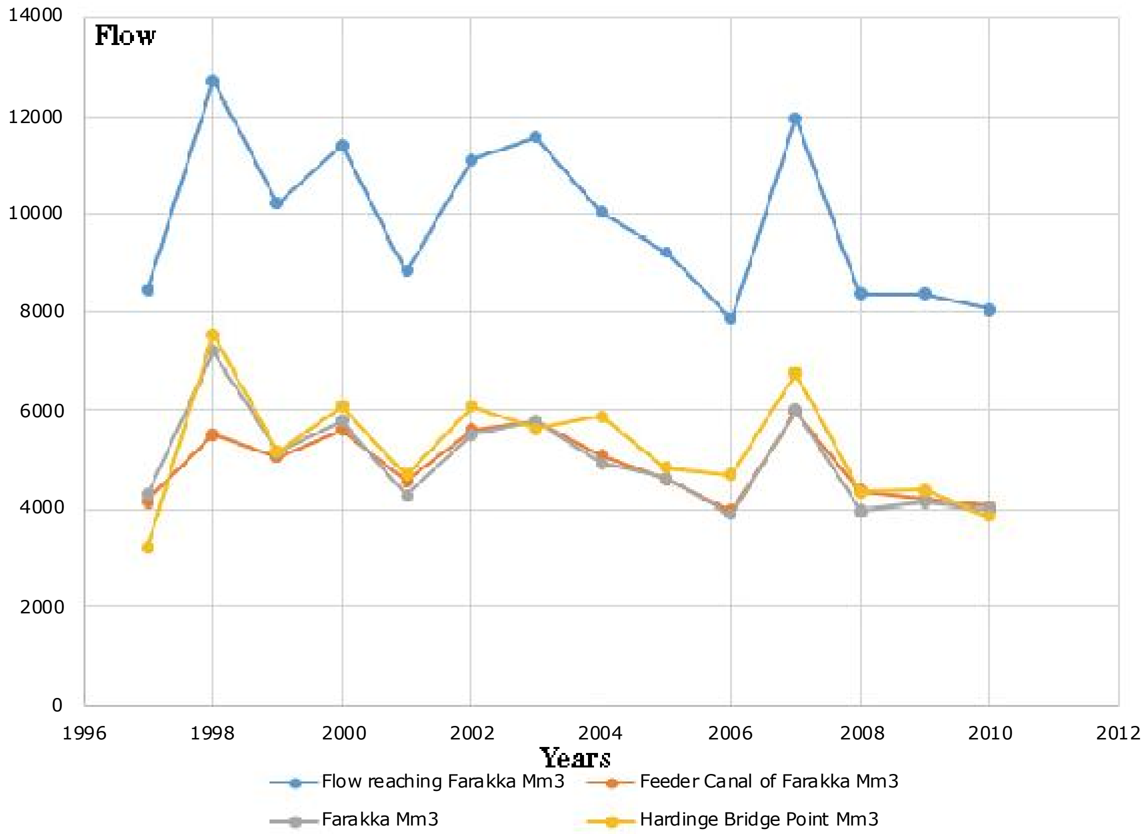


Fig. 5. Critical period of dry season (Jan-May) flow (m^3s^{-1}) from 1996 to 2010 (source: Bangladesh Water Development Board, 2010).

The functioning and role of the GWT-JC is debatable. The JC emerged from a bilateral arrangement as a joint institution to liase between the two countries and maximise the benefits from common river systems. But in reality, it is operates as two parallel national river commissions with separate offices, JRC Bangladesh in Dhaka and JRC India in the Union Ministry of Water Resource in Delhi. There is no uniformity in the organizational structure of JRC India and JRC Bangladesh. JRC Bangladesh comprises technical experts, mostly engineers, and is headed by a director and a member, from Bangladesh, both with technical backgrounds. JRC India includes both policy makers and engineers in its structure, and is headed by a Commissioner of the Department of Ganges River Management within the Ministry of Water Resources. There are no social scientists, environmentalists or any legal exprts in either JRC.

The JRC Bangladesh has created a website where it uploads an annual press release on the 10-day flow sharing data at Farrakka and flows at Hardinge Bridge in Bengali. The website of JRC India has a page with its organizational structure on the Union Minister of Water Resources website, but has not made any data available to the public on the Ganges water sharing at Farakka, flow at Farakka and flow to the feeder canal. This limits scientific research, in-depth analysis and informed discussion on water sharing.

Implementation of the GWT is monitored separately by these two national institutions. The different terminologies used by the two institutions make shared information ambiguous. Flow data at various points of the Ganges are collected by each institution on its own side (country) and a meeting is held every year to share the data. These meetings are limited to technical data sharing such as dry season flow data and rainy season floods, and issues related to the construction and repair of embankments. However, there is no clear process for settling any disagreements between the two parties about the data. There is a provision in the GWT which states that if the Joint Committee fails to settle any dispute arising out of the implementation of the treaty, the dispute should be referred to the Indo-Bangladesh JRC. If the dispute is not resolved, it should be left to the two governments, which would meet urgently at the appropriate level to resolve the issue

(Salman 1998). But there is no agreement on what level of government is required to settle disputes, nor any legal mechanism that binds the two parties to resolve disputes within a specified time frame (Rahaman 2009).

At the bilateral level, interactions are limited to just two diplomacy tracks, namely Track-1 and Track-2. Track-1 involves official discussions between high-level political leaders and ministries on issues related to treaties, agreements, cease fires or peace talks. Through Track-1 interactions, the two governments signed the "Framework Agreement on Cooperation for Development" in 2011, emphasizing the promotion of transboundary cooperation in the management of shared water resources and ecosystems, and joint development and financing of water resource management and hydropower projects (Government of India 2011). This, however, remains just a paper agreement and nothing concrete has been done towards meeting any common basin management research studies or projects. On Track-2, unofficial interactions are held involving influential academics, water experts, NGO leaders and other civil society actors. But this, too, has been limited to closed-door discussions without any concrete results.

3.3 Loss of navigability of the Bhagirathi-Hooghly: How relevant is Farakka Barrage and the 1996 GWT?

3.3.1 Provisions in the 1996 GWT versus reality

The 1996 GWT working agreement provided minimum dry season flows to both Kolkata Port in West Bengal and to Bangladesh. The flow to the port was expected to flush out sediments to the deeper part of the estuary, and keep the navigation channel silt free. However, this has not been very successful in improving the navigability of Kolkata Port (Chief Hydraulic Engineer, Hydraulic Department, Kolkata Port Trust, personal communication, 2013). The minimum requirement for achieving this, a flow of 40,000 m^3s^{-1} from the feeder canal, is not being met. As a result, sediments are accumulating in the navigation channels and big vessels are not able to enter Kolkata Port or Haldia Dock. Some experts in India claim that implementation of the 1996 GWT has diminished the dry season diversion into the feeder canal, affecting the maximum possible draft for navigation (Biswas 2011).

3.3.2 Is the maintenance of Kolkata Port becoming a liability?

Kolkata Port was commissioned on 17 Oct 1870 under the Calcutta Port Act. Construction of Kolkata Port was a poor decision given the hydraulic characteristics of the river channel. The inadequate dry season flow in the Bhagirathi channel was evident during 1768 and 1777 (Mukherjee 2011). The Hooghly-Bhagirathi River had lost its connection with the main channel of the Ganges long before construction of the port.

A steady water flow during the dry season is needed to flush the silt from the navigational channels of Kolkata Port into the Bay of Bengal (Case Study 2: The Ganges Basin-with Focus on India and Bangladesh 2007). But with inadequate freshwater flow, increasing siltation along with morphological changes in the Hooghly-Bhagirathi River system have limited the use of Kolkata Port by big vessels. The port suffers from a low draft of 7 to 9 m and traffic dropped from 43.4 Mt in 2011-12 to 39.9 Mt in 2012-13 (Sanyal 2013). Even small vessels are not able to navigate the system during the low flow period. The port is suffering heavy economic loss due to reduced cargo volume. Downstream of Kolkata Port, Haldia Port is also losing cargo volume due to sedimentation in the navigation channels. There is an urgent need to explore alternatives to these ports (Jayanta Bandhyopadyay, Indian Institute of Management, Kolkata, personal communication, 2013). Dredging is used to sustain the navigation channel and to mitigate the heavy siltation in the Hooghly-Bhagirathi River, with enormous subsidies from the government. The increasing dredging cost has become a major burden. The amount of dredging increased from 7 million cubic meters in 1974-75 to 14 million cubic meters in 1995-96 and to 22 million cubic meters more recently (Bahadur 2004).

The development of Mongla and Chittagong Ports in Bangladesh is another challenge for Kolkata and Haldia Ports. Kolkata will lose two of its major traders, Nepal and Bhutan, if they shift their dependency to the ports in Bangladesh. Another big challenge for Kolkata Port is implementation of the proposed Sittwe Port in Myanmar, under the Kaladan Multi-Modal project to connect Kolkata and Sittwe port.

3.3.3 Farakka Barrage: from solution to problem

The failure of the Farakka Barrage to reduce siltation of the navigational channels of Kolkata Port raises major questions about the existence and usefulness of Farakka Barrage. First, the original objective for which it was constructed has not been met, although the feeder canal does provide water for domestic and agricultural purposes in the adjoining municipalities, and for a few industries and thermal power plants.

Second, the changing course of the Ganges poses a major threat to Farakka Barrage, with the possibility of the river outflanking the barrage and forming a new route through Kalindri and Mahananda channels (Rudra 2004). If the Ganges bypasses Farakka Barrage this will have serious consequences for the 1996 GWT arrangement.

Third, instead of generating benefits, the construction of Farraka Barrage has resulted in environmental degradation and socio-economic problems in the river basin. The Ganges is a meandering river with natural processes of riverbank erosion and accretion. This has been exacerbated by the Farakka Barrage intervention; the problem of siltation was exacerbated, leading to erosion upstream in Malda and increasing siltation downstream of the barrage along the Bhagirathi-Hooghly and Ganges/Padma River systems (Islam and Gnauck 2011).

According a report of the Government of West Bengal, as a result of the devastating erosion, 236 villages upstream of the barrage lost their land holdings, with an estimated 5043 ha of cultivable land lost between 2000 and 2001 (Government of West Bengal 2007). Downstream of the barrage, in the district of Murshidabad in West Bengal, 79,190 people were displaced from 1988 to 1994 as a result of floods and land erosion (Basu et al. 20**). The increased erosion and siltation have greatly changed the demographics of the area (Maiti et al. 2014), with large socio-economic impacts.

The large quantities of silt flowing over the plains create vast stretches of land patches/islands in the riverbed (Mukherjee 2011). These riverine landmasses are called c*har*s in Bengali (in West Bengal and Bangladesh) or *diaras* in the middle Gangetic plains of northern Bihar and eastern Uttar Pradesh Districts of India. As the *chars* are temporary, they are usually occupied by unauthorized migrant settlements (Dutt 2004). The *chars* are eroded by the monsoon floods every year. The eroded silt is carried by the river, and the silt accumulates and forms new land patches elsewhere. The *char* inhabitants are highly vulnerable. With the disappearance of the *char* where they were previously settled, inhabitants are forced to migrate to newly emerged *chars*. Some of the *chars* turn into permanent human settlements but their legal status as 'land' remains contested (Dutt 2004).

There is a high incidence of migration of people from the disappearing *chars* to the newly emerging *chars.* Due to the fertile soil of the *chars*, many inhabitants from Malda and Murshidabad Districts of West Bengal also choose to migrate to them (Banerjee 1999). Within India, a dispute arose between West Bengal and Jharkhand over newly formed *chars* that formed across the border between the states.

The erosion and formation of new *chars* has also created border disputes between India and Bangladesh. The disappearances of *chars* on one side of the border and emergence of new *chars* on other side results in forced migration. The concept of a border seems to remain vague for the inhabitants, who migrate between the *chars* in search of better livelihoods. Between 1992 and 1994, nearly 10,000 hectares of *chars* emerged that were inaccessible from the Indian side but were readily accessible from Bangladesh. Many inhabitants of *chars* in India migrated across the border without legal documentation to reach these *chars*. Similarly, the *char* lands in Jalangi in India have been occupied by Bangladesh immigrants. This raises major questions regarding responsibility for the management of resources and socio-economic development of the inhabitants of the *chars* (Dutt 2004). There are major risks and vulnerabilities in such unpredictable and unstable human migration and settlement including poverty, environmental hazards, border disputes, illegal migration, trafficking of women and children, and health problems (Sawin 2009).

3.4 Moving forward to effective and sustainable collaborative water management

3.4.1 From water sharing to holistic water resource management

According to Ilyer (2008), "It is greed that lies at the heart of water conflict. Agreements, accords and treaties may temporarily bring peace, but conflict will erupt again unless we re-define development challenges and learn to view water as a scarce and precious resource to be conserved, protected and used with extreme economy". Indo-Bangladesh Ganges cooperation has been limited to just water sharing. It needs to expand to a more collective regional water management approach, and to view the Ganges as a precious resource, one that must be jointly managed to maximize benefits.

A multilateral arrangement including all the riparian countries would be more useful. To address the challenge of downstream dry season freshwater flow, the involvement of Nepal in institutional arrangements and interactions over Ganges water sharing and management is essential. Nepal is the upper riparian country of the Ganges and nearly 71% of the dry season freshwater flow originates in this Nepal.

There have been studies proposing the construction of storage reservoirs in the basin area of Nepal to augment the dry season flow of the Ganges (Rahaman 2009), which would change the denominator for water sharing. However, different countries view the benefits/detriments of these reservoirs differently (Khan 1996; Jayanta Bandhopadhya, Indian Institute of Management, Kolkata, personal communication, 2013), indicating that any "water sharing" agreement needs to take into account upstream developments.

To develop arrangements for the mutual benefit of all the riparian countries, collective efforts and joint studies are needed. These include studies on the hydrological and morphological changes in the Ganges, feasibility studies of the construction of storage reservoirs upstream and modeling of the hydrology of the basin (Bharati et al. 2011). Water sharing arrangements should be reviewed and revised based on the findings and new agreements could be made. Joint optimum water utilization, legal water sharing arrangements and institutions for sustainable management of the Ganges water resources would result in socio-economic development and ecological benefits and improve the livelihoods of the lower Ganges population in addition to preventing potential future conflicts.

A more equitable and sustainable solution to the contemporary challenges could be achieved by shifting the focus from just water sharing to the wider development objectives of utilizing the benefits from integrated water management and development of the river basin. To achieve these objectives, the riparian countries must approach the basin as a single ecological entity and the elements of sustainability and equity should be incorporated in water planning and policy goals for the basin.

3.4.2 Enhancing institutional setups

The GWT successfully settled the Farakka Barrage dispute, but only temporarily. The existing Indo-Bangladesh JRC could act as the driving force to foster multilateral cooperation and successfully implement its policy initiatives. But this would require major changes in the role, function, structure and supervision mechanism of the JRC (Fig. 8) such as:

- Strengthening the capacity and function of the JRC. The JRC must be seen as a basin-wide institution supervising the management of the river basin. Policy development and implementation and dispute settlement over the Ganges basin must be supervised by the JRC.
- Towards this, frequent interaction between the riparian countries is essential to bring transparency in information sharing. To reach mutual agreement on the organizational structure, objectives and functioning of the JRC the riparian countries must organize interactions at various levels and include all stakeholders. There is a need to create a platform where official and non-official actors meet at a common forum (Track-1.5 diplomacy, Fig. 6). Along with these interactions, a platform for interaction between stakeholders at the grassroots level is important (Track 3 diplomacy, Fig. 6), as proposed by various experts and authors (Mapendere 2007). To understand the real problems and challenges of

the basin meetings must be conducted involving all stakeholders, including smallholder producers/farmers, processors-traders/private sector, local and provincial government of all member countries. More often than not, the voices of the grassroots level remain unheard. To disseminate the information from these interactions and bridge the gap between the grassroots and higher policy levels, a platform of Track-2.5 diplomacy (Fig. 6) is proposed. Track-2.5 diplomacy would involve the conducting of dialogue workshops involving grassroots stakeholders and the classical participants of Track-2 level, and is proposed as a useful medium for the development of cooperation in a politically tense region (Kappameier et al. 2012).

Task forces at Track-1.5 and Track-2.5 levels would be formed to conduct frequent discussions and share reports of the interactions held at Tracks-1 and -2 and Tracks-2 and -3, respectively. These interactions and the formation of task forces would facilitate the achievement of a joint institutional framework.

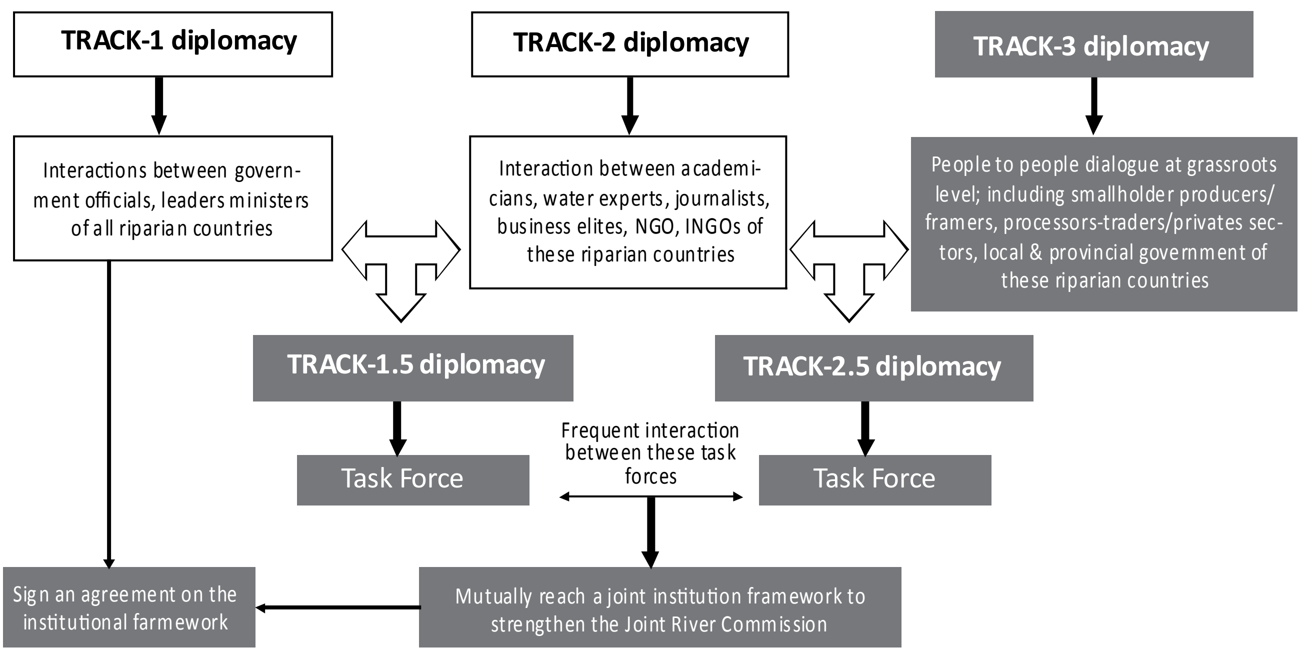


Fig. 6. Interactions between the riparian countries of the Ganges at various levels; proposed levels in blue boxes are Track-3; Track-1.5 and Track-2.5 diplomacy; Track 1.5 means interaction involving representatives of both Tracks 1 and 2; Track 2.5 means interaction involving representatives of Tracks 2 and 3.

- Through these discussions and information sharing, the riparian countries could mutually reach and sign an agreement on a joint institutional framework (Fig. 6). Through this framework the functions and organizational structure of the JRC could be strengthened (Fig. 7).
- Inclusion of all the riparian countries of the Ganges basin in the JRC.
- Establish the JRC as a joint institution instead of several parallel institutions, with headquarters (JRC Secretariat) in the region headed by one of the riparian countries on a rotating basis.
- Under the JRC Secretariat atTechnical team should be established consisting of technical experts including engineers, hydrologists, environmental scientists and social scientists from the riparian countries. This team would coordinate the research/technical studies by establishing a joint study team that would work towards the development of an integrated basin management plan for sustainable development of the basin.
- An administrative team under the JRC Secretariat would coordinate administrative activities such as meetings, financial management and communications.
- The monitoring and evaluation mechanism of the JRC must be reviewed and strengthened under a Monitoring and Evaluating (M&E) team. The M&E team would monitor implementation of the policy

frameworks and development of projects across the river basin. An effective information technology system with a satellite service to monitor river basin development would make the process more transparent and effective.

- A JRC website must be introduced for sharing and updating of data and information, and with press releases on JRC meetings and projects.
- Frequent meetings of the JRC should be conducted to exchange data and information on various aspects and issues of the river basin, discuss development issues along the transboundary river basin, translate the feedback into actions, identify the tradeoffs, find equitable solutions to the challenges and facilitate long-term planning and investment. The interactions and function of the JRC should be expanded from just water sharing to other water-related issues such as watershed management, water quality, coastal ecosystem management and sustainable development of the river basin (Nishat 1996).
- Under the JRC, a training institute should be set up at its headquarters to provide training workshops for the stakeholders.
- National committees will be needed to provide coordination between the JRC and the governments of each riparian country, to monitor the work at the national level and to report to the Technical and Administrative section at the JRC Secretariat. These national committees would be independent of the JRC and under the supervision of governments. A National Community Committee could be set up under each national Committee to coordinate work at the grassroots level, working with local NGOs, farmers, etc. The National Community Committee could organize pilot projects and training workshops for the stakeholders.
- Along with interaction at the JRC level, new mechanisms for dialogue and information sharing at the national level under each National Committee would be useful. At this platform, interaction among all relevant stakeholders including policy makers, scientists, engineers, academics, NGOs (national and international) and farmers could be conducted.

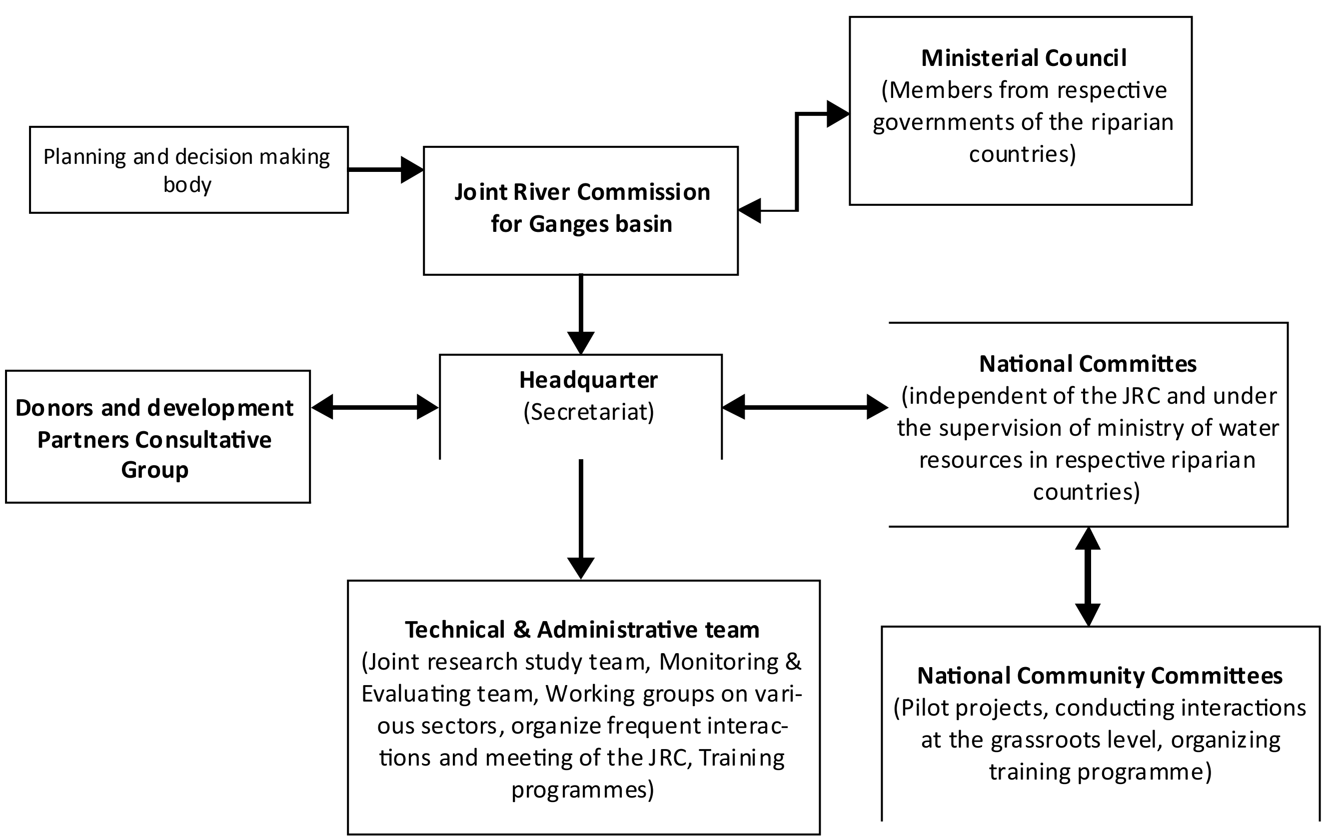


Fig. 7. Proposed governance structure of the JRC.

- National level and sub-basin level studies conducted by the National Committees of the respective countries and findings reported to the JRC Secretariat Technical Team. This would provide the best available information on the available resources and challenges of each country and the region. The exchange of information and data among the countries would assist in the development of policies for sustainable management of water resources at both national and regional levels.
- Under the Technical Team at the Secretariat, and working in close coordination with the National Committees, joint studies could be conducted to identify, analyze and communicate the potential benefits of the shared water resources in the basin area. Information on the water resources such as on shared aquifers in the Indo-Bangladesh Ganges basin area would help to maximize the available resources and address water scarcity problems in the GDA during the dry season. Despite the vast amount of freshwater stored as groundwater fed by heavy recharge from Himalayan snowmelt, the countries sharing the basin have not been able to make full use of this resource (Pant 2002). To devise and support technical interventions and policies towards sustainable management of the groundwater resources and meet the growing water demands in the GDA of West Bengal and Bangladesh, a detailed understanding of the groundwater resources and potential socio-economic impacts of their further development is needed.
- Exchange of information across the riparian countries and joint studies will be important to collectively address water management challenges and to propose joint projects towards the sustainable management of the resources. This could be done through area studies/macro-basin level studies of surface waters and shared aquifer systems, and future climate change impacts on the quantity and quality of those resources. Joint development initiatives and demographic studies of the chars could be conducted. At the National Community Committee-level, resettlement and rehabilitation programs, disaster management training and monitoring devices and warning systems for the char populations could be initiated.

4. Conclusions

The literature on Indo-Bangladesh transboundary water cooperation over the Ganges River generally ignores the potential role that the Indo-Bangladesh Joint River Commission (JRC) could play in enhancing transboundary cooperation between India and Bangladesh. If expanded, the JRC could provide a platform for cooperation among all the Ganges riparian countries.

The inefficiency in the present institutional arrangements between the riparian countries, the absence of joint assessment, the lack of transparency in exchange of information, and data with political asymmetries between the riparian countries have been major hindrances towards achieving collective benefits from the river basin.

An institution that manages and governs the transboundary river basin, with all riparian countries as members, is essential to achieve adaptive integrated water management, to resolve disputes, and to prevent future conflict among the riparian countries. This paper identifies the importance of strengthening and redesigning the organizational and institutional configuration of the JRC. The proposed institutional arrangement would be an effective policy initiative for building trust and confidence among the riparian countries and would enhance cooperation in information and data sharing. This would also provide a platform to collectively manage and govern the river basin, to coordinate and formulate policy, to implement joint projects, and to encourage stakeholder interactions, from policy makers to the grassroots level.

Acknowledgements

This paper presents findings from ‘G4 Assessment of the impact of anticipated drivers of change on water resources of the coastal zone’, a project of the CGIAR Challenge Program on Water and Food. The authors would like to acknowledge the cooperation and contribution of the government departments, academics, water experts and professionals from both India and Bangladesh interviewed for the study. The authors are grateful to B.G Varghese for his guidance at the inception of the study and his valuable suggestions on the literature. Sincere thanks also to Jeremy Bird, Director General of IWMI and the Joint River Commission, Bangladesh, for providing constructive comments and critical review that helped improve the quality of the report.

References

Ahmad, Q.K., Ahmed, A.U., Khan, H.R. and Rasheed, K.B.S. 2001. GBM Regional Water Vision: Bangladesh Perspectives. In *Ganges-Brahmaputra-Meghna Region: A Framework for Sustainable Development*. eds. Q.K. Ahmad, A.K. Biswas, R. Rangachari and M.M. Sainju. University Press Limited, Dhaka. pp.31-80.

Adel, Miah Muhammad. 2013. Upstream Water Piracy, the Strongest Weapon of Cornering a Downstream Nation. Environment and Ecology Research 1(3). pp 85-128.

Afroz, Rounak. and Rahman, Md. Ataur. July 2013. Transboundary River Water for Ganges and Teesta Rivers in Bangladesh: An Assessment Global Science and Technology Journal Vol. 1. No. 1. July 2013 Issue. pp. 100-111.

Bahadur, Pun Santa. 2004. Overview: Conflicts over the Ganga? In *PSA, Disputes over the Ganga: A Look at Potential Water-Related Conflicts in South Asia.* eds. Subba, Bhim.; Pradhan, Kishor. Panos Institute South Asia, Kathmandu, Nepal. pp. 2-20.

Bandyopadhyay, Sunando. and Nandy, Sreetapa. 2011. Trend of sea level change in the Hugli estuary, India. Indian Journal of Geo-Marine Sciences. Vol. 40(6). pp. 802-812.

Banerjee, Manisha. November 1999. A Report on the Impact of Farakka Barrage on the Human Fabric. South Asia Network on Dams, Rivers and People. New Delhi, India. pp.6-29.

Bangladesh Water Development Board (BWDB), September 2010. Interim Report of Consultancy Services for the feasibility study and detailed engineering for Ganges Barrage project. Volume II(Annex A-Hydrology) and Volume III(Annex B-Environmental and Social Baseline Condition in the Ganges Barrage Projects Study Area; Annex C- Estimation of Irrigation Water Demand in GDA and Inventory of FCD/FCDI projects of BWDB. Ministry of Water Resources. Government of the People's Republic of Bangladesh.

Basu, Parthiba., Sayani, Mukhopadhyay. and Jayaraman, T. 2***. Climate Change Adaptation in Flood Plain of West Bengal. Climate Change Policy Paper I. World Wildlife Fund (WWF). http://awsassets.wwfindia.org/downloads/climate_change_adaptation_in_flood_plains_of_west_bengal.pdf (accessed in August-September 2013).

Bharati, L., Lacombe, G., Gurung, P., Jayakody, P., Hoanh, C. T. and Smakhtin, V. 2011. The impacts of water infrastructure and climate change on the hydrology of the Upper Ganges River Basin. Colombo, Sri Lanka: International Water Management Institute. IWMI Research Report 142. 36p.

Bharati, Luna .,Hosterman,Heather R., McCornick, Peter G., Kistin, Elizabeth J., Pant, Anju ., Sharma, Bharat., August 2009, 'Water, Climate Change, and Adaptation: Focus on the Ganges River Basin' NI-WP 09-03. http://nicholasinstitute.duke.edu/sites/default/files/publications/water-climate-change-and-adaptation-1-paper.pdf (accessed in August 2013)

Biswas, A.K. 2011. Cooperation or conflict in transboundary water management: case study of South Asia. Hydrological Sciences Journal 56:4. pp. 662-670.

Chakravarti, Indranath. 2004. Water Problems for Kolkata Metropolitan Region. http://rwes.dpri.kyoto-u.ac.jp/~tanaka/APHW/APHW2004/proceedings/WRD/56-WRD-M108/56-WRD-M108.pdf (accessed in July-August 2013).

Case Study 2: The Ganges Basin-with Focus on India and Bangladesh. 10 July 2007. http://www.caee.utexas.edu/prof/mckinney/ce397/Readings/case-study2_Ganges.pdf(accessed in May 2013).

Crow, Ben. and Singh, Nirvikar. August 1999. Impediments and Innovation in International Rivers: The Waters of South Asia. World Development, 28:1907-25.

Crow, Ben. Lindquist, A. and Wilson, D. 1995, Sharing the Ganges: The Politics and Technology of River Development. Sage. New Delhi. 272p.

Dutt, Kuntala Lahiri. 2004. Fleeting Land, Fleeting People: Bangladesh Women in a Charland Environment in Lower Bengal, India. Asia and Pacific Migration Journal, Vol. 13, No. 4, 2004.

Government of India, 19 March 1972. Treaty of Peace and Friendship between [1972] Intser 6. Treaty of Peace and Friendship between the Government of India and the Government of the People's Republic of Bangladesh. http://www.commonlii.org/in/other/treaties/INTSer/1972/6.html (accessed in April 2013).

Government of India, 6 September 2011. Framework agreement on cooperation for development between India and Bangladesh. Ministry of External Affairs, Government of India. http://mea.gov.in/bilateral-documents.htm?dtl.5218/Framework+Agreement+on)Cooperation+for+Development+between+India+and+Bangladesh (accessed in August 2013).

Government of India. 2004, Farakka Barrage Project. Chapter 14. Ministry of Water Resources (MWR). http://wrmin.nic.in/writereaddata/Publications/anu141200246187.pdf (accessed in June 2013).

Government of West Bengal. April 2007. District Human Development Report: Malda. Development and Planning Department. http://wbplan.gov.in/htm/HumanDev/Human%20Development%20Malda.pdf(accessed in July 2013).

Government of Bangladesh. 5 November 1977. Agreement between the Government of the People's Republic of Bangladesh and the Government of the Republic of India on sharing of the Ganges waters at Farakka and on augmenting its flows. Ministry of Foreign Affairs (External Publicity Division) Dacca. Government of Bangladesh. http://ocid.nacse.org/tfdd/tfdddocs/394ENG.pdf (accessed in April 2013).

Gosain, A.K. and Rao, Sandhya. Basuray, D. 2006. Climate change impact assessment on hydrology of Indian River basins. Current Science 90(3). pp. 346-353.

Islam, S.N. and Albrecht, Gnauck. 2011. Water salinity investigation in the Sundarbans Rivers in Bangladesh. Int. J. Water, Vol. 6, Nos. 1/2, pp.74–91.

Iyer, Ramaswamy. 2008. Trans-boundary Water Conflicts: A Review'. In *Water Conflicts in India: A Million Revolts in the Making*. eds. Joy, K.J..; Gujja, Biksham.; Paranjpye, Suhas.; Goud, Vinod.; Vispute, Shruti. Routledge: New Delhi. pp. 375.

Joint River Commission (JRC), 1996. Treaty between the government of the People's Republic of Bangladesh and the government of the Republic of India on sharing of the Ganga/Ganges waters at Farakka. http://www.jrcb.gov.bd/attachment/Gganges_Water_Sharing_treaty,1996.pdf (accessed in May 2013).

Joint River Commission (JRC), 1996, 'Treaty between the Government of the People's Republic of Bangladesh and the Government of the Republic of India on Sharing of the Ganga / Ganges Waters at Farakka, Government of People's Republic of Bangladesh. http://www.jrcb.gov.bd/attachment/Gganges_Water_Sharing_ treaty,1996.pdf (accessed in May 2013).

Kappameier, Mariska. Redlich, Alexander. and Knyazev, Evgeniya. 2012. Building Local Capacity in Eastern Europe. In *From Identity Based Conflict to Identity Based Cooperation-The ARIA Approach in Theory and Practice*. ed. Rothman, Jay. Springer. Peace Psychology Boom Series. Series Editor: Daniel J. Christie. pp. 101-106.

Khan, Tauhidul Anwar. 1996. Management and Sharing of the Ganges. Natural Resources Journal. Vol.36.pp.455-479.

Maiti, Somnath. Ghorai,Debrabata. Satpathy, Rajat. and Bandyopadhyay, Jatisankar. October 2014. Monitoring of Land Use Land Cover Change over the years due to River Course Shifting: A Case Study on Ganga River basin near Malda district, West Bengal using Geo-Informatices Techniques. International Journal of Research in Advent Technology, Vol. 2. No. 10. E-ISSN: 2321-9637. http://www.ijrat.org/downloads/oct-2014/paper%20id-210201430.pdf (accessed in December 2014).

Mapendere, Jeffrey. 2007. Track One and a Half Diplomacy and the Complementarity of Tracks. COPOJ – Culture of Peace Online Journal, 2(1), 66-81. http://peacemaker.un.org/sites/peacemaker.un.org/files/TrackOneandaHalfDiplomacy_Mapendere.pdf (accessed in November 2013).

Mirza, Monirul Qader. and Hossain, Md. Altaf. 2004. Adverse effects on Agriculture in the Ganges Basin in Bangladesh. In *The Ganges Water Diversion: Environmental Effects and Implications.* eds. Mirza, M. Monirul Qader. Water Science and Technology Library. USA-Kluwer Academic Publisher. pp. 177-191.

Mirza, Monirul Qader, 1997. Hydrological changes in the Ganges system in Bangladesh in the post-Farakka period, Hydrological Sciences Journal, 42:5, 613-631, DOI: 10.1080/02626669709492062.

Mishra, Dinesh Kumar. and Hussain, Syed Monowar. 2012. Situation Analysis on Inland Navigation. Ecosystems for Life: A Bangladesh-India Initiative. International Union for Conservation of Nature and Natural Resources (IUCN). http://cmsdata.iucn.org/downloads/02inlandnavia.pdf (accessed on August 2013).

Mukherjee, Jenia. July 2011. No Voice, No Choice: Riverine Changes and Human Vulnerability in the 'Chars' of Malda and Murshidabad. Occasional Paper No.28, Institute of Development Studies Kolkata (IDSK).

Nishat, A.1996. Impact of Ganges Water Dispute on Bangladesh. In *Asian International water: From Ganges-Brahmaputra to Mekong.* eds. Biswas, A.K. and Hashimoto, T. Oxford University Press, Bombay. pp. 60-80.

Panda, Surajit and Bandyopadhyay, Jatisankar. 2011, 'Morphodynamic Changes of Bhagirathi River at Murshidabad District Using Geoinformatics', Journal of Geographic Information System, 2011, 3, 85-97. file:///C:/Users/773611/Downloads/JGIS20110100004_53874435.pdf (accessed in July 2013).

Pant, Niranjan. 2002. Groundwater Issues in Eastern and Western Alluvium of Ganga Basin. International Water Management Institute (IWMI). IWMI Tata Water Policy Program Annual Partners Meet 2002 Discussion Paper. 25p.

Rahaman, M.M. 2009. Principles of Transboundary Water Resources Management and Ganges Treaties: An Analysis, Water Resource Development, Vol. 25, No. 1, 159-173.

Rahaman, M.M. 2006. The Ganges water Conflict-A comparative analysis of 1977 agreement and 1996 treaty. International Water Law. 1/2: 195-208. ISSN 1886-5860/ http://www.internationalwaterlaw.org/bibliography/articles/general/Rahaman-Ganges-Asteriskos.pdf (accessed in August 2013).

Rudra, Kalyan. 2004. The Encroaching Ganga and Social Conflicts: The Case of West Bengal India. West Bengal: Dept. of Geography, Habra H.C. Mahavidyalaya, 2003. pp 9-40.

Schmeier, Susanne, August 2010, 'Governing International Watercourse: Perspective FROM Different Disciplines', Hertie School of Governance-Working Paper, No. 53. url:http://www.transboundarywaters.orst.edu/publications/publications/Schmeier%20RBO%20Literature%20Review%2010.pdf (accessed in May 2013).

Salman, M.A.S. and Uprety, K. 2011. Legal aspects of sharing and management of transboundary waters in South Asia: preventing conflicts and promoting cooperation. Hydrological Sciences Journal, 56:4, 641-661.

Salman, M.A.S. 1998. Sharing the Ganges Waters between India and Bangladesh: An Analysis of the 1996 Treaty. In *International Watercourse: Enhancing Cooperation and Managing Conflicts*. eds. Salman M.A.S. and De Chazournes, L.B. World Bank Technical Paper No. 414, The World Bank, Washigton, DC.

Salehin, M., Khan, M.S.A., Prakash, A. and Goodrich, CG. 2011. Opportunities for Trans-boundary Water Sharing in The Ganges, The Brahmaputra and The Meghna Basins. In *India Infrastructure Report 2011: Water-Policy and Performance for Sustainable Development*. eds. Infrastructure Development Finance Company Limited, India, New Delhi: Oxford University press. Chapter 3. pp. 29-43.

Sanyal, Shantanu. April 2013. Kolkata Port Trust traffic drops 8% in 2012-13. *The Hindu*. http://www.thehindubusinessline.com/industry-and-economy/logistics/kolkata-port-trust-traffic-drops-8-in-201213/article4576743.ece (accessed in October 2013).

Sinha, R. and Ghosh, S. 2012.Understanding dynamics of large rivers aided by satellite remote sensing: a case study from Lower Ganga plains, India. Geocarto International, 27:3. pp. 207-219.

Sawin, Ashok. 2009. Environmental Trap: The Ganges River Diversion, Bangladeshi Migration & Conflicts in India. Report No. 41, Department of Peace and Conflict Research Uppsala University, Sweden. pp. 63-65.

Upreti, B.C. 1993. Politics of Himalayan River Waters. Nirala Series 32. Jaipur, India: Nirala Publications.

Verghese, BG. 1997.Water Conflicts in South Asia. Centre for Policy Research. Studies in Conflict & Terrorism, 20:185-194, 1997. Taylor & Francis. pp. 185-194.

Wolf, Aaron T. Yoffee, S. and Giordano, M. 2003. International Waters: Identifying basins at Risk. Water Policy. Water Policy, 5(1): 29-60.

Wolf A T, 1998 Conflict and Cooperation along International Waterways, Water Policy 1, 251-65.

Wolf, Aaron T, 1999, Çriteria for Equitable Allocation: The heart of International Water Conflict, Natural resources Forum, 23: 3-30.

WLE, CGIAR. 2012. Dependent Area Map, http://wle.cgiar.org/wp-content/uploads/2012/09/Ganges1.jpg (accessed in April 2013).

Community water management and cropping system synchronization: The keys to unlocking the production potential of the polder ecosystems in Bangladesh

M.K. Mondal[1], E. Humphreys[1], T.P. Tuong[1], M.N. Rahman[2] and M.K. Islam[2]

[1]International Rice Research Institute, Bangladesh and Philippines,
m.mondal@irri.org, e.humphreys@irri.org, t.tuong@irri.org
[2]Bangladesh Agricultural University, Bangladesh,
nefaur25@gmail.com, khairulislam521@gmail.com

Abstract

Despite huge investments in the polders of the coastal zone over the past 50 years, crop productivity remains much lower than in most of Bangladesh. Most farmers in the polders cannot adopt high yielding varieties (HYV) of *aman* rice due to the risk of submergence after transplanting. The local *aman* varieties mature late, delaying establishment of *rabi* (non-rice) crops, which, as a consequence, are often damaged or destroyed by pre-monsoon rains or cyclones prior to harvest. A pilot was undertaken to test the hypothesis that community water management is the key to increasing productivity in a six ha watershed with 37 farmers in polder 30 in Khulna district from May 2012 to June 2014. The research team worked with the community to define the boundaries of the pilot watershed and to construct small drains/levees separating lower and higher lands. A drainage outlet was installed to connect the watershed to the adjacent *khal*. The farmers were trained in drainage water management and production of HYV *aman*, and in the early establishment and production of high yielding *rabi* crops. In 2012 the farmers were provided with enough HYV rice seed to plant the whole area, but only approximately 50% of the area was planted with HYV while the rest of the land was planted with traditional *aman* varieties. The pilot watershed was inundated twice in 2012 as a result of heavy rainfall, but the community drained the excess water within three to four d through systematic operation of the sluice gate. This indicated that with community involvement and proper infrastructure management, water stagnation can be avoided. However, at the time of maturity of the HYV rice, the local rice was just flowering so instead of terminal drainage, more water was brought into the watershed to finish the local rice crop. As a result, *rabi* (mostly sesame) crop establishment was delayed until late February/early March and the crops were subsequently destroyed by heavy rainfall in mid-May 2013. In the 2013-14 cycles, six farmers in a contiguous area of 1.3 ha strictly followed the water management and cropping system plan; they cultivated HYV *aman*, drained the fields prior to topdressing nitrogen (N) fertilizer (twice), drained at the end of October, and then planted maize, sunflower and wheat on 10 December 2013. Yields of rice, sunflower, maize and wheat were approximately 5.0, 2.8, 5.9 and 1.3 t/ha, respectively. Yields of maize and wheat were lower than expected due to inability to irrigate, as instead of storing fresh water in the canal for use during the dry season once the river water became too saline, the sluice gate was left slightly open to prevent siltation of the canal intake. Therefore, the water in the *khal* was too saline for irrigation from the beginning of February until June. The yield of the local rice crops of the farmers in the rest of the original pilot watershed averaged 2.6 t/ha and yield of the HYV rice averaged 3.4 t/ha (with no or very little fertilizer). As in the previous year, there was no sesame harvest due to late establishment and early monsoon rains. This pilot demonstrated that due to the prevailing hydrology, individuals alone cannot successfully modify their cropping system schedule and adopt improved agricultural technologies in coastal polders. It requires synchronized cropping patterns among farmers within community water management units, and community coordination at a range of scales – within small community water management units, within a sub-polder and at the polder scale. Further engagement with polder communities is needed to determine how they can take advantage of opportunities for increasing cropping system productivity through improving water management and use of improved varieties and management.

Key message: Community water management and cropping system synchronization are essential if farmers of the polders of the coastal zone are to benefit from the tremendous opportunities to increase productivity through adoption of improved varieties and cropping system technologies.

Keywords: drainage, rice, maize, sunflower, Khulna

1. Introduction

Most of the world's rice production takes place in the Asian mega deltas where large areas of rice land are subjected to stagnant flooding—0.3 to 0.5 m water depth for prolonged periods (several weeks to several months)—during the monsoon. Modern high yielding varieties (HYV) of rice adapted to stagnant flooding are not yet available. Therefore, in locations such as the coastal zone of Bangladesh most farmers grow a single rice crop (*aman*) during the rainy season using tall, photoperiod sensitive, local landraces that can survive stagnant flooding but have low yield (2.0 to 3.5 t/ha) and mature late (growth duration 155 to 170 d). The *aman* crop is often followed by a late sown, low input and low yielding *rabi* crop (0.5 to 1.0 t/ha, but with severe damage or crop failure in about 40% of years due to the pre-monsoon rains and cyclones in May). Thus much of the coastal zone remains as fallow land for three to seven months every year. There is huge scope for increasing cropping system productivity in the coastal zone. Trials conducted in farmers' fields under the CGIAR Challenge Program on Water and Food have shown that the use of HYV *aman* can double rice yield, provided that water is managed to avoid stagnant flooding (Ruhul et al. 2015). On-farm trials have also shown that the earlier maturity of HYV *aman* (growth duration 115 to 145 d) enables double and triple cropping with rice or rice and *rabi* crops (Bhattacharya et al. 2015; Mondal et al. 2015a; Ritu et al. 2015; Saha et al. 2015). The earlier maturity of HYV *aman* creates the possibility of drainage in early November and earlier *rabi* crop establishment. This in turn allows for diversification to higher yielding and/or higher value *rabi* crops. However, the key to being able to change to HYV rice and thus to cropping system intensification and diversification is improved water management – through improved drainage management and separation of lands of higher and lower elevation to prevent accumulation of water in the lower lands (Bhattacharya et al. 2015; Saha et al. 2015). The challenge is how to achieve wide scale implementation of improved water management to enable cropping system intensification and diversification.

The rivers of the coastal zone of Bangladesh are tidal and this effect extends about 150 km inland. The tidal fluctuation is more extreme (up to several meters) during the rainy season, resulting in tidal flooding of adjacent lands. About 1.2 Mha of the agricultural lands of the coastal zone of Bangladesh were therefore poldered by humanitarian projects during the 1960s and 1970s to prevent inundation and saline water intrusion, creating scope for improving productivity through improved water management.

Salinity is commonly perceived to be the main reason for non-adoption of improved agricultural technologies in the coastal zone. But we hypothesized that water stagnation and waterlogging are the primary constraints and that community coordination is needed to enable wide scale adoption of improved agricultural technologies in polder ecosystems. At low tide (twice daily) river water levels are usually lower than the land level within the polders, creating the opportunity for drainage of excess water by gravity to a level that would allow good growth and yield of HYV *aman*. We also hypothesized that drainage shortly prior to *aman* harvest would allow the soil to dry sufficiently for timely establishment of *rabi* crops. However, these opportunities have not yet been recognized. The present study was therefore undertaken to work with a community to demonstrate the benefits of improved management of water in a polder, and how to achieve this. Specific objectives of the study were:

- To work with a community to implement improved water management and improved cropping systems within a pilot watershed
- To evaluate the performance of the pilot project in terms of water management, crop performance and community coordination

2. Methodology

2.1 Site

The hypotheses were tested in a six ha pilot watershed (latitude 22.7^{0}N, longitude 89.5^{0}E) with 37 farmers in polder 30 (at Kismatfultola village, Batiaghata *Upazila*, Khulna District) from July 2012 to June 2014. An area adjacent to a *khal* (canal) and near the sluice gate connecting the *khal* to the Kazibacha River, enclosed on two sides by a regional highway and rural roads, was selected in consultation with the local community (Fig. 1). Earthen dykes (50 cm high x 50 cm wide) were constructed on the eastern and western sides in order to attain hydrological separation of the pilot area from the adjacent lands.

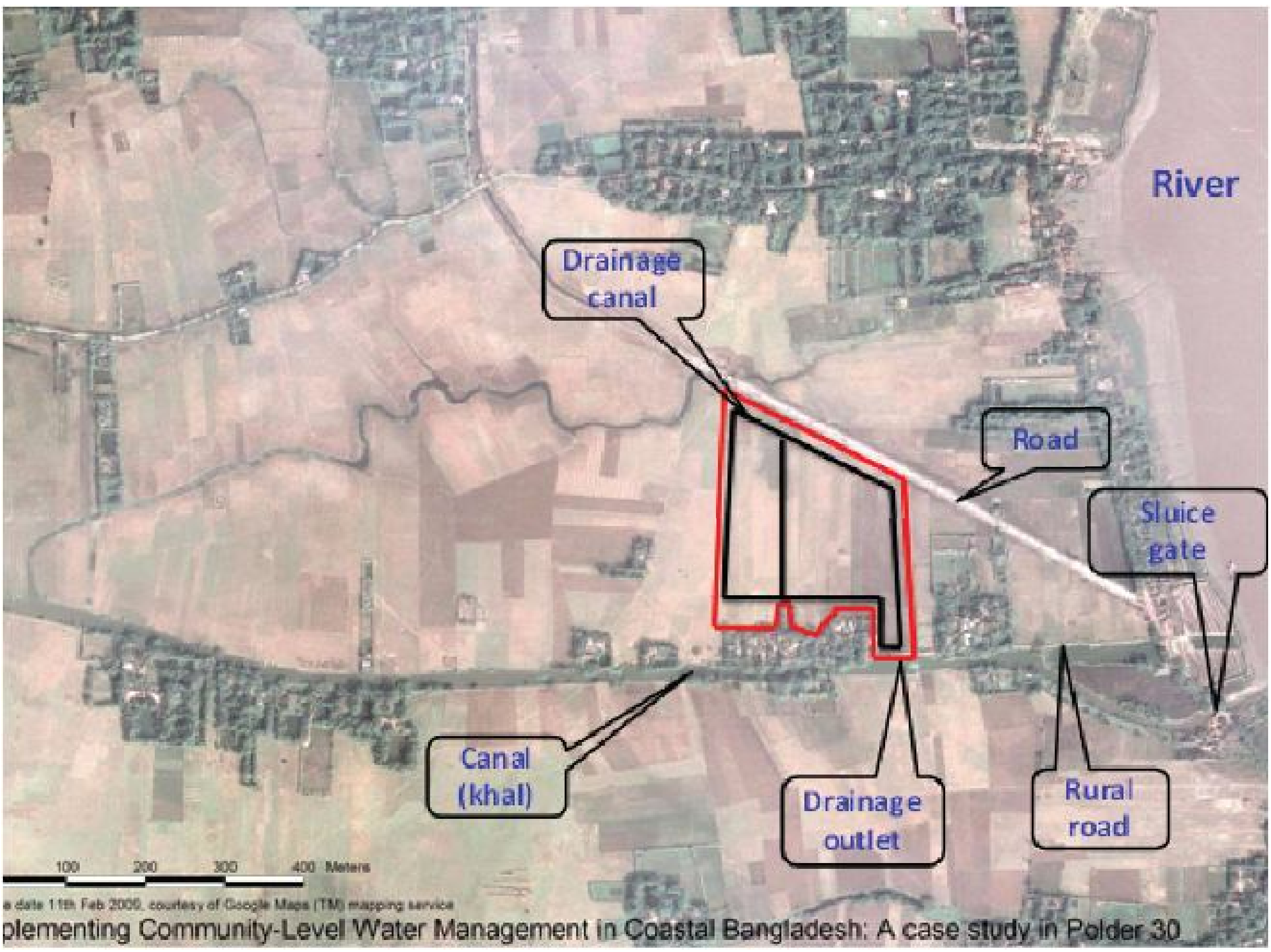


Fig. 1. Map of the study site showing the pilot watershed area in polder 30, Kismat Fultola, Batiaghata, Khulna, Bangladesh. The canal (*khal*) is used for drainage to the river at low tide during the rainy season and for water intake during the dry season.

The Kazibacha is a tidal river with water depth fluctuations of two to three m at the location of the sluice gate. The water users' association (WUA) generally operates the gate. Monitoring over several years has shown that the river becomes too saline for irrigation (4 dS/m) in early to mid-February and salinity increases to around 18 dS/m in early June (Mondal et al. 2015b). The salinity then decreases rapidly to <1 dS/m until January, when it begins to increase again. The predominant soil texture within the mini-watershed is silty clay and the dominant cropping pattern involves local *aman* landraces transplanted in August and harvested in late December/January followed by sesame sown in late February and harvested in late May/early June. This cropping system predominates throughout polder 30.

2.2 Development of collaborative arrangements with the community on sluice gate management

From January to June 2012 several informal meetings were conducted with the pilot watershed farmers, neighboring farmers, officials of the local water management group (WMG) and the *Union Parishad* (UP – the lowest administrative unit) to discuss the community water management proposal. Three formal meetings involving the above groups were also organized from April to June 2012 to discuss implementation details. Several meetings were also organized with the local WMG officials and pilot watershed farmers to come to an agreement on the cropping systems to be practiced in the watershed and on the water management practices (mainly management of the sluice gate to enable growth of the agreed cropping systems). The (informally) agreed upon water management and cropping systems involved:

- HYV *aman*, using non photoperiod sensitive, medium duration varieties (135 to 145 d) that would be transplanted (using 25 to 30 d-old seedlings) in the first week of August to enable harvest by the third week of November
- *Rabi* crops of maize and sunflower to be sown in early December, and sesame and mungbean to be sown in early February
- Drainage during the *aman* crop whenever the water was too deep (taking into account the development stage and height of the crop) by systematically opening the sluice gate at low tide to drain the *khal*, and draining water from the pilot into the *khal* until the desired field water depth was achieved
- Terminal drainage of the *aman* crop – drainage of the standing water (if any) in early November, about two weeks before harvest maturity
- Establishment of maize and sunflower by dibbling into the moist soil; tillage for the sesame and mung in early February (once the soil had dried enough for tillage using a power tiller driven by a two-wheel tractor) followed by sowing in the first week of February
- Filling of the canal with river water and closure of the sluice gate in early February before the river water became too saline to use for irrigation
- Irrigation of the *rabi* crops as needed (two to three irrigations for the maize and sunflower); one irrigation of the sesame and mungbean if needed

Thirty-seven farmers grow crops within the six ha pilot area, 30 farmers on their own land and seven farmers on leased land. The landowner farmers cropped 0.01 to 0.40 ha within the pilot watershed and the tenant farmers 0.04 to 0.45 ha. All the farmers in the pilot watershed were male, 69% of whom were middle-aged (40-60 years), 14% were <40 years and 17% were >60 years old. Almost all the famers had some level of formal education; about 38% had completed primary (grade I-V), 35% secondary (VI-X), 13% higher secondary (XI-XII) education and about 11% had completed a bachelor's or master's degree.

2.3 Construction of the drainage system

A topographic map of the study area was collected from the Bangladesh Water Development Board (BWDB). Using this map and farmer local knowledge, the locations of the watershed boundary and internal drains were determined. Internal drains (~20 cm x 20 cm) and bunds (~30 cm x 30 cm) were constructed to separate low, medium and high land, together with a drain (~25 cm x 30 cm) around the perimeter of the watershed. A gated drainage outlet (25 cm diameter) connecting the watershed to the *khal* was also installed at the lowest point. The farmers did all the earthworks, but were paid to do so.

2.4 Rainfall and water depth monitoring

A standard rain gauge was installed in the vicinity of the pilot watershed and 20 staff gauges were installed on a grid within the watershed. These devices were read each morning between 9 and 11 o'clock and average water depth was determined.

2.5 Training on crop cultivation and sluice gate operation

Formal training on the production of HYV *aman* varieties and on drainage management was provided to the farmers prior to the start of the rainy season. Enough seed of HYV was provided to each farmer so that they could grow HYV on all of the land they cultivated in the watershed. Prior to rice harvest training was provided in the cultivation of maize and sunflower and seeds were provided to farmers interested in growing these crops. The farmers were mentored during the rainy and dry seasons, on-farm at times of key activities such as transplanting, fertilizer application, and sowing of *rabi* crops. This included guidance on water management, especially drainage in times of excessive water depth following rainfall, prior to topdressing nitrogen (N) fertilizer, and two weeks prior to rice harvest.

3. Major achievements and lessons learned

3.1 Year 1 (July 2012 to June 2013)

3.1.1 Water management in 2012-13

In 2012, there were two heavy rainfall events in excess of 250 mm each, the first one during 8-14 August, immediately after transplanting, and the second during 3-5 September. Both events led to flooding of the entire polder including the pilot watershed area. The farmers successfully drained the excess water within three to four d on both occasions in collaboration with the WMG officials, whereas other parts of the polder were waterlogged for seven to ten d. At the time of the first heavy rainfall the HYV seedlings were only ~15 cm tall and were completely submerged. The mean water depth in the pilot watershed was ~23 cm on 6 September 2012 following the second heavy rainfall (Fig. 2a). At this stage the height of the HYV plants was 20 to 25 cm and thus they were almost completely submerged. The water depth in the pilot watershed was lowered to ~11 cm by 9 September 2012. As a result of rapid drainage on both occasions the HYV rice in the pilot watershed was not damaged. However, the rice crops in some low-lying areas of the polder were damaged and many farmers had to re-plant using older seedlings, increasing their production cost and decreasing yield due to the use of old seedlings.

Although the farmers were very efficient in handling the drainage of floodwater during the *aman* 2012 crop they were unable to implement the terminal drainage plan in 2012 because approximately 50% of the farmers planted long-duration traditional rice varieties instead of HYV. The plan was to drain the rice field in the first week of November. But at that time the traditional rice was only in the early grain filling stage and instead of draining, more water was brought into the field (Fig. 2a) to finish the traditional rice crops that were scattered across the area. As a result, soil drying was delayed and most farmers could not establish *rabi* crops until late February/early March 2013.

In the 2012-13 dry season the sluice gate was not closed once salinity of the Kazibacha River started to increase beyond 4 dS/m. This decision was made by the WMG in order to prevent siltation of the intake canal because of a lack of volunteers to de-silt the canal at the end of the dry season. As a result, the salinity of the water in the *khal* beside the pilot watershed gradually increased to 20 dS/m in mid-May as the salinity of the river increased (Fig. 3). Therefore, the farmers could not irrigate the dry season crops.

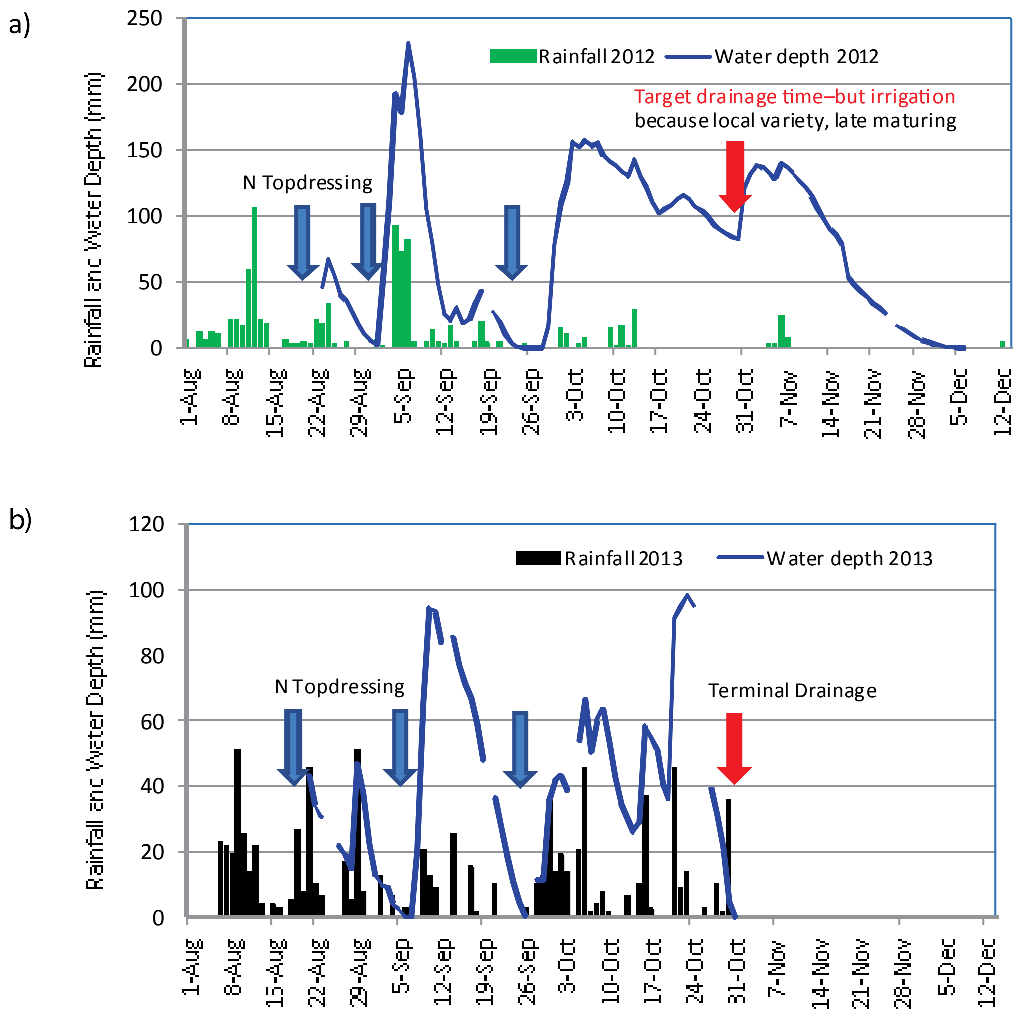


Fig. 2. Rainfall and water depth in the pilot watershed in the *aman* seasons of 2012 (a) and 2013 (b) showing drainage for N topdressing (blue arrow) and terminal drainage (red arrow).

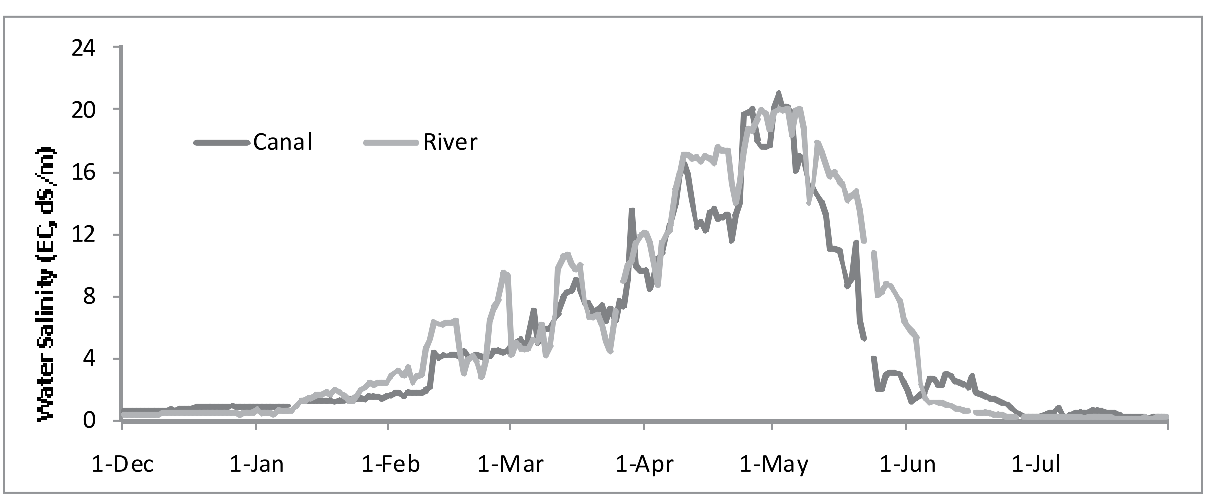


Fig. 3. River and canal water salinity (electrical conductivity, EC) at Kismat Fultola during the 2012-13 *rabi* season. (EC meter was out of order during the 2013-14 dry season.)

3.1.2 Crop management and performance in 2012-13

The farmers transplanted rice (HYV and traditional) in mid-August, within the recommended time, using 30 to 35 d and 30 to 40 d old seedlings of HYV and traditional varieties, respectively (recommended HYV seedling age is ~30 d). Those who grew HYV adopted wider row spacing than recommended (20 cm x 20 cm or 15 cm x 25 cm) and applied no or very little fertilizer. Therefore, yield of HYV rice as reported by the farmers was low (~3 t/ha) and similar to that of the traditional varieties. The HYV rice was harvested in the second half of November and the traditional rice was harvested in the second half of December. As a result of delayed drainage and harvest of traditional rice, *rabi* crop establishment was delayed until the second half of February/early March 2013. About 60% of the farmers cultivated traditional sesame (broadcast on plowed land) with no fertilizer input or management other than weeding. The rest of the farmers cultivated improved varieties of sesame, maize, sunflower and mungbean. The project provided good quality seeds of the improved *rabi* crops and the farmers bought and applied fertilizer, but at about half the recommended rate.

While most *rabi* crops were sown late, two farmers were able to establish sunflower on 1 January 2013 by dibbling into the moist soil. But despite moderate to good growth and development of the crops, they did not take proper care of the sunflower crops (no fertilizer, irrigation or weeding). These crops were harvested before the end of April with a yield of 1.4 t/ha (about half the expected yield with proper management).

Initially, growth of the late sown crops was poor due to lack of rainfall and inability to irrigate, but all the crops (sesame, mungbean, sunflower and maize) recovered strongly after rainfall in mid-March (~22 mm) and mid-April (~70 mm) of 2013 (Figs 4a; 5a,b). Just when the farmers' hopes for a good harvest were rising, a cyclone developed in the Bay of Bengal and cyclone Mohasen made landfall in mid-May, bringing huge rainfall (420 mm). As a result, the entire polder including the pilot watershed was flooded and all the *rabi* crops (except the early sown sunflower in the pilot watershed, which had already been harvested) were damaged or destroyed due to waterlogging (Figs 5c,d). Only two farmers near the drainage outlet were able to drain their late sown maize and sunflower and harvested 5.4 and 1.5 t/ha, respectively. Yield of both these crops was low as the maize farmer applied only about 50% of the recommended fertilizer and the sunflower farmer did not apply any (although weeding and irrigation were done, with water carried from the nearby hand pump in an earthen pitcher). Some farmers picked mature sesame pods from the waterlogged fields—about 42% harvested an average of ~340 kg/ha of poor quality sesame (less than half of the harvest in a good year, 700-1000 kg/ha), while others abandoned the crops, having invested about Tk. 11,000 per ha (total production cost) (Fig. 6). Thus, the potential crop production benefits through improved management of water could not be demonstrated for both the *aman* and the *rabi* crops in the first crop cycle (July 2012 to June 2013).

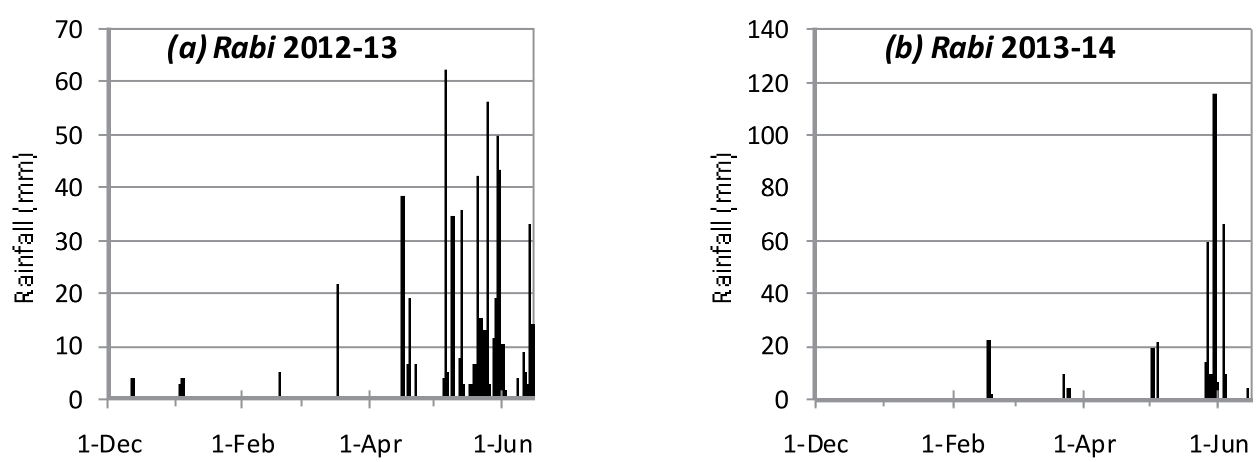


Fig. 4. Rainfall in the pilot watershed in the *rabi* seasons of 2012-13 (a) and 2013-14 (b).

a)
b)
c)
d)

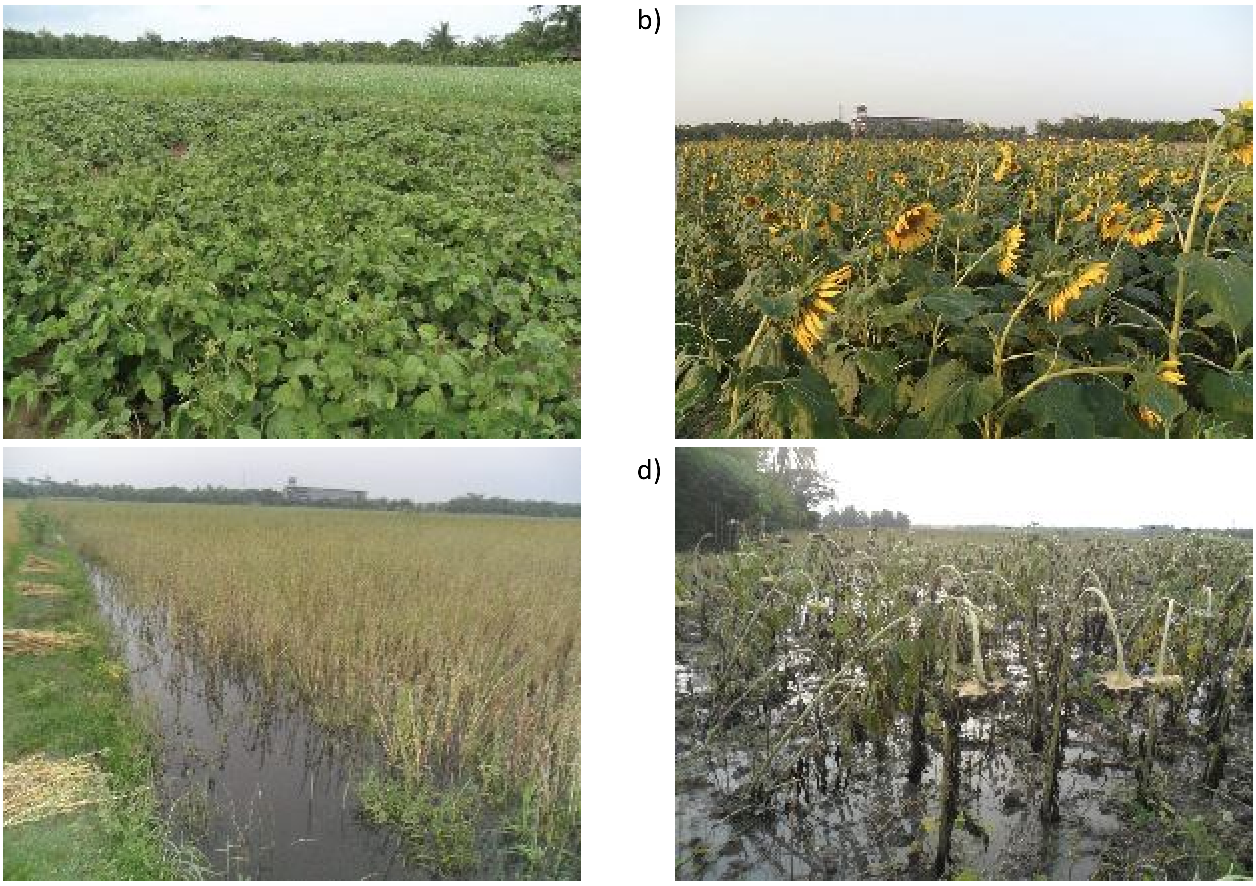


Fig. 5. Early growth of late sown mungbean and sesame (a) and sunflower (b); following the cyclone, flooded sesame (c) and sunflower (d) fields in the pilot watershed in 2013 (destroyed by rain prior to harvest).

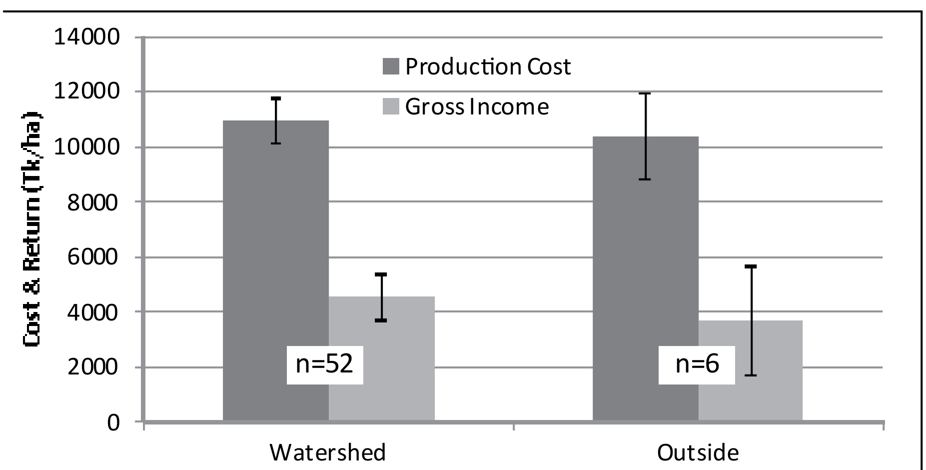


Fig. 6. Average production cost and gross income (net income is negative due to cyclone damage, not shown in the figure) from sesame in 2012-13 cultivated by the farmers inside (HYV and traditional) and outside (traditional) the pilot watershed. Vertical and capped bars indicate standard error. (Tk. 2000 @ USD 25)

3.2 Year 2 (July 2013 to June 2014)

Following the experience of the first year, a sub-watershed (1.3 ha) was created within the pilot watershed near the drainage outlet. A farm dyke was constructed with an internal drainage canal alongside the dyke. The six farmers agreed to properly implement the water management and cropping plan during the second crop season (July 2013 to June 2014). Both technical and financial support was provided to all six farmers to cultivate HYV rice on the whole area, followed by *rabi* crops.

3.2.1 Water management

There were no high rainfall events in 2013 and water depth in the sub-watershed fluctuated between two and ten cm during the 2013 *aman* season (Fig. 2 b). The sub-watershed farmers drained out ponded water three times to topdress N fertilizer (Fig. 2b). Terminal drainage was done as planned on 31 October 2013, about two weeks before harvest. Water depth in the rest of the watershed varied from two to sixteen cm, and terminal drainage was done by the farmers from 23-26 November 2013, later than in the sub-watershed because of the cultivation of traditional rice by the majority of the farmers in the rest of the watershed. As in the previous year, the sluice gate was left open during the dry season, meaning that the water in the *khal* was too saline for irrigation by the time that the *rabi* crops required irrigating.

3.2.2 Crop management and performance

The farmers of the sub-watershed transplanted HYV *aman* on 7 August 2013, two weeks earlier than their traditional practice, and implemented recommended fertilizer and crop management practices (BRRI 2012). The crop was harvested on 27 November with an average yield of about 5.0 t/ha (Fig. 7). The pilot watershed farmers outside the sub-watershed and those adjacent to the watershed cultivated both HYV and traditional rice using no or very little fertilizer (<1/4th of the recommended dose) and harvested their crops around mid-January, obtaining 2.6-3.4 t/ha.

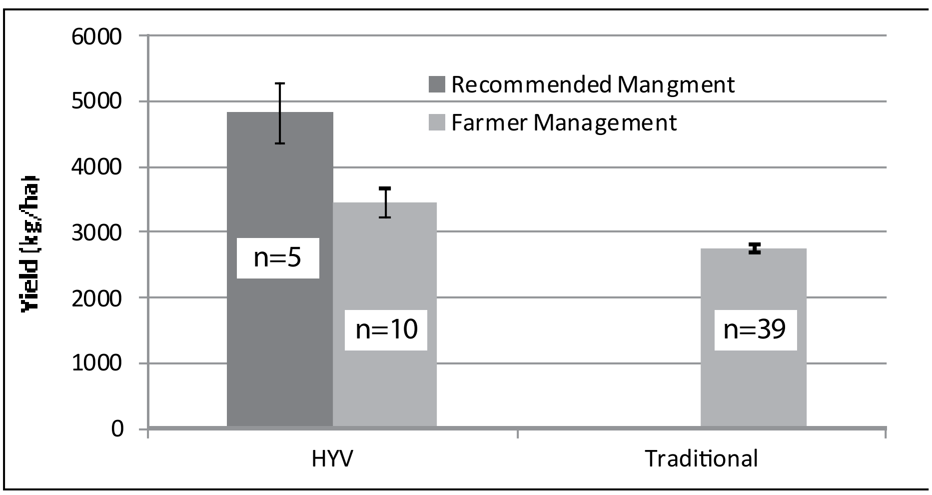


Fig. 7. Yield of HYV rice in the 2013 *aman* season under recommended management in the sub-watershed, and yield of HYV aman and traditional varieties in the rest of the watershed and adjacent areas. Vertical and capped bars indicate standard error.

During the following *rabi* season (December 2013 to May 2014), maize, sunflower and wheat were cultivated by the research team in the sub-watershed with the help of the farmers as paid laborers. The crops were established by both conventional tillage with a two-wheel tractor and power tiller, and by zero/minimum tillage. Maize and sunflower were sown by dibbling into moist soil on 10 December 2013 and following conventional tillage on 04 February 2014. Wheat was established by surface seeding on the moist soil surface and by making furrows with a traditional hand plough (*achra* or *kota*) on 9 December 2013. Sunflower, maize and wheat were grown with and without rice straw mulch applied immediately after sowing. The farmers in the main watershed area sowed sesame during the second half of February 2014.

The 2013-14 *rabi* season was exceptionally dry, with only 36 mm rainfall from 1 December 2013 to 30 April 2014 (Fig. 4b). As a result, establishment, growth and development of the farmers' sesame crops were very poor. The sesame was also damaged by waterlogging as a result of 245 mm rain in late May and early June 2014 and the sesame yielded only 0.4 t/ha. On the other hand, despite the drought and lack of irrigation, growth of the early-established maize, sunflower and wheat crops on residual soil moisture in the sub-watershed was reasonable. However, these crops suffered from N deficiency as the top dressed urea was not effectively used due to lack of topsoil moisture and inability to irrigate following urea application. Despite the lack of rain or irrigation, sunflower yield was good (2.8 t/ha) (Fig. 8), revealing its greater drought tolerance than that of wheat and maize. Yield of maize and wheat were 5.9 and 1.3 t/ha, respectively (Rahman et al. 2015; Islam et al. 2015). There was no effect of mulch on yield, probably because all crops ultimately suffered from water deficit stress. Soil moisture at a depth of 37.5 cm in the mulched plots was higher than in the no-mulch plots throughout the growth period of sunflower, and up to the end of February 2014 in the maize and wheat; after that both mulched and non-mulched maize and wheat plots had similar moisture content (Rahman et al. 2015; Islam et al. 2015).

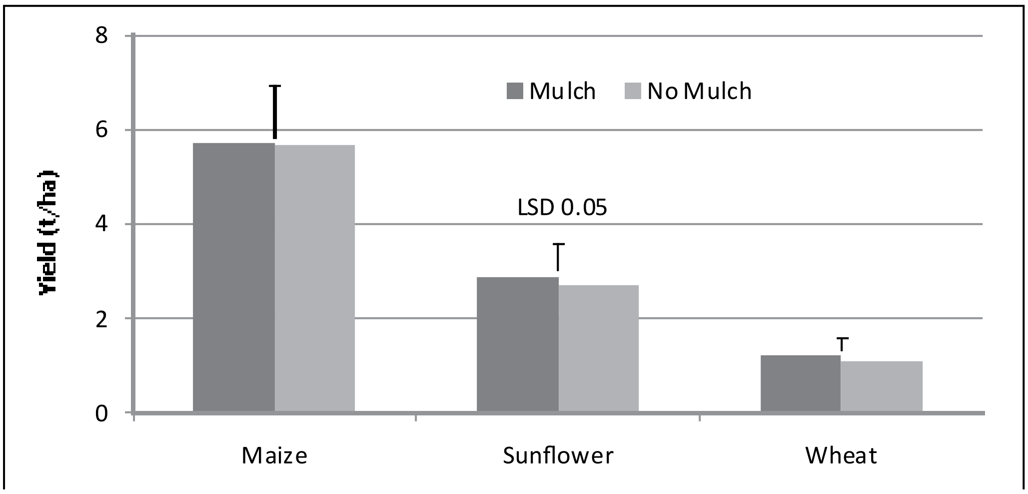


Fig. 8. Yield of *rabi* crops with and without mulch in the 2013-14 dry season 2013-14 (source: adapted from Rahman et al. 2015; Islam et al. 2015).

4. Major challenges to the success of the community watershed pilot

4.1 Non-adoption of HYV rice and recommended cultural practices

Although HYV rice seed and practical training were provided to all the farmers in the pilot watershed only about 50% of them cultivated HYV rice in 2012. The reasons probably include: (1) lower market price of HYV rice than local varieties in 2012 (HYV prices improved in 2013); (2) tenant farmers have to give two-thirds of their harvest to the land owner while having to bear all cultivation costs; (3) higher labor requirement/cost for transplanting HYV rice due to closer plant spacing than that used for traditional rice, and; (4) the cost of fertilizer (although it is subsidized by the government). Some farmers also felt that fertilizer is bad for the soil and were reluctant to apply synthetic fertilizer, although many farmers noted that soil fertility is declining and similarly rice yield. Another possible reason for the reluctance to apply fertilizer may be the fact that there were several projects in the area giving the farmers cash or in-kind support, and the pilot watershed farmers may have been waiting to see what support they could extract from our project.

4.2 Non-availability of tillage equipment for early crop establishment

Land preparation is highly mechanized in Bangladesh, and farmers depend on rented two-wheel tractors with a power tiller to prepare their land for planting. In 2013, the pilot watershed farmers contracted local service providers well ahead of time to plw their land in the dry season. But once the soil was dry enough for tillage, the small tractor owners doubled their price because they knew that the farmers wanted to prepare the land quickly to establish the crops as early as possible. So the farmers had to wait for about two weeks until four-wheel tractors reached the area and did the tillage at a lower price. The big tractors usually come from Jessore once there is sufficient land ready for tillage. Hence, most farmers have to establish their *rabi* crops late every year, even if their fields are dry enough for earlier tillage.

4.3 Non-availability of fresh water for irrigation and N topdressing

As described above, the pilot watershed farmers could not irrigate their dry season crops because the sluice gate was left open to prevent silting of the intake canal and the water in the *khal* became too saline for irrigation in mid-February. This also hindered effective topdressing of N fertilizer.

4.4 Soil drying

Despite early drainage from the rice field of the sub-watershed, drying of the soil was slow, probably due to a range of factors: (1) a high perched water table as the water in the *khal* was high, and adjacent rice fields were still flooded; (2) heavy textured soil with slow internal drainage, and; (3) low evaporation in December/January. For these reasons, the soil reached field capacity later than desired, which delayed plowing and sowing of *rabi* crops (although the soil in the sub-watershed was ready for tillage about two weeks earlier than in the adjacent area). While crops can be established much earlier by dibbling into the moist soil rather than waiting for the soil to dry to moisture suitable for tillage, cracking is a serious problem on these soils.

4.5 Soil cracking

Rabi crops can be established by zero or minimum tillage (dibbling or creation of a sowing furrow only), but soil cracking in these soils is severe in the absence of tillage. This results in root breakage and crop damage, and increases the rate of soil drying due to exposure of the soil surface in the cracks to the air. Straw mulching reduced the cracking considerably and conserved soil moisture for better growth (Rahman et al. 2015; Islam et al. 2015), but requires more labor.

5. Conclusions and recommendations

The possibility of reducing drainage congestion for growing HYV *aman*, and for advancing and diversifying *rabi* cropping, has not yet been recognized by policy makers, water management and agricultural extension authorities, and the millions of farming families living inside the polders. The pilot proved that with appropriate operation of the sluice gate, excess water can be drained from inside a polder during low tide within a few days to enable the cultivation of HYV *aman.* Furthermore, timely drainage shortly before rice harvest hastened soil drying and allowed “early” (timely) establishment of *rabi* crops. Early sowing meant that the *rabi* crops were harvested by the end of April, before the onset of the pre-monsoon rains and the May cyclones.

This pilot study also demonstrated that individuals alone cannot successfully modify their cropping system schedule and adopt improved agricultural technologies due to the prevailing hydrology in the polder. Adoption of improved technologies requires synchronized cropping patterns among farmers within community water management units and community coordination at a range of scales – within small hydrological units, within a sub-polder based on the catchment area of a sluice gate and finally at the polder scale. Until this is addressed, farming communities of the polders of the coastal zone will not be able to adapt and benefit from the green revolution technologies that much of Bangladesh benefits from.

To harness the production potential of the polders, the watershed area of each sluice gate needs to be delineated and hydrologically separated (with gates where appropriate) from other catchments of the polder. Within each sluice gate watershed, smaller water management units need to be defined and hydrologically separated, taking advantage of existing infrastructure (roads) and separating lands of different elevation with small levees. Crop and water management need to be synchronized based on the water management units and management of the sluice gate. Further, engagement with polder communities is needed to test these recommendations at a wider scale, with particular emphasis on empowering communities to enable them to take advantage of the available opportunities to increase productivity and improve livelihoods.

Acknowledgements

This paper presents findings from 'G2: Productive, profitable, and resilient agriculture and aquaculture systems', a project of the CGIAR Challenge Program on Water and Food. The authors are grateful for high quality technical assistance from Amal Ray, Lincoln Ray, Tanmoy Ray and Mithun Ray.

References

Bangladesh Rice Research Institute (BRRI) 2012. Modern rice cultivation (in Bangla). BRRI, Gazipur, Bangladesh.

Bhattacharya, J., Mondal, M.K., Humphreys, E., Saha, N.K., Rashid, M.H., Paul, P.C. and Ritu, S.P. 2015. Rice-rice-*rabi* cropping systems for increasing the productivity of low salinity regions of the coastal zone of Bangladesh. These proceedings.

Islam, M.K., Amin, M.G.A., Mondal, M.K. and Humphreys, E. 2015. Appropriate crop establishment techniques for *rabi* crops cultivation in the saline coastal zone of Bangladesh. These proceedings.

Mondal, M.K., Paul, P.L.C., Humphreys, E., Tuong, T.P., Ritu, S.P. and Rashid, M.A. 2015a. Opportunities for cropping system intensification in the coastal zone of Bangladesh. These proceedings.

Mondal, M.K., Saha, N.K., Ritu, S.P., Paul, P.L.C, Sharifullah, A.K.M., Humphreys, E., Tuong, T.P. and Rashid, M.A. 2015b. Optimum sowing window for *boro* cultivation in the coastal zone of Bangladesh. These proceedings.

Rahman, M.N., Amin, M.G.A., Mondal, M.K. and Humphreys, E. 2015. Residual soil moisture utilization techniques for improving land productivity in the coastal zone of Bangladesh. These proceedings.

Ritu, S.P., Mondal, M.K., Tuong, T.P.,Talukdar, S.U. and Humphreys, E. 2015. An a*us-aman* system for increasing the productivity of a moderately saline region of the coastal zone of Bangladesh. These proceedings.

Saha, N.K., Mondal, M.K., Humphreys, E., Bhattacharya, J., Rashid, M.H., Paul, P.L.C. and Ritu, S.P. 2015. Triple rice in a year: Is it a feasible option for the low salinity areas of the coastal zone of Bangladesh? These proceedings.

How successful are community-led organizations for water management? Evidence from an assessment of Water Management Organizations in Coastal Bangladesh

N. Kenia and M.-C. Buisson

[1] International Water Management Institute, India, n.kenia@cgiar.org, m.buisson@cgiar.org

Abstract

In Bangladesh, water is abundant and often excessive during the monsoon season and scarce during the dry season. These issues are exacerbated in the coastal zone, which is subject to tidal and saline intrusion and highly vulnerable to climate change. Combined, these factors make water management one of the most imperative issues for Bangladesh. Polders were initially created in the 1960's to prevent flooding and intrusion of saline water. Implementation of a successful management system to deal with operation and maintenance of the polders is required for their long term sustainability. In 2001 the Government of Bangladesh (GoB) decided to establish Water Management Organizations (WMOs) to facilitate community-based natural resource management, collective decision-making and participation in water management. In this article, we discuss and analyze the success of these WMOs in the coastal zone of Bangladesh.

On the basis of a literature review and qualitative insights, we identify criteria used to assess the WMOs: participation, transparency, financial accountability, legitimacy and activities carried out in terms of water management (operation and maintenance). Then we analyze these criteria using qualitative and quantitative data from extensive fieldwork conducted in 44 villages across the coastal zone in locations with formal and informal water management institutions.

The in-depth analysis underlines the lack of legitimacy, interest and consideration given to these community-led organizations by most households. However, we also establish that most influential households, larger farmers and WMO members frequently overrate the success of these organizations that *de facto* serve their interests. We conclude by questioning the sustainability of these organizations and their role in promoting equity in water management. Finally, we suggest to formalize the role of local government institutions (*Union Parishads*) in water management for a more sustainable and legitimate governance framework and to apply a targeted approach for more vulnerable segments of the communities in order to promote equity in natural resources management.

Keywords: community based natural resources management, water management, coastal Bangladesh

1. Introduction

Bangladesh occupies one of the largest deltas in the world. The whole country is crisscrossed by creeks, canals, and rivers including the Ganges, the Brahmaputra and the Meghna. In this part of the world, water is abundant and often excessive during the monsoon and scarce during the dry season. Managing water resources in Bangladesh is consequently a major challenge. This is especially true in the coastal zone where the challenges are exacerbated by tidal surge-induced floods and salinity intrusion. In response, embankments were built throughout the coastal zone in the 1960s and '70s. An additional aim of the embankments was to increase agricultural production[1] and to develop the area, still the coastal zone remains locked in a poverty trap. Indeed, of the 8 million inhabitants of the polders[2] 85% of rural households live under the national poverty line (Tuong et al. 2014).

[1] Initially only a single crop—low yielding paddy—was cultivated in the coastal zone. By controlling water intrusion, polders allowed for increased yields and the cultivation of a second or even a third crop (sesame, *boro* paddy, pulses or oilseeds) in some locations.

[2] Polders are low-lying lands that are surrounded by rivers and have been artificially isolated through enclosure by embankments.

With water being so central in driving economic activities (mostly for agriculture and aquaculture) and in the day-to-day livelihoods of coastal communities, water management is one of the most imperative issues for the coastal zone of Bangladesh. Dealing with water management in this complex environment is akin to dealing with conflicting interests: between agriculture and aquaculture, between lower and higher land, between the landless and landowners or even between productive and domestic water uses. Due to the specificities of the ecology of coastal Bangladesh, the issues around quantity, quality, timing and targeting of water access are much more complex than in any part of the world. Policy has consequently played a central role in creating a framework around which to organize water management.

The National Water Policy (MoWR 1999) was an attempt to link various institutions and mainly considered cross-sectorial coordination (Dewan 2012). However, the policy suffered from an urban focus and did not specify which institution would be responsible for water issues related to agriculture or aquaculture in the rural areas. Thus, the National Water Policy created areas of ambiguity amongst various institutions. Then in 2001 the Guidelines for Participatory Water Management (MoWR 2001) practically defined how the policy should be implemented. The institutional framework gives importance and responsibilities to local stakeholders and especially to coastal communities for organizing themselves and leading decision-making over water infrastructures. Local stakeholders are supposed to participate into water management by forming Water Management Organizations (WMOs). In polders, WMOs were created based on a three-tier system comprising Water Management Groups (WMGs) – the smallest hydrological or social unit at the village level, Water Management Associations (WMAs) and Water Management Federations (WMFs). These organizations are given the responsibility for operating the gates that flush water in or out between the polder and the river via canals. In addition, these organizations are responsible for minor maintenance over the infrastructures (canals, gates, and embankments). Implementing agencies including the Bangladesh Water Development Board (BWDB) and Local Government Engineering Department (LGED) are supposed to finance major maintenance.

Our purpose in this article is to understand to what extent these community-led WMOs have been successful in coastal Bangladesh. The following section presents the sources of the data on which the present analysis is anchored. Our objective questions the criteria used to assess the success or lack of success of these organizations. We exploit qualitative insights and the rich, available literature to identify five criteria that will be used to assess the community organizations. The selected criteria are presented in section 3. Then, based on a quantitative survey conducted among 1000 households from 44 villages across the coastal zone, we analyze community organizations on the criteria in section 4. In the fifth part of the article, we propose an overall rating and analyze the differences. Finally the conclusion underlines the main findings, questions the sustainability and the equity of the community organizations for water management and suggests implementable policy recommendations.

2. Methodology and data sources

For the purpose of this analysis, we use two complementary sources of data: qualitative data from one side and quantitative data from the other side. Learnings from the qualitative data together with the literature review helped us to identify the criteria considered as essential for the success of the WMOs. Then quantitative data allow us to measure to what extent these criteria are satisfied.

Qualitative data were collected in 2012 in five polders (polder 3, polder 30, polder 43-2F, polder 31, polder 24G) covering different agro-ecological zones (low, medium and high salinity zones) and four sub-projects of the coastal zone (Jabusa, Jainkati, Latabunia, Bagh-Anchra Badurgacha). These locations were purposely selected with the aim of covering different degrees of salinity and different institutional set ups. The exact locations of the data collection were selected after analyzing maps of the area, transect walks and consultations with the communities. Qualitative data collection took the form of Focus Groups Discussions (FGDs) and Key Informant Interviews (KIIs). In both cases the discussions followed a structured outline. FGDs were conducted with general groups of community members, WMO members and women. KIIs targeted farmers, women headed households, Labour Contracting Societies' group members, gatemen, *Union Parishad*

(UP) members, WMO members, and BWDB and LGED officials. In total, transcripts were recorded for 57 FGDs and 92 KIIs. The transcripts were coded using Atlas Ti and the frequency of the codes is used in the following section to highlight the predominance of some criteria as perceived by the community members.

The assessment of community WMOs is also based on a quantitative survey conducted in the same locations of coastal Bangladesh in January 2013. A sample of 1000 household from 44 villages in three polders and three sub-projects were surveyed. Villages were randomly selected in the three surveyed polders (polder 3, polder 30 and polder 43-2F). Thanks to this random selection, some of the villages selected are located close to the canals and the gates whereas others are located in the middle of the polder, with different water access and resources. The three sub-projects (Jabusa, Jainkati, Latabunia) selected were purposely chosen to represent different agro-ecological zones. Figure 1 presents a map of the coastal zone and the location of the study areas.

With this sample we gathered information on different community-led WMOs. The participatory policy for water management mentioned above is implemented by two major implementing agencies and by the projects they lead in partnership with the Government of Bangladesh (GoB) and donors. The BWDB is responsible for schemes of up to 5000 hectares and therefore leads the work conducted in the polders. The Integrated Planning for Sustainable Water Management (IPSWAM) project and its successor Blue Gold, started in 2013, are the most important projects implemented by BWDB in the coastal zone for community management of water. These two projects put the policy into practice and create Water Management Groups in the locations where they operate. In total IPSWAM created 242 WMGs from 2003 to 2011 (EKN and BWDB 2011). Formed in 1995, LGED is in charge of areas of less than 1000 hectares[3] and led the Small Scale Water Resources (ADB 2007) project funded by the Japan International Cooperation Agency and Asian Development Bank. The project completed 280 sub-projects in its first phase and 300 in its second. This project works outside of the main polders and provides infrastructure work and community organization to communities located outside of the main embankments. The project also follows Bangladeshi policy and takes a participatory approach through the creation of Water Management Cooperative Associations (WMCA). Even if the implementing agencies and projects apply the government policy in the locations where they work, large spans of the coastal zone are left without implementation of the policy. For example, IPSWAM worked in only nine of the 123 polders and to date Blue Gold works in 12 polders. As a consequence, in spite of the existing policy that creates a framework and pushes for a participatory approach to water management, informal institutions still govern water management decisions and operations in many locations[4].

Therefore, three different types of community institutions for water management can be found in our sample. WMCAs were found in the sub-projects, whereas in former IPSWAM project areas (polder 30 and polder 43/2F) we met with WMGs. Finally, the third type of organization, identified mostly (but not only) in polder 3, can be considered to be informal organizations taking the form of *gher* committees, gate committees, *beel* committees or any other informal groups managing water in the area. All three types of groups are community-led WMOs; this assessment will consequently consider the different forms of WMOs and the differences between these three types of institutions. Table 1 summarizes the types of institutions surveyed in each location.

---

[3] These small areas are usually called sub-projects whereas the word 'polder' refers to larger areas created in the 1960s and '70s when the embankments were built.

[4] Before the 90s gatemen were appointed and paid by BWDB throughout the coastal zone, the role played by communities was reintroduced in the 90s after the system of state employed gates operators disappeared.

Table 1. Number and type of institutions surveyed, by location

Type of WMO	Polder 3	Polder 30	Polder 43/2F	Latabunia Jainkati Jabusa	TOTAL
WMCA				4	4
WMG		12	12		24
WMA			1		1
Gate committee	2				2
Gher committee	4				4
Other informal committee	8		1		9
Total	14	12	14	4	44

The survey instruments included a household questionnaire and a WMO questionnaire. The household survey targeted 20 households per village in polders and 40 households in each sub-project. The households were randomly selected using a walking transect method in the villages. The WMO questionnaire was answered in each surveyed village by members of the community-led organizations responsible for decisions regarding water management in the village. As a result some respondents were members of formal WMOs while others were not. The WMO questionnaire contained five sections and the objective was to gain perspective about the functioning of the organization, institutional structures and financial accounting that was taking place in the organization. Similarly, ten sections were included in the household questionnaire with one section focusing on water management. In the analysis below we use data from the WMO questionnaire as well as information collected individually with the household questionnaire. This allows us to get a balanced perspective that includes the points of view of organization members and non-members.

The data used in the below analysis also combine responses to behavioural questions and to attitudinal questions. Attitudinal questions were used to collect opinions and beliefs of the respondents regarding WMOs. These responses are based on the perceptions of respondents and can therefore be highly subjective. In order to limit variation in the way the attitudinal questions were understood, enumerators had to read the definition of the criteria that respondents were asked to rate. In addition, a Likert scale was used for the responses and the scale was shown on a piece of paper in order to help the respondent.

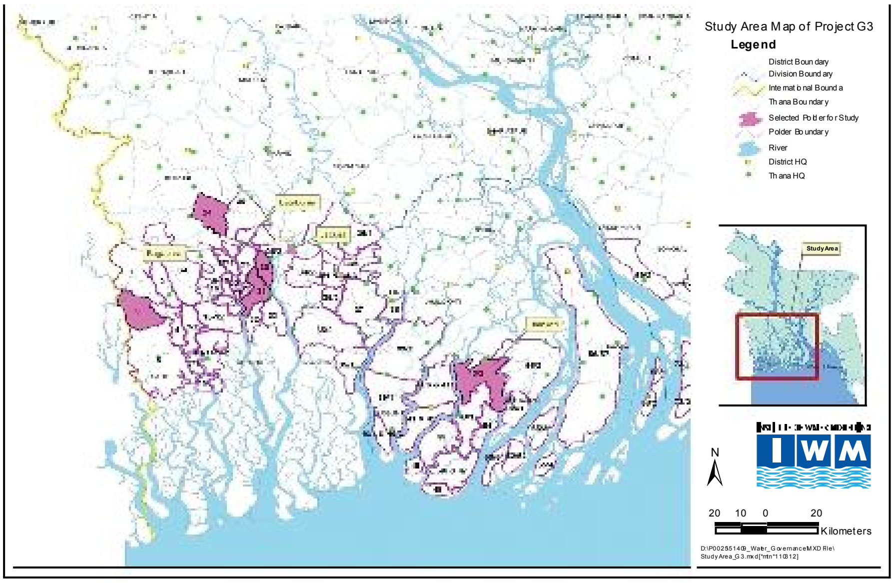


Fig. 1. Map of the study areas (source: Institute of Water Modelling for the CGIAR Challenge Program on Water and Food G3 project).

3. Identification of criteria to assess water management organizations

The criteria for assessing the success of WMOs in coastal Bangladesh were initially based on insights from the qualitative data and are here further justified by the way they are considered in the literature on community natural resource management. As mentioned by Bardhan (2000), the literature on natural resource management and community cooperation for irrigation or water management remains largely led by social and anthropological empirical studies. We dig into this large body of literature with the addition of a few existing quantitative analyses to identify the criteria to be used.

The success of these community-led organizations depends first on the objectives they were given. Here we refine the definition of success from the Bangladeshi policy that assigned roles to WMOs. As per the Guidelines for Participatory Water Management (MoWR 2001), the main objective of those guidelines, both immediate and long term, was to improve and develop the participation of local stakeholders in water resource management and to achieve sustainable participatory water management.

If participation is clearly the first aim of Bangladesh water management policy, it is also one of the main concerns of the community members. Hence, in the qualitative transcripts, the first topic discussed was the participatory process employed at the formation of the organization[5]. The focus on participation emerged again while discussing conflicts in the community and was even the second cause of conflict mentioned[6].

Participation emerged as an essential indicator of success from the qualitative data and was also frequently assessed in the literature, with questions regarding the true participatory nature of participatory water management both in Bangladesh (Sultana 2009; Dewan et al. 2014) and in other contexts (Cleaver 2001). While the participatory process is considered to be essential for establishing sustainable water management practices(Thompson et al. 2003), still too often participation remains imposed by donors and participatory management fails to achieve a high degree of control over the decisions and resources of communities.

With participation also comes the equitable distribution of benefits. This perspective assumes that the views of all community members with conflicting interests are considered. In an impact evaluation from Peru that employed a spatial regression discontinuity design, Datar (2009) studied the equity impact of irrigation rehabilitation projects with a community-led component and found significant and positive impacts on the poorer beneficiaries. But more often, the equity of programs that transfer water resource management responsibilities to communities is questioned (Social Development Department 2008; Dewan et al. 2014). The degree of participation of local stakeholders in these community-led WMOs will therefore be one of our criteria.

In the analysis below, we will consider participation at the creation of the WMO as well as the inclusion of all the stakeholders in the decision making process on a day-to-day basis.

Governance of the organization is also key for explaining the level of success of WMOs and for understanding their sustainability. Governance refers to the rules that guide the functioning of the organization. These rules include the election process, decision making, participation in meetings, the way water should be allocated, solving disputes (Haider 2009; Gain 2012) and the collection and allocation of resources.

We will consider two governance-related criteria: transparency and financial accountability. The transparency of an institution refers to the degree of information that is shared by the institution. In our case, this concerns the level of publicity for decisions or meetings that have taken place. Financial accountability refers to the policy organizations adopt to meet their responsibility for ensuring an efficient and fair collection and allocation of financial resources. These governance issues were also highlighted during our qualitative discussions with groups and key informants, appearing under different topics including conflicts, maintenance and institutions[7].

---

5 Atlas Ti code: 'PROJECT_Process_formation_WMG/WMCA', frequency 84, 1st code related to WMOs

6 Atlas Ti code: 'CONFLICT_Participation:exclusion_non-elites', frequency: 135, 2nd code related to conflicts.

7 For example: Atlas Ti code: 'BWDB_perception: negative: corruption', frequency 82, 1st code related to implementing agencies.

Another body of literature assessing community-led natural resource management considers the linkages between the institutions in charge of water management and other institutions, and particularly local government elected bodies (Shackelton 2002). Even if the idea that the water sector is part of a broader framework that includes the social, political and economic spheres is widely recognized (Social Development Department 2008), the role of politics and of local government institutions is still discussed. This also relates to acknowledging that water management is a political process (Mollinga 2008), from the day-to-day politics of conflicting interests regarding gate operation to the global politics of water and environment. Duyne (1998) similarly underlines the existence of politics as well as informal activities for supporting the water management needs of the coastal communities of Bangladesh. The role of local government institutions in community-led natural resource management organizations has been positively reviewed for community-based fisheries management (Thompson et al. 2003; Rab 2009). In those cases the link between community organizations and local government institutions has been identified as a tool to sustain the organizations in the long-term, especially after project withdrawal. Also, in an impact evaluation led by the Independent Evaluation Group of the World Bank on Andhra Pradesh irrigation projects (Social Development Department 2008), the authors conclude that it is necessary to involve local governments to ensure continuity in water management beyond the community-led organizations. However, local government institutions can also be seen as competitive actors that can weaken the legitimacy of the community-led organizations and may bring political interference and elite capture.

Local government institutions, and especially the *Union Parishad*, are a subject that has been largely covered in the qualitative data. Among the 693 quotes related to *Union Parishads* in the transcripts, 68% can be considered as positive and support an increased role for this institution in terms of coordination, supervision and funding of water management.

We will consequently consider the legitimacy of the community-led water management organizations that exist in coastal Bangladesh as well as their interactions with other formal and informal institutions, including local government institutions, as one of the assessment criteria.

Finally, the activities of the WMOs must be considered, namely operation and maintenance. The way in which operations are conducted, the existence of conflicts related to these operations and the quality of infrastructure maintenance are commonly considered as outcomes of the community-led management of natural resources. *De facto*, the transfer of responsibilities from central governments to communities for operation and especially for maintenance happened at a time where the limited resources allocated by the governments resulted in infrastructure deterioration (Shackleton 2002; Heer and Jenkins 2012; Dewan et al. 2013). Hence, the ability of the community-led organizations to perform these activities indicates their ability to succeed. For example, in a qualitative analysis Bardhan (2000) considers the role of community-led organizations in cooperation. He measures cooperation by the quality of the maintenance, the absence of conflicts and the respect of water-allocation rules. These three indicators clearly decipher the quality of the operation and maintenance activities carried out by WMOs. In another case study from the Philippines, Bandyopadhyay (2007) assesses the impact of irrigation management transfer on revenue collection for irrigation and identifies the significant impact of community-led water management on maintenance activities.

The importance of operation and maintenance criteria are clearly confirmed by the FGDs and KIIs; these two topics gathered the most number of quotes[8] and are in the top five codes related to WMOs.

Consequently, the last criteria for our assessment is the activities in which the WMOs are involved and especially their operation and maintenance performance.

[8] Atlas Ti codes: 'OPERATION', frequency 616; 'MAINTENANCE', frequency: 1005.

4. Assessing community-led water management organizations

4.1 Participation

One of the vital factors for creating sustainable WMOs is participation by all stakeholders. A dynamic and integrated approach should be designed such that each and every member is a part of this group and has the opportunity to participate in all decision-making processes.

From Figure 2 we can observe that at the time of WMO creation, the level of participation was high. During this period donors were still active and they initially involved all the community members in the organization. However, we can clearly see that there is barely any participation in the informal set-up. People organized themselves and the larger *gher*- and landowners took the initiative for the operations of the gates and maintenance of the embankments. This is not the most viable solution, however, as in many cases small and landless farm owners suffer due to intrusion of saline water. What is also seen in most of the organizations surveyed is that the initiative for creating the group was taken by external bodies (BWDB, LGED donors, NGOs) rather than by the villagers themselves. This calls into question the participatory process and the sustainability of the involvement of community members in these organizations.

The participation of specific groups and particularly more marginalized groups is also important to consider. In polders 30 and 43/2F, where all the WMOs surveyed are formal and were registered to the cooperative department, the ratio of male to female members is 3:1 as per the guidelines (MoWR 2001). However in most villages women are primarily only figureheads, as men make most of the water management decisions. Further analysis reveals that female WMO members of are not representative of all women in the communities and do not consider the needs and interests of women in decision making related to natural resources management (Buisson et al. 2014).

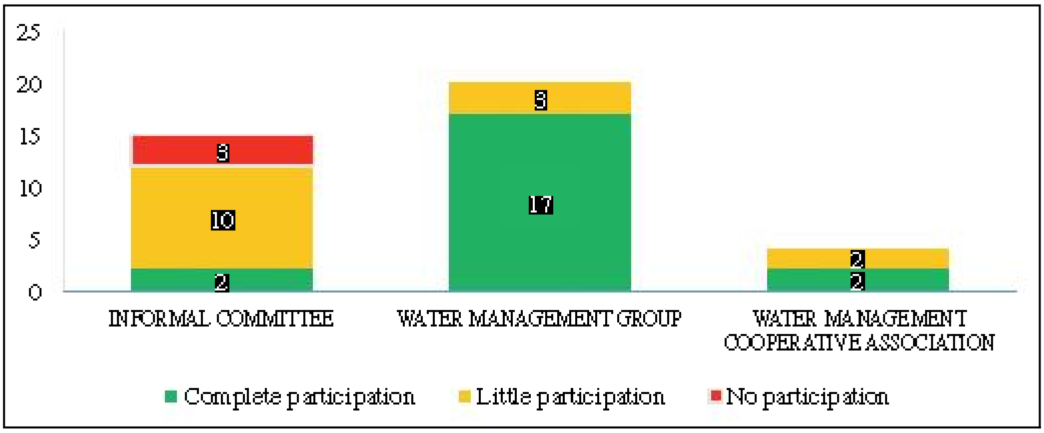


Fig. 2. Perception of participatory process at the creation of WMOs (source: CGIAR Challenge Program on Water and Food G3 project quantitative survey from 44 villages selected in polders and sub-projects).

Qualitative and quantitative data also reveals that the WMOs struggle once donors or projects end their support. The expectation is that the community organizations will function independently. This can be seen in Figure 3: six years after the creation of the WMOs, the participation level has declined steeply. At this time, nearly half of the organized WMOs don't conduct any meetings during the year. Around one-third of them claim to have conducted meetings once in a quarter but this could be a formal routine with a small number of participants and without inclusive discussion or any constructive activity. Amongst the informal committees no such meetings are held. Indeed, since the *gher* or large farm owners have political influence they maintain their decision-making authority and dominate decisions regarding operation and maintenance without participation from other stakeholders. In the sub-projects, the WMO questionnaire indicates that meetings are conducted every quarter, but qualitative insights also suggest a decline in interest in these organizations over time.

Finally, participation can be considered through the number of members, trends in membership or the election processes of WMOs. We note that the number of members in the committees ranges from 20 to 25 per village, but in some villages there are more than 100 members. Most of the WMO member respondents mentioned that over the past few years the number of members has remained the same, but this has been made possible only because of the lack of payment of annual membership fees. Considering elections, voting has taken place recently in only a few villages, which reflects the lack of renewal in executive committees. When elections did occur, there was no contest for the position of president or secretary; this again points to the inactive status of most of these organizations and the lack of long-term participation.

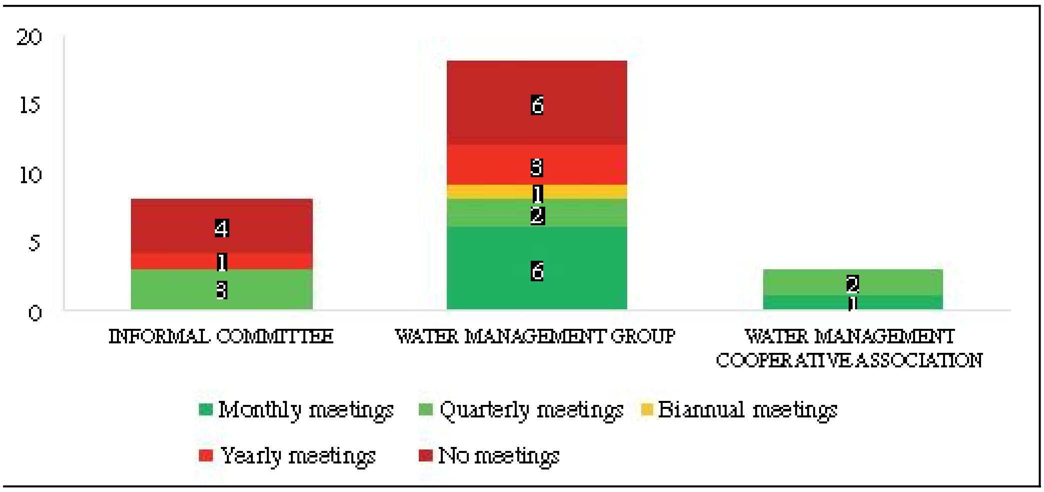


Fig. 3. Number of times organizations held meetings in 2012 (source: CGIAR Challenge Program on Water and Food G3 project quantitative survey from 44 villages selected in polders and sub-projects).

4.2 *Transparency*

We next consider transparency and note that the overall rating for transparency remains very low in all polders and sub-projects. It also remains low among the households regardless of the size of their farms, or whether household members are members and non-members of the WMO. According to our findings, there is no formal mode of communication between various actors such as community members, local government institutions, LGED or BWDB. This means that large amounts of potentially relevant information are unavailable in the public sphere. This could include times for opening and closing of gates, publicizing decisions taken and the agendas of public meetings to name a few. FGDs reveal that many community members could feel excluded from water management and their faith in community-led institutions such as WMOs has eroded over time. One practical consequence is that the community's willingness to contribute (through money or volunteering work) declines. This is in turn has a direct effect on the operation and maintenance of the embankments, canals and the gates. In Figure 4 we can see that the transparency rating from WMOs members is neither good nor bad, suggesting that members themselves don't have much faith in the organization to which they belong.

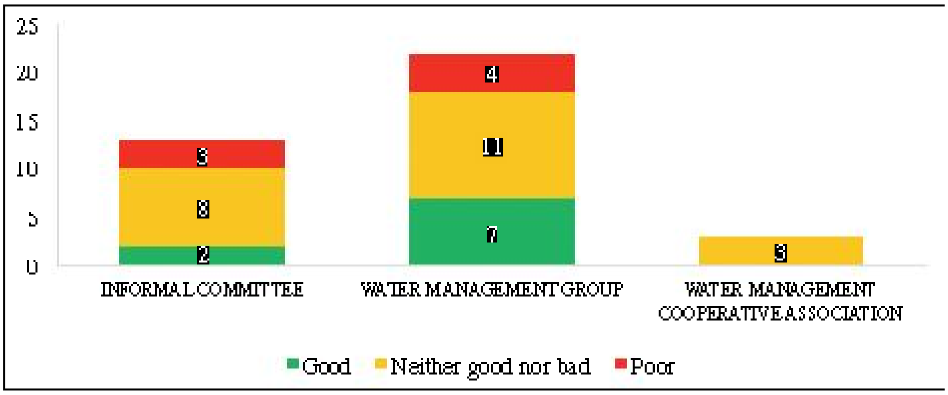


Fig. 4. Perception of transparency by WMO respondents (source: CGIAR Challenge Program on Water and Food G3 project quantitative survey from 44 villages selected in polders and sub-projects).

4.3 *Financial Accountability*

The difficulty of collecting information on income and expenses from WMOs gives an idea of the financial accountability situation. It further denotes the lack of information and sometimes the lack of activity in these organizations.

There are no WMOs registered in polder 3 and hence there are no accounts and no organized structure. However, most of the WMOs in polders 30 and 43/2F are registered and consequently have savings accounts. In addition, some villages also have accounts dedicated to maintenance or other activities. But the existence of an account is not a guarantee for solving the issues of these organizations or for maintaining activities. Indeed, most of these accounts are non-functional or have become dormant. Even in polder 30 and polder 43/2F, only a few villages have registered some expenses for the year. This confirms that in villages in which organizations are present, community members are too often unwilling to contribute to the cost of water management operations and rather expect support from donors or projects.

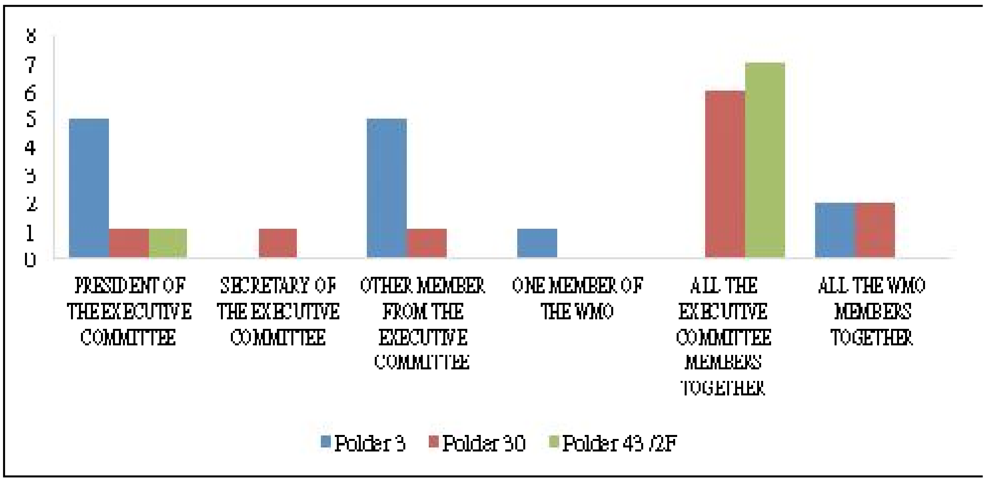


Fig. 5. Who makes the decision on the expenses in the WMO? (source: CGIAR Challenge Program on Water and Food G3 project quantitative survey from 44 villages selected in polders and sub-projects).

However, in polder 3, in spite of the absence of formal organization, it is of interest to note that communities have indeed spent money on maintenance. In those locations, influential people or large *gher* owners take charge and take responsibility for maintaining the gates. Although there is no official record of bank accounts, the maintenance activities are still carried out and supported by contributions given by these *gher* owners.

In terms of finance-related decisions, we note that generally, decisions are made jointly by the executive committee members in polders 3 and 43/2F, whereas in polder 3 a single person makes the decisions (Fig. 5).

In the sub-projects, all three WMCAs are registered as cooperatives but the case of Jabusa is worth highlight. The WMCA of Jabusa is quite financially active[9]. The community organization has a savings account, a maintenance account and an emergency account into which money is deposited. This financial activity can be linked to the ability of the organization to receive income, mainly from canal leasing but also from interest from microcredit, interest from savings and from a grant from LGED. All the records are well maintained in the WMCA office and are said to be open to all members. In Jainkati and Latabunia, the WMCAs have savings accounts into which money is deposited but the amounts remain very limited due to the lack of regular contributions and the absence of additional sources of income. Finally, in all the surveyed WMCAs, all elected members of the executive committee take decisions on contributions or resource allocation collectively.

Hence, amongst the project and sub-projects, the latter have been more financially active and their accounting systems seem more sustainable.

[9] This was at least the case in 2012; since then conflicts have started hindering the activities of this WMCA.

4.4 *Legitimacy*

The legitimacy of an organization is a function of the reliance that people place on it for solving their problems. In this regard, the success of community-led models is largely limited. While analyzing the data collected we realized that the powers held by the communities are relatively limited compared to those of local government institutions. Interestingly, the legitimacy given by community members to WMOs—supposedly community-led organizations—is lower than the legitimacy given to other institutional actors.

When household respondents were asked which institution they would go to first to solve a water management issue they were least likely to approach a WMO to resolve their problems and instead rather chose to go to *Union Parishads*. These results are displayed in Figure 6. Respondents located in areas where informal committees are in place for water management matters (polder 3) are most inclined to approach *Union Parishads* and only around 21% of them consider community members capable of solving these issues. But the scenario is not so different in locations with formal WMOs. Where WMGs are in place, most of the respondents (37%) would first approach BWDB. Where WMCAs are in place, respondents indicated they would first approach LGED. In no locations were community organizations considered legitimate actors for solving water management issues; less than 3% of the respondents choose WMOs as the organization they would contact first.

These results underline the inability of WMOs to establish themselves as legitimate institutions for solving water management issues and leading water governance; the households who should be the beneficiaries of these institutions clearly don't recognize their usefulness. On contrast, the legitimacy of Local Government Institutions, especially of *Union Parishads*, and the level trust accorded to them by community members is a robust result throughout the different polders and sub-project considered in this analysis.

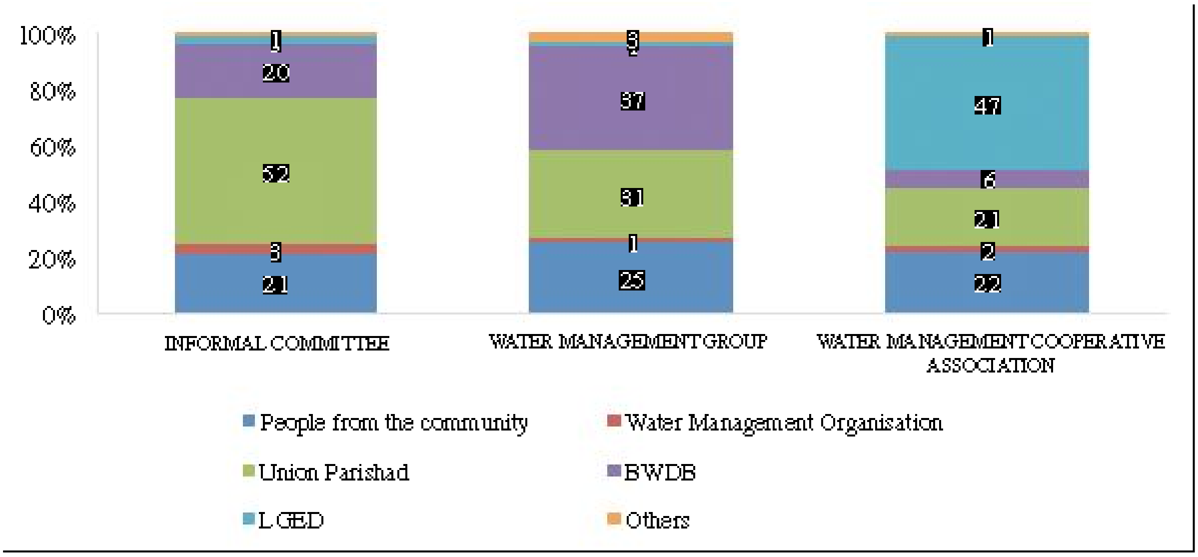


Fig. 6. Which institution would you contact first to solve a water-related issue? (source: CGIAR Challenge Program on Water and Food G3 project quantitative survey from 1000 households selected in polders and sub-projects)

4.5 *Activities*

There are various activities required to ensure that an organization runs efficiently. In our case there are two main activities that take place in the polders and sub-projects: maintenance and operation. Maintenance applies to the canals, embankments and gates whereas operation mainly applies to the gates. Below we consider the activities undertaken on these three types of infrastructure.

First, annual maintenance activities on the canals are rarely observed. In polder 30, polder 43/2F, Latabunia, Jabusa and Jainkathi, the quality of the canals is especially poor and these water bodies are heavily silted. There is no work or money invested in these canals. Indeed, most of the villages surveyed claim that there has been no re-excavation or de-siltation in the canals for decades. Some others mentioned that the last re-excavation occurred in 2009. Thus the state of the canals is worsening year after year. If one argues that canal leasing may be a way to collect funds for improving the maintenance of the canals, the case of Jabusa does not support this assumption. Despite leasing the canal for several years and receiving substantial money from the leasing contract, the main canal of Jabusa is not well maintained and, on the contrary, leasing has contributed to segmentation of the canal and flow disruption.

Annual gate operation in these polders tells a similar story. Opening and closing of the gates remains one of the most controversial and debated issues in the polders. The conflicts occurring between shrimp culture and agriculture, small and large farmers, and low and high land farmers are due to issues coordinating water quantity, quality (salinity) or timing. The timing of gate opening and closing is supposed to be decided jointly by all the members of the WMO but more often than not the decision is made by influential people to suit their own needs. It is common for the gates to be operated by a gateman who is formally or informally appointed by the decision makers. When formal WMOs exist, the executive committee of the WMO appoints the gateman. But in the case of polder 3, *gher* owners select the gateman themselves. The gateman generally lives near the gate and is then compensated in kind or in cash (as is the case in polder 3).

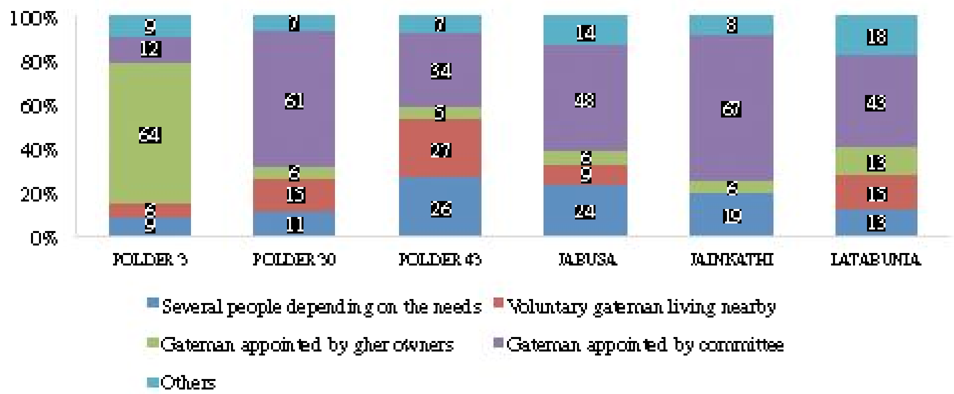


Fig. 7. Who makes decisions regarding the operation of the gates? (source: CGIAR Challenge Program on Water and Food G3 project quantitative survey from 1000 households selected in polders and sub-projects)

Lastly, embankments are the pillars of the polders and need constant maintenance to prevent water intrusion into the polder. But, despite being so essential, the amount of time and money invested in embankment maintenance is inadequate. Across polders and sub-projects, only half of the surveyed villages have carried out maintenance activities on their embankments. In more than half of these villages, no rehabilitation work has been undertaken in the last four years. This lack of maintenance is again related to the absence of contributions from community members. In addition, the act of a few farmers or *gher* owners digging and adding pipes through the embankment further puts the infrastructure at risk.

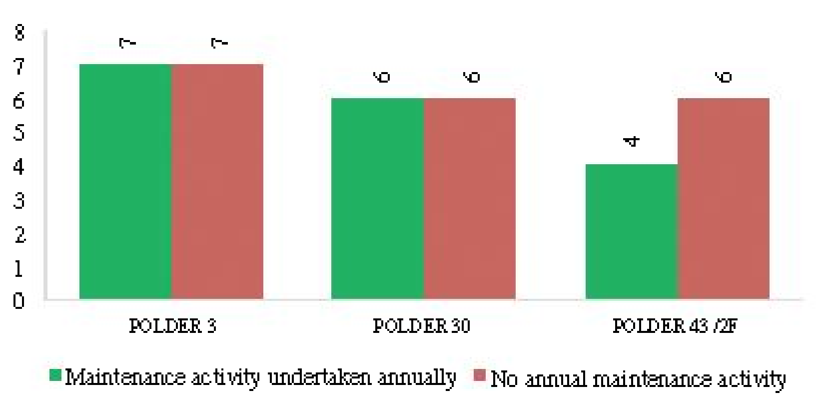


Fig. 8. Annual maintenance activity to the embankments (source: CGIAR Challenge Program on Water and Food G3 project quantitative survey from 44 villages selected in polders and sub-projects).

5. Ranking the community-led water management organizations and discussion

One way to synthesize the above-mentioned results is to consider rankings from the WMO respondents and households for the five indicators.

Rankings were included in the WMO and household questionnaires. Respondents were asked to rate the different parameters on a Lickert-type scale from one to six. One was the lowest value and meant the community-led organization completely failed in achieving this objective. Six meant that the organization was very successful with respect to that indicator. The six[10] topics considered were:

(i) Participation, to what extent all members were involved in the organization when created and are still involved in decision making;

(ii) Transparency, to what extent community members have access to information related to the actions of the WMO, to WMOs meetings, decisions or rules;

(iii) Financial accountability, to what extent the organization is able to provide clarity on budgets and expenditures or to what extent the organization is free of corruption;

(iv) Legitimacy, to what extent the organization plays a fair role in conflict resolution and is able to uphold the rules and decisions related to water management in the community;

(v) Maintenance, to what extent the organization is able to maintain the state of the water infrastructure and the quality of the infrastructure in the village; and

(vi) Operation, to what extent the community-led organization is able to take joint decisions regarding the operation of the gates and to what extend the decisions satisfy user needs.

We first examine the ranking from the WMO respondents and then from the households respondents. Figure 9 gives an overview of the average ranking for the different polders and sub-projects by WMO respondents. These graphs demonstrate the self-satisfaction of WMO respondents on the success of their respective organizations regarding multiple parameters. Obviously, since the respondents are members of these organizations (most of the time, presidents or secretaries), the responses can be biased and driven by a willingness to show the strength of their institutions.

In the case of the community-led organizations from polders 3, 30 and 43-2F, the average rating was between 4 and 3 denoting a neither good nor bad situation. The only clear differences is seen in the rating for maintenance in polder 43-2F, which seems relatively better than in the two other polders. Also, polder 30's rankings on several criteria (maintenance, operation, legitimacy and financial accountability) are lower than in other locations. Considering that most of the respondents from polder 30 were members of the WMG established by IPSWAM, this is somewhat surprising and may translate a difference in expectations. By initiating community mobilization and strengthening the role of communities in water management, these projects also create new expectations among the communities. Another explanation is related to the status of these organizations in polder 30; many were *de facto* non-functional at the time of the survey and the respondents were consequently keen to share their real feelings and disappointment regarding these organizations.

[10] Maintenance and operation are considered independently for the ranking, we consequently give six indicators instead of the five previously mentioned.

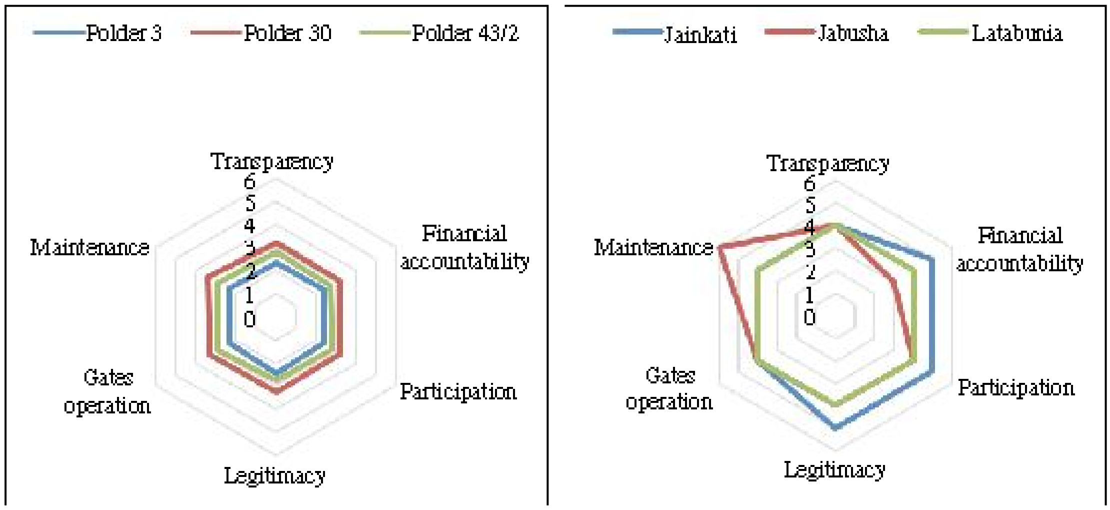


Fig. 9. Ratings by WMO respondents (source: CGIAR Challenge Program on Water and Food G3 project from 44 villages selected in polders and sub-projects).

Overall the ratings are higher in sub-projects than they are in polders. All the sub-project ratings exceed 3, except for financial accountability in Jabusa. Maintenance was considered to be very successful in Jabusa, where large sluice gates are indeed well maintained even if the embankment is weakened by erosion. Interestingly, Jainkati appears to be the most successful among the three sub-projects with high rankings for participation, legitimacy and financial accountability. This situation is consistent with the qualitative insights.

We then consider the same rankings from the household survey. Rankings from Figure 10 are averages from all respondents in each location. Our purpose here is to understand the perception from the households, i.e. from the water users or beneficiaries of the services provided by the water organizations in each village. We are also interested in noting consistencies or differences in the ratings given by households and by the WMO respondents. The first observation is that the ratings dropped down to 2.5 on most of the parameters. On average, household members rated each criterion below 3. This clearly indicates that community members are not satisfied with the functioning of the WMOs. It may also suggest that the members from the organizations overestimate the benefits the institutions have on the stakeholders.

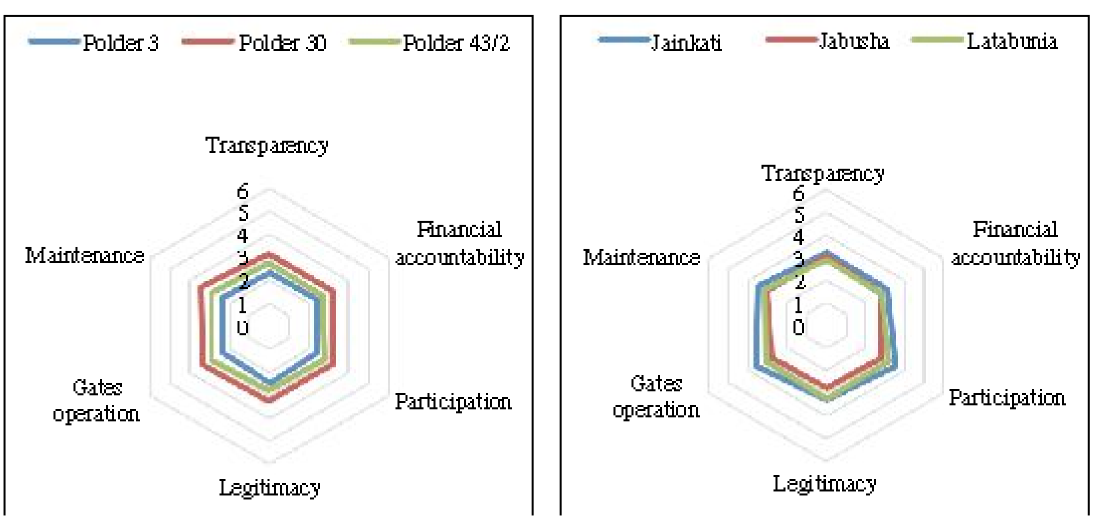


Fig. 10. Ratings by households respondents (source: CGIAR Challenge Program on Water and Food G3 project quantitative survey from 1000 households selected in polders and sub-projects).

From the household ratings, the particular case of polder 3 comes to light. In this polder, the average household rating for the six indicators is close to 1.5. The primary reason for this very low rating could be the informal way in which water is controlled and the frequency of conflicts. Indeed in this polder, where no large-scale projects have been implemented, what we call community-led water management is actually informal organizations led by influential *gher* owners who dominate gate operation. Small and marginal farmers generally do not have any say in the decision making process related to water management in this polder. In polder 30 ratings are higher than in the other polders. The fact that IWPSAM was involved in this polder for a long time, set up the organizations through a participatory process and empowered the community members may help explain this result.

Of the sub-projects, Jabusa received the lowest scores. While WMO respondents rated Jabusa highly, a clear difference can be seen with household respondents, who indicated their dissatisfaction with the organization and its activities. Since Jabusa is a comparatively large sub-project, at least in terms of population, the activities require more vigorous monitoring and evaluation and coordination may become more difficult to achieve. Also, this is the only sub-project where the WMO respondents acknowledged a political influence on water management. In Jainkathi, household members seemed relatively satisfied with the WMO.

Finally, intrigued by the difference of perspective between the WMO and household respondents, we analyze the responses for different categories of respondents from the household survey. First, we consider members of the WMOs and non-members and second we consider the ratings from different land size ownership groups (Figure 11). The results obtained confirm that the WMOs primarily serve the needs of larger landowners, whereas smaller farmers and the landless are commonly excluded.

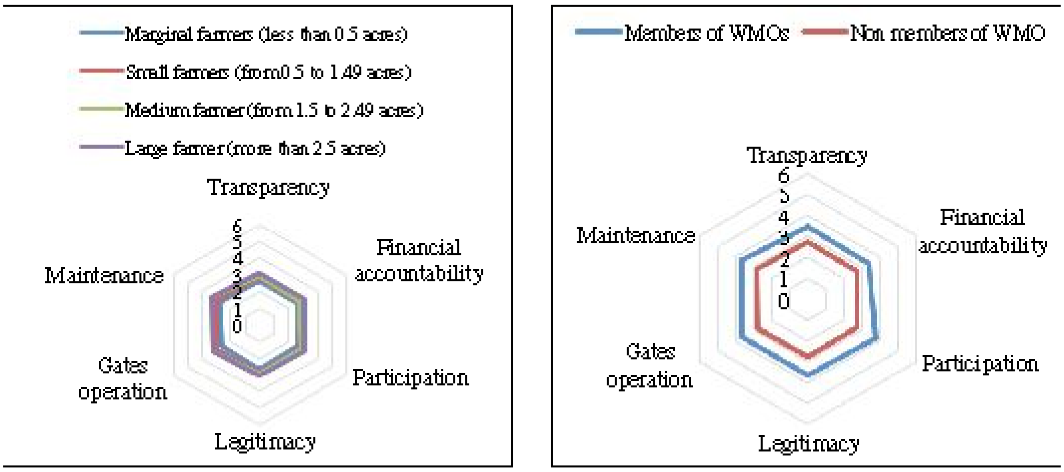


Fig. 11. House respondent rating, by WMO membership and land size group (source: CGIAR Challenge Program on Water and Food G3 project quantitative survey from 1000 households selected in polders and sub-projects).

The same issue appears when comparing the ratings of WMO members and non-members. On average, 11.3% of the households from the sample have at least one member in a WMO. These households ranked the WMOs significantly higher than the non-members did for all six criteria, and especially for participation.

6. Conclusion

In 2001, the Government of Bangladesh decided to establish Water Management Organizations as the main tool for improved water management and for community involvement in this matter. Following this policy, donors and implementing agencies initiated the creation of community-led WMOs in their projects, mostly for the renovation of water infrastructure. Water management is a common requirement across coastal Bangladesh, so in locations without projects endogenous and informal organizations emerged from the communities to take care of operation and maintenance.

Our purpose here was to understand to what extent these community-led WMOs have been successful in the context of coastal Bangladesh. On the basis of a literature review and insights from qualitative data, we identified the criteria used to assess WMOs: participation, transparency, financial accountability, legitimacy and water management activities carried out (operation and maintenance). Then, we analyzed the indicators using quantitative data from extensive fieldwork in 44 villages across the coastal zone in locations with formal and informal water management institutions.

The in-depth analysis underlines a lack of participation, which declines over time along with the interest and the legitimacy that community stakeholders accord to these organizations. Both transparency and financial accountability are very poor, indicating that most of these organizations became dormant after project and donor withdrawal. Finally, elite capture is a widespread issue across the study areas, and not only in locations with informal water management. We indeed establish that most influential households, larger farmers and WMO members frequently overrate the success of these organizations that *de facto* serve their own interests.

These results lead us to question the long-term sustainability of these organizations and their role in promoting equity in water management.

The analysis presented in this paper also indicates that a series of reforms need to be implemented on multiple fronts to improve water governance in coastal Bangladesh and to find a better fit between the water management needs of various stakeholders and the way water is controlled and shared. Through the above assessment the paper attempts to shine light on the following first-level policy recommendations to tackle.

First, there is an immediate need for improved coordination among stakeholder institutions through implementation of a clear water governance framework. While basic institutions on water governance at the local community level are already present, clear understanding of their roles and responsibilities is lacking. This is confirmed by the clear lack of legitimacy for community-led organizations underlined in this analysis. Currently, according to the guidelines (MoWR 2001), the *Union Parishads* are supposed to provide support to projects and sub-projects by facilitating effective coordination among the existing institutions. However, the lack of specificity regarding their responsibilities limits the span of control of the *Union Parishad* and curtails their effectiveness in performing a coordination role. This reality is mismatched with the level of trust that community members give these institutions and with the legitimacy they benefit from in terms of water management. Giving *Union Parishads* a formal role to coordinate the actors involved in water management would reduce conflicts and promote more sustainability in the water governance framework.

Second, equity is seen as being at risk. This is indicated by the lack of participation from more vulnerable segments of the communities and from elite capture. This is especially relevant for women, who in spite of the water needs they may have, are excluded from decision making over the management of the resource. While female participation needs to be encouraged in all roles, it is extremely important to tap their inherent strengths and support their participation in roles that make them feel comfortable and thus ensure their greater involvement. For example, women could provide feedback regarding the activities taking place near sluice gates or act as key informants in case any illegal activity takes place. Although it is already mandatory for an organization to be inclusive, we suggest adopting a more targeted approach that would reconcile individual water needs with the requirement for coordination at the community scale.

Acknowledgements

This article is based on data collected for the project 'G3: Water Governance and Community-based Management in Coastal Bangladesh', part of the Ganges Basin Development Challenge of the CGIAR Challenge Program on Water and Food and the CGIAR Research Program on Water, Land and Ecosystems. The authors thank the NGO Shushilan for the data collection throughout the southwest coastal zone of Bangladesh and the respondents. Camelia Dewan is also thanked for her work in the qualitative data and especially coding of the transcripts that are used here.

References

Asian Development Bank. 2007. Small-Scale Water Resources Development Sector Project. Performance Evaluation Report. Operations Evaluation Department.

World Bank Group. (2008). An Impact Evaluation of India's Second and Third Andhra Pradesh Irrigation Projects. World Bank Group .

World Bank. (2008). The Political Economy of Policy Reform: Issues and Implications for Policy Dialogue and Development Operations. Social Development Department .

Buisson, M.-C., & Mitra, A. a. (2013). Households and Water Management Organizations Quantitative Surveys. Dhaka, Bangladesh: Challenge Program on Water and Food.

Bandyopadhyay, S. S. (2007). Yield Impact of Irrigation Management Transfer: Story from the Philippines. World Bank Group.

Bank, A. D. (2007). SSWRDP. Bangladesh: ADB.

Bardhan, P. (July 2000). Irrigation and Cooperation: An Empirical Analysis of 48 Irrigation Communities in South. Economic Development and Cultural Change, Vol. 48, No. 4 , 847-865.

Cleaver, F. (2001). Institution, agency and the limitations of participatory approaches to development . In B. K. Cooke, Participation: The New Tyranny (pp. 36-55). London: Zed Books.

Cooke, B. a. (2001). The case for participation as tyranny.

Embassy of the Kingdom of the Netherlands Dhaka, B. (2011). IPSWAM. Dhaka.

Duyne, J. E. (1998). Local Initiatives: People's Water Management Practices in Rural Bangladesh. Development Policy Review Vol 16 , 265-280.

Datar, G. X. (2009). Are Irrigation Rehabilitation Projects Good for Poor Farmers in Peru? World Bank Group.

Dewan, C. M. (2013). Evolution of Participatory Water Management in Coastal Bangladesh: A review of project and policies.

Dewan, C. M. (2014). The Imposition of Participation? The Case of Participatory Water Management in Coastal Bangladesh. Water Alternatives 7(2) Volume 7 | Issue 2 , 342-366.

Dewan, C. (2012). SWOT analysis of Bangladesh's key water.

Dewan, C. (April 2012). Review of the historical evolution of policies and institutions of community based management in coastal Bangladesh. G3: Water Governance and Community Based Management.

Gain, A. a. (2012). An Assessment of Water Governance trends: the case of bangladesh. Water Policy 14 , 821-840.

Humphreys, E. B. (2014). Messages from the Ganges Basin Development Challenge. Research for Development Series.

Haider, H. (2009). Community-based Approaches to Peacebuilding in Conflict-affected and Fragile Contexts. Governance and social development .

Heer, J. a. (2012). Practices of Cross Cultural Collaboration in Sustainable Water. International Journal of Business Anthropology .

MoWR. (2001). Guidelines Participatory Water Management, GoB. Ministry of Water Resources.

Mollinga, P. P. (2008). Water, Politics and Development: Framing a Political Sociology of Water Resources Management. Water Alternatives 1(1) , 7-23.

Pal, S. a. (2010). Challenges and adequacy of water resources management policies in Bangladesh. School of the Built-Environment, Heriot-Watt University, UK .

Sultana, F. (2008). Community and participation in water resources management: gendering and naturing development debates from Bangladesh. Transactions of the Institute of British Geographers .

Silva, S. d. (2012). The experiences of Water Management Organizations in Bangladesh.

Shackleton, S. C. (March 2002). Devolution and community - based natural resource management: creating space for local people to participate and benefit. Natural Resources Perspectives (ODI) 76: 1-6. , Number 76.

Rab, A. (2009). River fisheries management in Bangladesh: Drawing lessons from community Based Fisheries Management (CBFM) experiences. Ocean & Coastal Management 52 , 533-538.

Thompson P., S. P. (2003). Lessons from community based management of floodplain. Journal of Environmental Management 69 (2003) 307–321, 15.

Multiple actors, conflicting roles and perverse incentives: The case of poor operation and maintenance of coastal polders in Bangladesh

F.Naz[1] and M-C Buisson[2]

[1] World Agroforestry Centre (ICRAF), Vietnam, f.naz@cgiar.org
[2] International Water Management Institute, India, m.buisson@cgiar.org

Abstract

The government of Bangladesh invested in large scale coastal embankment projects in the 1960s and 1970s. The polders that were developed played an important role in protecting coastal communities from water-related disasters and in increasing agricultural productivity. However, over time maintenance of these infrastructures became a major concern leading to the creation of a national policy that requires local communities to participate in their operation and maintenance.

In this paper we are interested in understanding what determines the poor state of affairs of the polders. One way to examine this will be through the lens of operation and maintenance (O&M) and the practical strategies adopted by different actors for O&M. This paper consequently discusses the roles and responsibilities of these multiples actors in operation and maintenance of water infrastructure in the coastal zone of Bangladesh. The analysis is based on primary data collected in 2012 and 2013 in nine study sites from the coastal zone. Qualitative data was collected in these nine sites through focus group discussions and key information interviews.

An in-depth analysis of how operation and maintenance activities actually take place reveals that the multiplicity of actors involved in operation creates overlaps and conflicts, resulting in the strategic deferral of maintenance by different actors and eventual disrepair and degradation of the infrastructures. Ultimately, the unclear demarcation of roles and responsibilities for these actors curtails the short and long term sustainability of water management in the polder area. The paper recommends revising the legal water management framework, improving coordination and giving a formal role to local government institutions.

Keywords: water management, community-based natural resources management, decentralization, actors, power

1. Introduction

In the coastal areas of Bangladesh inundation, salinity intrusion and severe flooding are frequent occurrences. To overcome these challenges, the Bangladesh government has invested in coastal zone management through construction and rehabilitation of polders. A polder is a low-lying tract of land enclosed by embankments that create an independent hydrological entity. Gates and sluices ensure both irrigation and drainage of the area. In the 1960s the former Government of East Pakistan through its Water and Power Development Board (WAPDA), now Bangladesh Water Development Board (BWDB), constructed polders to protect agricultural crops, land and human settlements. Efforts intensified in 1967 with the Coastal Embankment Project, which was funded with USAID assistance (Islam 2005; Chowdhury and Rasul 2011). In total 123 polders were built along the coastal zone. Much later, in late 1990s and early 2000s, the Local Government Engineering Department (LGED) of Bangladesh also constructed polders, but on a smaller scale, which were therefore called sub-projects.

Benefits from the polderization of the coastal zone were short lived. The structures delinked the wetlands from the rivers and caused drainage problems and waterlogging. This further added to the natural processes of river erosion and siltation in the very active delta, resulting in the need for continuous rounds of rehabilitation to preserve the infrastructures (embankments, gates and canals). In many developing countries, with Bangladesh no exception, large-scale public irrigation systems are often characterized by "inefficient, unreliable, and inequitable water service; chronic underinvestment in maintenance; rapid deterioration of infrastructure; and reduction in service areas" (Araral 2005: 113).

In conjunction with a shift in donor discourses, the continuous challenge of operation and maintenance of water infrastructure induced regular shifts in water management governance in the coastal zone and the introduction of new actors. What had been a local and indigenous system prior to the 1960s became a top-down, engineering-driven system in the 1960s and 1970s before returning to a decentralized and depoliticized community water management system in the 2000s (Dewan et al. 2015).

In this paper we are interested in understanding what determines the poor state of affairs in the polders. One way to examine this issue is through the lens of Operation and Maintenance (O&M) and the practical strategies adopted by different actors toward O&M. The concepts of O&M are often considered together although they are quite different: whereas operation has short term benefits and involves daily acts in this context, maintenance is less immediate and its effects are only perceived in the medium to long term. Apart from their timeframes, the incentives for the different actors to undertake O&M and their funding sources also differ. Consequently, we consider separately activities related to O&M and analyze how different stakeholders contribute to these two sets of activities.

The article is organized as follows. Section 2 discusses the methods used for data collection and analysis. The third section then provides context on water management in Bangladesh and the main actors involved in the sector. Section 4 focuses on the results with an emphasis on the roles of actors in operation and section 5 focuses on the actors involved in maintenance. Finally section 6 concludes the analysis and provides policy recommendations.

2. Methods

This analysis is based on primary data collected in 2012 and 2013 in the coastal zone of Bangladesh. Fieldwork was conducted at nine study sites: five large polders built by BWDB and four sub-projects (less than 1000 hectares) under the supervision of LGED. These nine locations were purposely selected from three different agro-ecological zones in order to capture differences in environmental constraints (e.g. salinity and waterlogging) and institutional backgrounds (small scale vs. large scale; project coverage). The location of the study area is given in Figure 1. Table 1 summarizes the agro-ecological and institutional features of these study sites.

Qualitative data were collected in these nine sites through 57 Focus Group Discussions (FGDs) and 92 Key Informant Interviews (KIIs). Data collected was representative of different contexts in terms of distance from the main rivers and sluice gates, level of siltation of the surrounding canals and concentration of various types of cropping systems. The KIIs were held with different stakeholders: farmers, women-headed households, Labor Contracting Society group members, gatemen, *Union Parishad* members, Water Management Organization (WMO) members, and BWDB and LGED officials. Apart from the qualitative primary data, secondary data such as government and donors reports and statistics were also used to support our analysis.

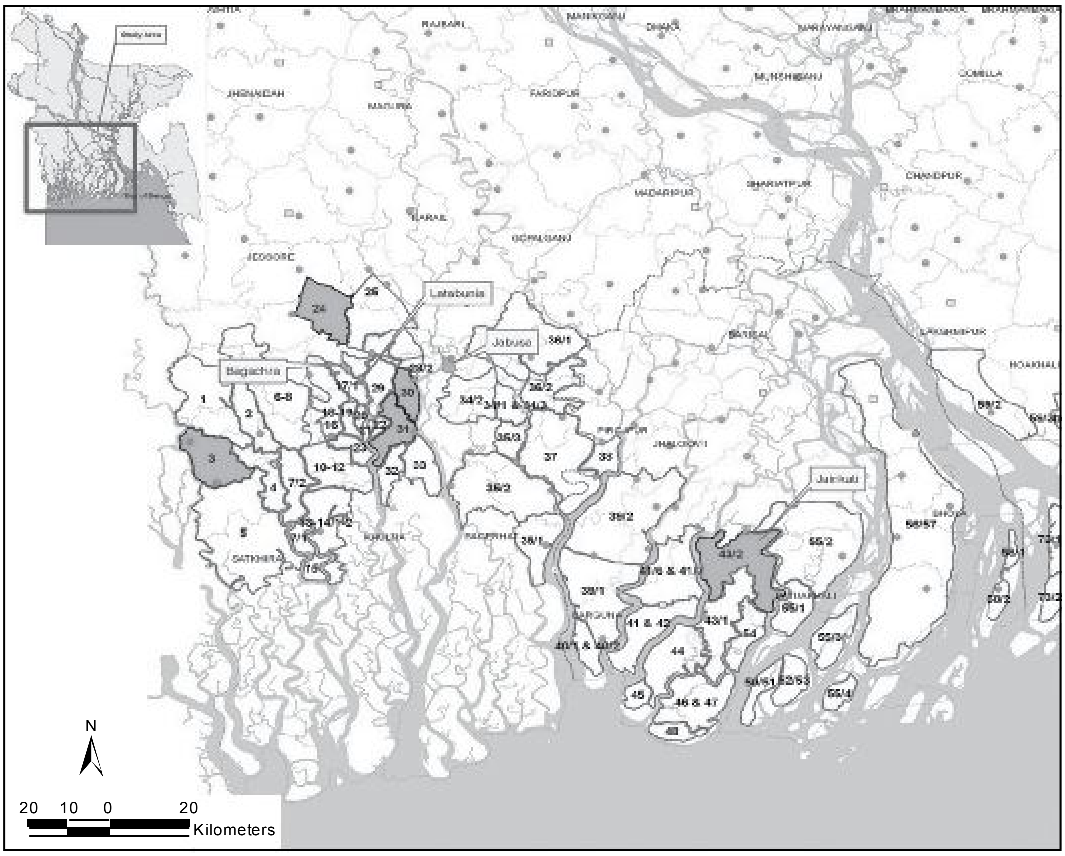


Fig. 1. Map of the study area, coastal zone of Bangladesh.

Source: Institute of Water Modelling

Table 1. Main characteristics of the study sites

Study site	Area (sq. km)	Approximate population (2011)	Number of sluice gates	Salinity levels	Agency	Project coverage for water management
Polder 3	194.3	39,584	32	Very high	BWDB	None
Polder 24G	258.56	61,867	8	Medium to low	BWDB	KJDRP
Polder 31	148.31	32,576	67	High	BWDB	4th Fisheries
Polder 30	72.09	36,017	28	Medium	BWDB	IPSWAM
Polder 43-2F	56.22	28,485	11	Very low	BWDB	IPSWAM
Latabunia	2.0	446	1	Medium	LGED	SSWRDP
Jabusha	4.11	6195	5	Low to medium	LGED	SSWRDP
Jainkati	1.0	325	2	Very low	LGED	SSWRDP
Bagarchra	3.5	1299	2	Medium to high	LGED	SSWRDP

3. Water management of Bangladesh: a multiple actor framework

3.1 Decentralization and formalization of water management

In parallel with and resulting from the physical, political and economic changes of the coastal zone, institutions involved in water management have witnessed several evolutions. The introduction of new institutions follows two historical trends: decentralization and formalization. In Bangladesh decentralization has largely been a political tool employed by ruling parties (Islam and Fujita 2012). Political decentralization can be defined as the transfer of authority to a sub-national body. Political decentralization aims to give citizens, or more often, their elected representatives, more power in public decision making. In rural Bangladesh there are three local government tiers: *Zila Parishad* at the district level, *Upazila Parishad at* the sub-district level and *Union Parishad* for groups of villages. In spite of decentralization, local governments in Bangladesh are still largely dependent on central governance. For example, the central government can legally dissolve a local authority that is not able to meet its objectives (due to inefficiency, power abuse, financial bankruptcy, etc.) (Habibullah 1996). Therefore, the predominant sentiment is that Bangladesh's local government institutions were created to spread the control of the central state to remote locations, rather than for reasons of empowerment. In that respect, the lowest tier of rural administration, *Union Parishads*, are largely dependent on *Upazila Parishads* and thus play only a limited role in rural development programs (Islam and Fujita 2009).

Decentralization of Bangladesh's water management was initiated in 1999 with the formulation of the Bangladesh National Water Policy (GoB 1999) and then operationalized in 2001 with the Guidelines for Participatory Water Management (GoB 2001). These guidelines clearly state that communities are the main stakeholders. The National Water Policy of 1999 recognized for the first time the role of water in poverty alleviation and introduced inclusive water management (Quassem 2001). At the same time, these policies argued for a formalization of the community institutions involved in water management and *de facto* weakened existing formal and informal organizations. The guidelines opened participation in water management to a large range of actors, but also created confusion on the respective roles of each actor. It is also worth mentioning that despite the National Water Policy's focus on participation, the different steps defined in the Guidelines for Participatory Water Management gave more importance to communities for consultation rather than implementation and did not define effective mechanisms for transferring the decision-making responsibilities (Dewan 2012, Dewan et al. 2015).

3.2 Defining the actors: top-down scale, formalization and power

Actors are defined here as individuals or group of individuals actively involved in water management who influence water access and water control based on their degree of power. Actors can be formal or informal and they are classified in this paper on a scale of formal and informal institutions[11]. The definition of power used in this paper is drawn from Lukes (2005); power manifests itself by shaping the values, norms and preferences of a group. It is close to the form of power illustrated by Foucault (1975) who argues that power is not the apanage of a central state, but rather is consolidated in the daily enforcement of social and political practices. Therefore in this paper we are interested to assessing power in the Foucault sense, where institutions and power are closely interrelated.

Bangladesh Water Development Board (BWDB) is the oldest actor in water management in coastal zone, and a key formal one. BWDB can be considered a governmental implementing agency in terms of water management. It started its operations in 1959 as the water wing of the erstwhile East Pakistan WAPDA. BWDB has held the responsibility of executing flood control, drainage and irrigation projects to boost productivity in agriculture and fisheries through major investments in the water sector supported by the Ministry of Water Resources and international donors. It was and still is predominately an engineering, construction-oriented agency, characterized by a centralized structure that was suited to the type of large-scale investments implemented in the 1960s and 1970s (Chadwick and Datta 2003). As per the National Water Policy, BWDB is responsible for water management in polders larger than 1000 hectares. BWDB implemented the Integrated Planning for Sustainable Water Management (IPSWAM) project from 2003 to 2011 and now leads the Blue Gold project funded by the Dutch Embassy.

---

[11] Institutions in this paper are referred to by the "rules of the game" (North 1990). We recognize that the terms formal (i.e., modern, bureaucratic) and informal (i.e., social and traditional) may sometimes be misleading; indeed traditional institutions can also be formalized though not necessarily in the bureaucratic forms that are considered here (Cleaver 2001).

Local Government and Engineering Department (LGED) entered into the water management arena in the 1980s. LGED is also an implementing agency in terms of water management but pertains to the Ministry of Local Government Rural Development and Cooperatives. LGED formalized its role in the water sector through the Small-Scale Water Resources Development Sector Project (SSWRDSP), which began in 1995. Through this project, LGED has provided flood control, drainage and irrigation infrastructures to sub-project areas of less than 1000 hectares. Their approach relies heavily on local stakeholder initiative to identify interventions and support engineering design (De Silva 2012).

As previously mentioned, *Union Parishads* are the lowest tier of elected local government institutions. In that respect they are a formal actor and stand at an intermediate level between the government and the communities. *Union Parishads* are under the supervision of the Ministry of Local Government. They are comprised of 12 members: nine members from nine wards of the union and three women members, one each from three wards. All members are elected through direct universal adult suffrage (Mujeri and Singh 1997). As defined by the Guidelines for Participatory Water Management (GoB 2001) *Union Parishads* were supposed to be 'advisors' to the Water Management Organizations. In addition, in command areas of less than 1000 hectares, they were to gradually receive ownership of the infrastructures. However, facing a lack of legal mechanisms and resources to take on these roles, the *Union Parishads* are only informally involved in water management. Their limited role is not only contrary to the intent of the policy but also to the wishes of most community members (Dewan et al 2014).

As part of the process of decentralization in the water sector and following the Guidelines for Participatory Water Management (GoB 2001), Water Management Organizations (WMOs) were also created (de Silva 2012). These WMOs are intended to function as the institutional mechanism by which local stakeholders participate in water management. In areas of more than 1000 hectares, WMOs should ideally be comprised of Water Management Groups (WMGs) and managed by BWDB; in areas of less than 1000 hectares they should be comprised of Water Management Cooperative Associations (WMCAs) and under LGED management. They are intended to hold decision-making power at all stages of local water resource management and are responsible for planning, implementing, operating and maintaining local water schemes (GoB 2001). Previous research highlighted how these organizations have failed to enhance the participation of the most vulnerable community members (notably women and the landless) and have resulted in elite capture (Dewan et al 2014). Due to the process of decentralization of the water sector in Bangladesh, LGED follows a one-tier system, whereas BWDB follows a three-tier model: associations (WMA) welcome representatives from the different WMGs, with federations (WMF) at the upper-most level. In spite of their institutional differences, all these WMOs are registered as cooperatives[12] and are therefore formal institutions.

Apart from the above-mentioned formal actors, there are many informal actors, individuals or groups involved in water management in Bangladesh. Gate committees, *gher* committees and *beel* committees are some examples of informal actors. Some of these actors are related to formal institutions whereas some are not. It is typical however to find individuals within these informal groups who have a formal role in other institutions.

Figure 2 locates the different actors in a two-dimensional space. The first dimension is related to the level of decentralization; the actors are located in a top-down scale. The second dimension is the formal recognition of the actors, for which a formal-informal scale is applied. As noted in the following sections, the power of these actors is context-specific, determined at a small scale and is not consistently aligned with their location in this framework.

[12] Since February 2014 and as per the Water Management Rules (GoB 2014), Water Management Organizations initiated by BWDB or its projects are not required to register with the cooperative department but must register with the local Water Management Department.

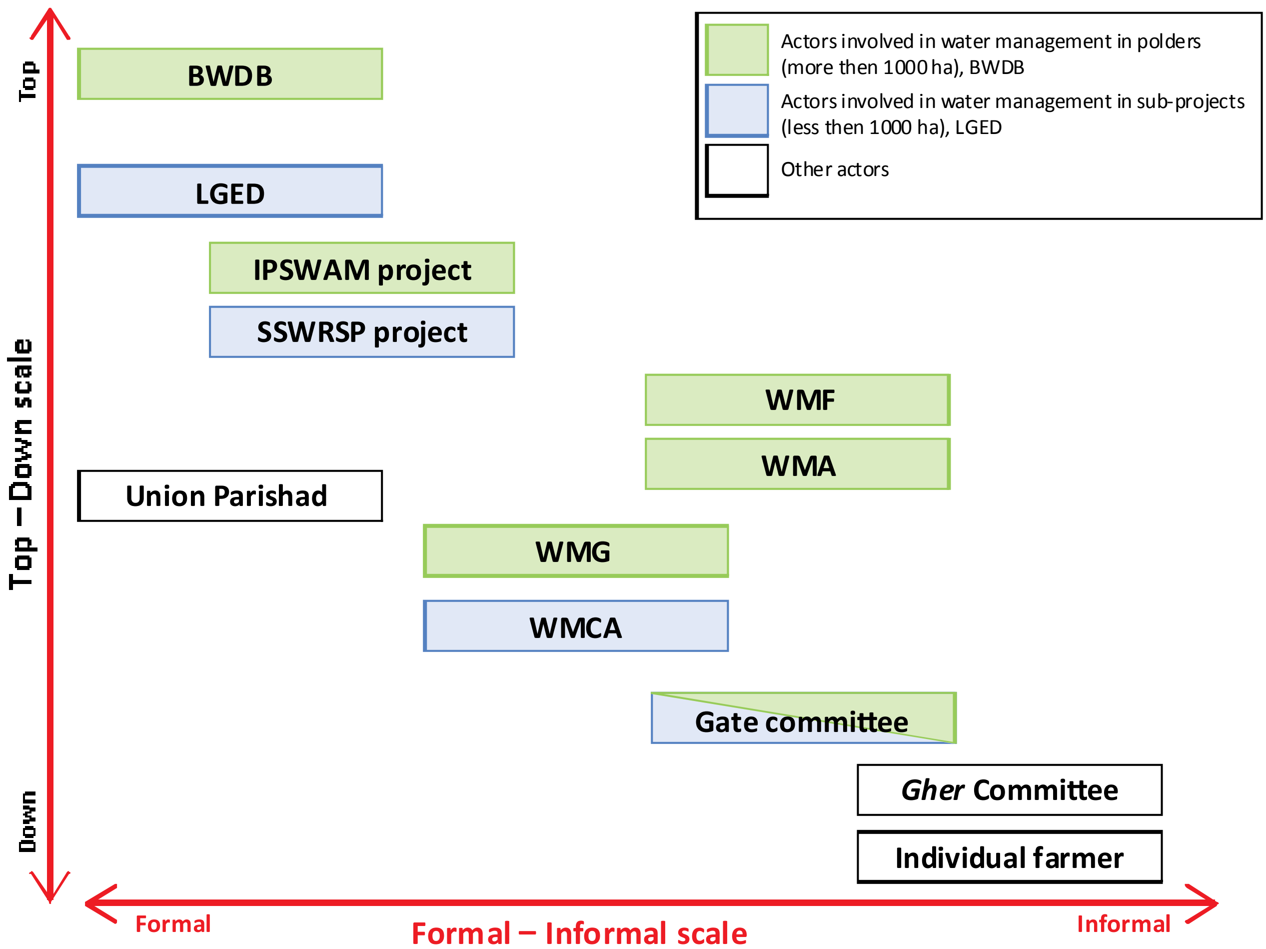


Fig. 2. Actors involved in water management in the coastal zone of Bangladesh.

4. Actors in operations: from decentralization to informal management

4.1 Centralized and formal operations: the former khalashi *system*

Initially, after the creation of polders in the 1960s, BWDB employed government-funded gatemen called *khalashis* to operate the gates based on local requests. At this time the government did not expect communities to be involved in the day-to-day management of water infrastructures. The *khalashis* system worked efficiently, as there was someone responsible for the operation of the gates and the communities did not hold financial responsibilities for O&M.

> *"There used to be* khalashis *in the BWDB sluice gates but not anymore. They were paid by the East Pakistan government and the system was quite efficient."*
>
> *-Polder 43/2F, KII, 10-04-2012*

However, the 1990s saw a push for decentralization and people's participation, which led to a structural adjustment process requiring BWDB to downscale its activities and payroll, and ultimately to change its approach to water management (Dewan et al 2015). As a result, the system of state funded 'gatekeepers' was abolished and the responsibility was placed with communities.

4.2 Formal water management groups, the principal actors in operation

According to the Guidelines for Participatory Water Management (GoB 2001), WMOs are responsible for internal water management; in sub-projects WMCAs are singularly responsible, while in BWDB polder the responsibility is shared between the different levels (WMG, WMA, WMF). In reality, this means that the WMOs are responsible for operation of the gates as well as for preliminary discussions required to reach a consensus on operation. This situation is indeed happening in some locations. For example, in polder 43/2F a farmer described the WMG's coordinating role for reaching consensus on operation.

> *"We open the sluice gate at the time of preparing seed beds in the month of Chaitro (March-April). Usually the group's members sit together, discuss among themselves and make decisions on opening the gate. The beneficiaries residing beside the canals attend the meetings. Sometimes people are divided in their opinions regarding opening of the gate. But with discussion, we are able to reach a consensus."*
>
> *-Polder 43-2F, FGD, 10-04-2012*

Similarly in sub-projects, LGED has given responsibility for opening and closing the gates to the WMCAs and there is no strong monitoring of these activities by local-level LGED officials. Through the inclusion of different stakeholders in the WMCA, this system can be effective in balancing power in the decision-making process.

> *"WMCA takes the decision regarding when to open and close the sluice gates. There are influential people in the WMCA. But nevertheless at least to some extent the WMCA has created a situation of balance of power to control water management of rivers and canals. Large and influential farmers cannot totally dominate the decisions of the associations."*
>
> *-Bagchara-Badurghacha Sub-Project, FGD, 25-03-2012*

4.3 Responsibility of operations delegated to gate committees

Given that Water Management Groups may supervise water management for several villages, they are often responsible for operating several gates. Consequently, they frequently delegate their gate operation role to lower-level gate committees. This delegation should simplify the decision making process by reducing the stakeholders to the users of this particular gate. These committees can sometimes be informal but they can also be formally related to the formal WMG. Even if gate committees are supposed to report to the WMG, by holding the decision on operation, these small groups also hold the power.

> *"Gate committees are the most powerful in operating gates as they are in charge of everything."*
>
> *-Polder 43-2F, KII, 10-04-2012*

WMCAs also delegate their responsibility to decide on the operation of gates, including their opening and closing, to gate committees. For example, in Jabusha sub-project which has 10 gates, there are sub-committees i.e., gate committees formed with local farmers and fishermen. Opening and closing the gate is generally done through voluntary work, without a fixed gateman, and the responsibility of operating the gates rotates amongst the members. In these cases, no remuneration is given to gate operators. In some other cases, the committee assigns the responsibility to the owners of a house located close to the gate. When opening of gate is required, people approach the gateman and he opens the gate, if needed with the permission of the gate committee president or with the agreement of the other members, as in the case of Jainkati.

> *"The gate committee has a gateman but he is not specified. They do not receive any allowance. Any fisherman or farmer can be a gateman."*
>
> *Jabusha sub-project, FGD, 30-03-2012*

4.4 Informal operations and elite capture

If the inclusion of all the stakeholders in the WMOs is supposed to ensure a balanced decision making process, in practice WMOs are not always able to prevent elite capture in operation of the gates. For example, it was commonly found that *gher* owners or local elite dominate the decision over the operation of gates.

"The influential people make the final decision about the closing and opening of the gate. They take the decision as they have the economic power and direct connections with the Union Parishad *chairman. This badly hampers water management. Moreover it is the large land owners who have unlawfully grabbed the khal*[13]*."*

Polder 30, KII, 15-04-2012

Due to elite capture, gate operation often fails to reach an efficient and fair outcome. In Jainkati, the WMCA only controls one of the two gates due to a land dispute involving influential families. In Jabusha, factions within the WMCA have resulted in canals being blocked and used for aquaculture, disrupting irrigation through the main canal.

Officially, WMCAs are supposed to make decisions regarding flushing and draining of water during different farming seasons and within farming seasons. However, the adjoining *gher* owner effectively holds effective control in Latabunia. In Latabunia where approximately 50% of land belongs to outsiders, elite capture over water control is a clear source of conflict. Conflicts occur between outside leaseholders or fish farmers and local paddy farmers, particularly regarding the drainage of water from the *gher* before planting *aman* paddy. In these cases, the theoretical role of conflict resolution that lies at the WMOs level is unlikely to be seen.

The data collected establishes that elite capture is prevalent in most of the polders but this is predominantly in areas where no water management project was implemented and consequently where no WMOs have been formed, such as polder 3. In these polders operations are informally managed and capture by influential elites is the standard. Diverse situations have been observed with different degrees of informal management and capture. For example for some gates in polder 3, a BWDB section officer gives a decision or intervenes on decisions regarding the opening or closing of particular gates. Although the BWDB officer insists on keeping the gate closed in the dry season, it can be opened any time if the interested person bribes the staff or gives tips to the proxy gateman.

"In order to get the gate open, if one pays a bribe to the proxy gateman he opens the gate. A prominent gher owner pays 1000 Taka and the gateman open the gates."

-Polder 3, FGD, 17-02-2012

Thus in polder 3, larger *gher* owners are often the elite and the main decision makers regarding the opening and closing of the gates. In the absence of any formal WMOs informal committees have been formed under the leadership of *gher* owners who require frequent renewal of saline water in their *ghers*.

"We do not have any formal committee. Gher *owners have an informal committee to open and close the gates. It is usually the* gher *owners who decide when and where water is needed. The one who owns more* ghers *is the most powerful, leads the decision and calls the final shot." --Polder 3, FGD, 18-02-2012*

Some of these informal committees hire a gateman for the operation of the gate, who is paid through fishing rights or given cash remuneration. In some villages in polder 3 it was also found that *gher* committees collect contributions from the *gher* owners, sometimes based on the size of their land under operation.

The same phenomenon occurs under informal management when formal WMOs become inactive after project withdrawal. In those cases, informal committees tend to take over operation and benefit from the vacuum of power regarding water control and access. For example, informal *beel* committees decide the opening or closing of gates in polder 30 and in some villages of polder 43-2F; these committees are supported by *gher* owners or large landowners rather than all local stakeholders. Again, the involvement of informal actors means that influential elites dominate decisions related to the operations of the gates. This is apparent from a large number of focus group discussions.

[13] Khals are internal canals, mainly found inside the polders.

4.5 From collective to private operations

Community water management, even when the decisions are subject to elite capture, induce collective decisions over control and access of the resource. Although it has been noted that a large number of decisions related to water access are taken out of the collective sphere and can therefore be considered to be private operations. Indeed, private actors develop their own strategy in terms of water management to fulfil their water requirements. In polder 31 there are about 24 private gates and seven pipes according to the mapping done for this analysis. Respondents indicated that the private gates are operated by neither the gate committees nor by the WMGs; they are privately operated by individual *gher* owners.

Similarly, despite operating within a smaller area, sub-projects also face issues of private operations. There are number of private gates in LGED polders, which are apparently under the control of the landowners. In Latabunia, the embankment is crossed by tens of underground pipes, some temporarily closed with mud and some with more sophisticated closing systems. Individual *gher* owners decide the opening and closing of these pipes without any coordination with their neighbours. This situation makes the WMCA, who is hardly in control of one gate, powerless in preventing salinity intrusion and in draining the area for paddy cultivation. Therefore, private operations are tied up with vested interests and prevent multiple community stakeholders from efficiently controlling their access to water.

4.6 Union Parishads *in operation: substitutes, elite capture and conflict resolution*

As previously stated *Union Parishad* involvement in water management is supposed to be limited to an advisory role. In many places, *Union Parishads* do not even play this role and are absolutely removed from the operation of the gates. However, the data collected also suggests that in the absence of any formal and functional WMO, the *Union Parishad* can also become an important substitute for operating the gates. Thus a number of local gate committees are related to or headed by *Union Parishads*. The *Union Parishad* as an organization is not involved in operating the sluice gates but the *Union Parishad* chairman and the members of the concerned union could be involved. For example, *Union Parishad* representatives can be found in the *beel* committees and some local gate committees are headed by a *Union Parishad* member or by the *Union Parishad* chairman. However, as noted in the below quotation from polder 30, the involvement of *Union Parishads* in water operation does not always result in balanced power.

> *"Most of the committees are no longer functioning. The* Union Parishad *chairman controls the gates and he gives responsibility for opening and closing of the gates to his favorite people."*
>
> *-Polder 30, FGD, 16-03-2012*

Indeed, there is often a clear overlap between influential people and *Union Parishad* members. For example in polder 3, *Union Parishad* members tend to be *gher* owners and are also members of the informal gate committees leading the operation of the gates.

The same can also be true when there are functional WMOs. Even if the *Union Parishad* as an organization is not directly involved in gate operation some elected representatives could be members of the WMOs and can consequently influence the opening and closing of gates. These situations have been identified in polder 30 and Jabusha sub-project.

Finally, in terms of operation *Union Parishads* play a role in conflict resolution. Conflicts relate to paddy versus shrimp farming, to low land versus high land water access or drainage, and to timing depending on the cropping pattern chosen by the farmer and on the maturity of the crop. When these conflicts cannot be resolved locally by mutual agreement between farmers then mediation from the *Union Parishad* is required, which *de facto* involves the local government institution in operation.

4.7 Gaps and overlaps in operation

Institutional arrangements for regarding gate opening and water management decision making vary across and within polders. Indeed, from one gate to another one, the institutional arrangement that leads to a decision and to the physical operation of the gate is never exactly the same. The national policy, and especially the Guidelines for Participatory Water Management (GoB 2001), locates the responsibility for operation at the community level, making it a decentralized decision making process. But in all the locations, whether BWDB polders or LGED sub-projects, the informal, elite actors tend to dominate the operation of the sluice gates. Operation of the gates is vital to the livelihoods of those in the coastal zone. Taking advantage of this fact as well as the missing or unsustainable formal groups and of the vagueness of the policy, several actors have tried to put forward their own water management strategy that services their own interests. In some places this leads to conflicts between different actors, as in the case of Polder 31, Latabunia or Jabusha.

Thus, the multiplicity of actors involved in operation produces overlaps and conflicts. Due to the structure of power in rural Bangladesh, these overlaps and conflicts contribute to the benefit of private interests.

5. Actors in maintenance: deferred and substituted responsibilities

5.1 Breach at the central level: deferred major maintenance

Institutionally, BWDB owns the water-related infrastructure in the polders. In each district BWDB has a special wing called Operation and Maintenance for the polders and an O&M office headed by an executive engineer. However, findings from this fieldwork indicate that BWDB executes repair work only occasionally, when funds are available. These funds are typically only given some disaster takes place or when minor maintenance becomes major and attracts the attention of higher authorities or donors. BWDB engages contractors by tender or Labor Contracting Societies to carry out such maintenance. There is also a general view among community members that BWDB staff are outsiders, lacking both local knowledge and ownership.

> *"The employees of BWDB comes on motorcycles and just take rounds and do nothing. They do not represent us."*
>
> *-Polder 3, FGD, 18/02/2012*

As per the LGED's handover agreement with each WMCA, WMCAs hold responsibility for minor maintenance and repair while major repairs remain a responsibility of LGED. LGED also supports community organizations to design their maintenance plans for maintenance expenditure each year. For example in Jainkathi sub-project, to monitor, supervise and plan maintenance work, LGED staff visit the sub-project twice a year. A post-monsoon assessment of damages is established, which informs cost estimates and yearly budgets. The WMCAs typically inform LGED of their repair needs, raise demands for repairs, lobby if needed, and thus get funding allocated by LGED, usually once a year. However the funds allocated are often less than what is required for maintenance and may take time to reach the community. This is the case, for example, in Latabunia:

> *"LGED does not maintain the gates directly. But if the closing device of the sluice gate is damaged or it is oxidized or the plaster comes off, then LGED gives money to repair. But we have to communicate with them many times to get the work done."*
>
> *-Latabunia, FGD, 27-03-2012*

5.2 Water management groups: deferred minor maintenance

According to the Guidelines for Participatory Water Management, WMGs are responsible for planning, implementing, operating and maintaining local water resource schemes in a sustainable manner. WMGs are tasked with: (i) preventive maintenance of the medium and minor hydraulic structures, bridges, culverts, etc.; (ii) preventive maintenance of the main embankment and secondary embankment; (iii) routine/annual maintenance (desalting) of field channels, drains, etc.; (iv) clearing weeds, obstacles from secondary and tertiary channels, canals drains, etc.; (v) regular greasing of gates; and (vi) annual painting and minor repair of minor gates and replacement of fall board. Even if these repairs are referred to as minor, they are most of the time beyond the capacity of WMOs. To finance minor and regular maintenance the WMOs relies on its own funds. These resources come from either contributions by the community or from some additional sources of income (e.g. interest from micro-credit, leasing of canals). For example, several WMOs started to propose saving accounts and offer micro-credit services to their members in order to generate sustainable maintenance funds. Nevertheless, respondents across the study sites stated that savings and loan services were defunct; default of loans was more frequent than repayment. This has occurred in sub-projects as well as polders.

> *"In Latabunia polder, collection of monthly savings is effectively discontinued. The membership fee is not being generated as there are no new members and the existing members are not buying new shares. The microfinance program was intended to cover the cost of occasional repair and build up the capital of the WMCA. This objective has also not been achieved. The loan disbursed to members before Aila[14] has also not been recovered."*
>
> *-Latabunia, KII, 28-3-2012*

Similarly, where canal leasing has been implemented it has failed in the long run due to conflicts over the choice of tenant, water flow blockages and legal vagueness over who should be the leaser. Jabusha has experienced challenges with canal leasing.

Finally, very few WMOs have been able to maintain regular collection of contribution fees from their members. As such, all WMO sources of funding have dwindled over time.

The financial failure of the WMOs often reflects a more general situation. O&M fund inadequacy has been attributed to a general disinterest in assuming responsibility for maintenance and lack of competency in the case of WMCA management committees (ADB 2008; BIDS 2008). In an external evaluation commissioned by the Asian Development Bank it was found that some O&M sub-committees were inactive and half of the WMCAs had no O&M plan, despite this being a requirement for handover (ADB 2003).

Interestingly, the state of infrastructure in areas where WMOs have managed to obtain some sources of funds is not any better. In Bagachra-Badurgacha, despite considerable funds from canal leasing, additional funds were required from LGED. Similarly in Jainkati, where a fairly good system of contribution collection (based on land size) is in place, one gate is blocked due to property conflict and the canal from the second gate is silted. These situations bring into question the incentives that these WMOs may have for investing in minor maintenance.

In summary, the role of WMGS in minor maintenance is one of solving only the most urgent infrastructure problems and relying on rudimentary and unsustainable repairs. Exceptions occur during emergencies when WMOs uses their own saving fund, and collect special fees and material contributions from the community. They also play an important role in mobilizing people and organizing voluntary work in order to repair the embankments.

At a higher level, WMAs do not play any direct role in maintenance, as they don't have any dedicated funds for doing so. They nevertheless play a role in identifying needs and reporting them to BWDB. They can also be involved in supervising maintenance work. For example in polder 43/2F, through the IPSWAM project, once the funds were allocated to specific works the WMA made a list of Labor Contracting Society groups and members in the concerned area. The work was then allocated to the Labor Contracting Societies and the WMA monitored progress and reported on quality, which determined BWDB payments.

---

[14] Cyclone Aila struck the coast of Bangladesh in May 2009. Numerous villages were completely submerged. Apart from the short-term impact of lost housing and belongins the cyclone has had a long-term effect on households by increasing the salinity levels of both land and water.

5.3 Informal and local level involvement: safety net for essential maintenance

The deferred maintenance that has resulted from central actors as well as community-level formal organizations not fulfilling their roles has resulted in a lack of trust from water users and community members. Many community members believe they must rely on themselves to conduct maintenance activities.

> *"The local people work voluntarily to maintain the embankment. LGED does not work as it used to do earlier. Moreover the WMCA is also not working well, and we cannot complain against them, we have to work by ourselves."*
>
> *-Jabusha, FGD, 30-03-2012*

Communities often report that they have to protect themselves with low-cost repair work done on their own initiative. For example, in Bagachra-Badurgacha sub-project most households own land and it is therefore understood that they have to work voluntarily toward maintenance of the infrastructures in order to protect their land. For example, local farmers build bamboo pilings to prevent damage or to repair damaged parts of the embankments.

The role of individual community member becomes all the more crucial in emergency situations. Whereas formal and centralized levels need time to mobilize resources, the informal community level has more flexibility. Moreover, while households may have difficulties in valuing their interest in contributing to maintenance on a regular basis, emergency situations bring clear and short-term incentives.

Then, similar to operation, the main users and the ones for whom maintenance is essential take over formal organizations to finance maintenance. Thus the *gher* owners are very often involved in maintenance or repair of the gates. In the case of BWDB gates, the landowners and *gher* owners provide financial contributions for repairing or re-excavating the canal when it becomes essential and risks threatening their interests. These influential people can also play a role in mobilizing the material and human resources required for maintenance.

> *"Local people manage the small amount of the cost of repair of the gate. We made a wooden shutter with our own initiative as the door of the gate was damaged. In this a local elite person [...] played a key role in mobilising people."*
>
> *-Latabunia, FGD, 27-03-2012*

5.4 Union Parishads*: the constrained and substitute actor*

Union Parishads play a supporting role in maintaining water infrastructure alongside the informal and local actors. The initial role of *Union Parishads* in maintenance was limited to emergency repairs. As the lowest level of public administration in Bangladesh, they are also the first level of relief. Their role was therefore important after the Sidr and Aila cyclones. Apart from mobilizing financial resources they also mobilized communities and organized the voluntary work. This was particularly important in Latabunia sub-project where the embankment and the village were submerged.

> *"During floods our lives were saved because of the UP Chairman. He did some emergency work at the time of the disaster by organizing the villagers and took initiative in the repair work. Moreover we protected ourselves by collecting money, bricks and sand."*
>
> *-Polder 3, FGD, 18/02/2012*

Facing deferred maintenance in their unions, some *Union Parishad* members have gradually increased their involvement in maintenance in order to respond to the increasing demands of their voters. But *Unions Parishads* face a number of problems that limit their role in polder maintenance. First, as per the legislation, their role is to coordinate and to advise the WMOs; they therefore don't have any resources dedicated to water infrastructure maintenance. In addition, embankments are under the ownership of BWDB, so *Union Parishads* cannot rehabilitate the embankments without BWDB's consent. They similarly have to coordinate with LGED for maintenance work in sub-projects. Despite these financial, technical and institutional capacity constraints, *Union Parishads* execute some repair work and re-excavation. Their involvement in maintenance uses at least two tools. The first is mobilization. The chairman of the *Union Parishad* often mobilizes people to repair embankments, work which is regularly done on a voluntary basis. In addition people donate bamboo, timber and other materials.

> *"Villagers temporarily repaired the embankment in 2011 using bamboo fencing and UP chairman also mobilized people to do this."*
>
> *-Polder* 43/2F, *FGD, 10-04-2012*

Another way of being involved is through dedicating rural employment schemes to water infrastructures.

> *"UP has no fund by which sluice gate or embankments can be repaired but it still it conducts repair work to the road and the embankments by the 40 days programme."*
>
> *-Polder 30, FGD, 16-03-2012*

Indeed, some *Union Parishads* use rural employment schemes such as KABHIKA (Food for Work), KABITA (Cash for work) and 40-days work, funds for which are allocated from the *Upazila Parishad* to maintain roads, repair embankments, and re-excavate canals. This happened for example in polder 3 and in polder 30. *Union Parishads* do so either by sub-contracting NGOs or LGED, or by directly forming Labor Contracting Societies made up of rural and disadvantaged community members.

Despite these examples, financial and institutional constraints mean the role of *Union Parishads* in water infrastructure maintenance remains limited. They are unable to carry out the regular maintenance of all infrastructures that is required to sustain the livelihoods of the coastal areas.

6. Conclusion and recommendations

This analysis has shown that water management in the coastal zone of Bangladesh is much more confused than the procedures and roles defined by the policy may suggest. Indeed, a large number of actors anchored in different political, social, economic or administrative frameworks are involved in decisions and actions related to operation and maintenance. The roles of these actors have been assessed through a top-down scale to point out the level of decentralization and through a formal-informal scale. The multiplicity of actors involved in operation produces overlaps and conflicts; however the structure of power in rural Bangladesh results these overlaps and conflicts benefiting only private interests. On the maintenance side, gaps and deferred maintenance arise from the multiplicity of actors involved. This leads to disrepair and degradation of the infrastructures, which steadily weakens the sustainability of coastal zone livelihoods.

Thus we find that the policy has created confusion regarding the respective roles of each of these actors and does not take into account the social and institutional structure of Bangladesh and existing power relations. Where formal actors miss-fill their role and responsibilities, many informal actors, individuals or groups (gate committees, *gher* committees or *beel* committees) fill the gap. Similarly, while local government institutions have been largely overlooked in the policy, they remain informally involved in water management when required.

These results bring forward a number of recommendations. First, the water management policy must be revised and clarified. This policy has to take into account the particularities of the coastal zone and the existing power relations between central and decentralized actors as well as between formal and informal actors. Rethinking the water management policy may involve redefining the role of each stakeholder in terms of operations and maintenance. By deviating from the common discourse on the inclusion of all the stakeholders, the policy could be able to create a more efficient water management system.

Secondly, analysis from the qualitative data points out a lack of formal coordination between the different actors. A latent and rudimentary form of coordination occurs through conflicts but this type of coordination brings power relations into the game and prevents some actors from being taken into account. All actors involved in operation and maintenance should have access to a democratic platform for discussing and coordinating their actions. This coordination also requires a set of rules and a leader who will ensure that rules are respected. Following the Union Parishad Act of 2009, Union Development Coordination Committees were created at the union level to improve coordination in terms of development in the union. Water management is not clearly included as one of the mandates of these committees, but it should be formally included.

Finally, the role of local government institutions in water management should be formally recognized. The *Union Parishad*, the lowest-tier rural local government, closest to the rural people and elected by them, has a realistic possibility of playing a vital role in water management. *Union Parishad* involvement would ensure long term sustainability of the process and balanced adjudication. Nevertheless, this would only be possible through increasing their control over local resources and over choices regarding resource allocation (Ullah and Pongquan 2010).

Improved water governance and successful operation and maintenance in the polders requires the definition of a new legal framework that is more inclusive of the institutional realities of Bangladesh, improved coordination between all stakeholders and the formal recognition of the essential role played by local government institutions in water management.

Acknowledgements

This article is based on data collected for the project G3: Water Governance and Community-based Management in Coastal Bangladesh , part of the Ganges Basin Development Challenge of the CGIAR Challenge Program on Water and Food and the CGIAR Research Program on Water, Land and Ecosystems (WLE). The authors thank the NGO Shushilan for data collection throughout the southwest coastal zone of Bangladesh and the respondents. Camelia Dewan is also thanked for her work on the qualitative data and especially coding of the transcripts that are used here. We would like to thank Aditi Mukherji for her insightful comments on the earlier versions of this paper.

References

ADB. 2003. *External evaluation: Small-scale water resources development sector project-I. Final Report*. Dhaka: Asian Development Bank.

ADB. 2008. *Operation and maintenance study: Final report*. Incremental Support to TA-7041-BAN: Participatory Small Scale Water Resource Projects. Dhaka: Asian Development Bank.

Araral, E. 2005. Bureaucratic incentives, path dependence and foreign aid: An empirical institutional analysis of irrigation in the Philippines. *Policy Science* 38:131-157.

BIDS, B.I. 2008. *Impact evaluation study: Report of selected 10 sub-projects, SSWRDSP-I*, Benefits Monitoring and Evaluation (BME) Study, GoB, LGED, IWRM. Dhaka: Local Government Engineering Development, Government of Bangladesh.

Chadwick, M. and A. Datta. 2003. *Water Resources Management in Bangladesh: A Policy Review*. Livelihood-Policy Relationships in South Asia. London: Department for International Development.

Chowdhury, A.K.M.J.U. and G. Rasul. 2011. Equity and social justice in water resource governance: The case of Bangladesh. *South Asian Water Studies* 2(2): 44-58.

Cleaver, F. 2001. "Institution, agency and the limitations of participatory approaches to development" In *Participation: The New Tyranny*, by B. Kothari, U. Cooke, 36-55. London: Zed Books.

De Silva, S. 2012. Litterature Review: The experiences of Water Management Organizations in Bangladesh. Dhaka, Bangladesh: CPWF. https://cgspace.cgiar.org/bitstream/handle/10568/35137/Lit%20Reviews_Water%20Management%20Organizations.pdf?sequence=1

Dewan, C. 2012. Literature Review: Review of the Historical Evolution of Policies and Institutions of Community Based Management in Coastal Bangladesh. Dhaka, Bangladesh: CPWF. https://cgspace.cgiar.org/bitstream/handle/10568/35139/Lit%20Review_Historical%20Analysis.pdf?sequence=1

Dewan, C., M.-C. Buisson, and A. Mukherji. 2014. The imposition of participation? The case of participatory water management in Bangladesh. *Water Alternatives* 7(2): 342-366.

Dewan, C., A. Mukherji and M.-C. Buisson. 2015. Historical evolution of participatory water management in coastal Bangladesh: From indigenous temporary earthen embankments before 1960s to depoliticized community based management of Dutch styled polders in 2000s. *Water International*, forthcoming.

Foucault, M. 1975. *Surveiller et Punir. Naissance de la prison*. Paris: Gallimard.

Habibullah, M. 1996. *The Constitution of the People's Republic of Bangladesh*, Government Printing Press, Tejgeon, Dhaka, 10-65.

Islam, R. 2005. Managing diverse land use in coastal Bangladesh: Institutional approaches. Paper Presented at the International Conference on Environment and Livelihoods in Coastal Zones: Managing Agriculture-Fishery-Aquaculture, March 1-3, Bac Lieu, Vietnam.

Islam, M.T., and K. Fujita. 2009. Empowering Rural Administration at the Lowest-level in Bangladesh: A Comparison with India. *Journal of Regional Development Studies* 13, United Nations Center for Regional Development (UNCRD), Japan.

Islam, M.T., and K. Fujita. 2012. Dimension of decentralization process and rural local Government in India: A comparison with Bangladesh. *Kyoto Working Papers on Area Studies* 130:1-26. Kyoto University, Japan.

Lukes, S. 2005. *Power: A radical view* (2nd ed.). Basingstoke: Palgrave Macmillan.

Ministry of Water Resources GoB. 1999. National Water Policy.

Ministry of Water Resources GoB. 2001. Guidelines Participatory Water Management.

Ministry of Water Resources GoB. 2014. Participatory Water Management Rules.

Mujeri, M. K., and L.S. Singh. 1997. Case studies on decentralization: Bangladesh. Working Paper prepared for SDA Technical Consultation on Decentralization (TCD) FAO HQ ROME, CIRDAP Research Division Centre on Integrated Rural Development for Asia and the Pacific.

North, D. C. 1990. *Institutions, institutional change and economic performance*. Cambridge university press.

Quassem, M. A. 2001. Experience with operation of participatory water management: Country paper – Bangladesh. Dhaka.

Ullah, M.A., and S. Pongquam. 2010. Financial resources mobilization performance of rural local government: A case study of three Union Parishad in Bangladesh. *Asian Social Science* 6(11): 95-115.

The imposition of participation? The case of participatory water management in coastal Bangladesh

C. Dewan[1], M.-C. Buisson[2] and A. Mukherji[3]

[1]University of London, England, c_dewan@soas.ac.uk
[2]International Water Management Institute, India, m.buisson@cgiar.org
[3]The International Centre for Integrated Mountain Development, Nepal, amukherji@icimod.org

Abstract

Community-based Natural Resources Management (CBNRM) has been promoted as part of the development discourse on sustainable natural resources management since the mid-1980s. It has influenced recent water policy in Bangladesh through the Guidelines for Participatory Water Management (GPWM) where community-based organizations are to participate in the management of water resources. This paper reviews the extent of success of such participatory water management. It does so by first discussing the changing discourses of participation in Bangladesh's water policy from social mobilization to decentralized CBNRM. Second, Bangladesh is used as a case study to draw attention to how the creation of separate water management organizations has been unable to promote inclusive participation. It argues that the current form of decentralization through a CBNRM framework has not resulted in its stated aims of equitable, efficient, and sustainable management of natural resources; rather it has duplicated existing local government institutions. Finally, it questions the current investments into community-based organizations and recommends maintenance funds should be increased and made permanent through existing funding channels.

Keywords: Community-based natural resources management, participatory water management, local government institutions, Bangladesh

1. Introduction

Community-based Natural Resources Management (CBNRM) is based on a simple and attractive assumption that communities, defined by their distinct and integrated social structure and common interests, can manage their natural resources in an efficient, equitable, and sustainable way (Blaikie, 2006). CBNRM has been promoted by most major International Financial Institutions (IFIs) since the mid-1980s as part of the development discourse on sustainable natural resources management (Blaikie, 2006; Mansuri and Rao, 2003). Decentralization is defined in this paper as any political act in which a central government formally cedes powers to actors and institutions at lower levels in a political-administrative and territorial hierarchy (Ribot et al., 2006). It has been argued that any form of decentralization should increase efficiency, equity, and democracy "by linking the costs and benefits of local public services more closely" (World Bank, 1988: 154). CBNRM involves decentralization of power to community-based organizations where the underlying rationale is that decentralization to communities may increase local ownership, responsiveness to local needs and accountability to local people (Ingham and Kalam, 1992).

Bangladesh has seen significant involvement of major IFIs and donors in promoting CBNRM and decentralized water management in its water policy reforms. The National Water Policy (MoWR, 1999) and the Guidelines for Participatory Water Management (MoWR, 2001), shifted away responsibilities for water management from state implementing agencies to externally initiated community-based Water Management Organizations (WMOs), with limited formal involvement of local government institutions. To date, evaluations of participatory water management projects in Bangladesh's coastal infrastructure (embankments/polders, sluice regulators, canals) limit themselves to analyzing outcomes in light of stated project aims without questioning the theoretical framework of CBNRM (cf. MoWR 2001, 2005; ADB 2007a, 2007b; BIDS, 2008; Fujita, 2011); or how WMOs as parallel structures may undermine or compete with the role of local government institutions (Summers, 2001).

By analyzing the gaps between participation in policy versus participation in practice, this paper seeks to illuminate the weaknesses of decentralisation of water management through CBNRM and its inability to address coastal water challenges, while highlighting how it marginalises local government institutions. The paper first discusses the changing discourses of 'participation' in Bangladesh's water policy. Second, it uses field data from coastal Bangladesh to evaluate CBNRM against its stated aims of efficient, equitable and sustainable water management. Third, it discusses these findings in relation to the role that democratically elected local governments play in water management. It will conclude that maintenance funds should be increased and made permanent through existing funding channels and that the role of local government in water management must be acknowledged.

2. Methodology

This paper draws on large and original qualitative and quantitative data sets. First, information on how donors have been important in shaping water policy were gathered through 28 Key Informant Interviews (KIIs) with government officials, donors, academics and project consultants from participatory water management projects in Bangladesh. They were asked about their experiences of community participation, the role of the various stakeholders and the degree of 'success' of participatory approaches. The interviews were conducted in Dhaka from December 2011 to March 2012.

Second, to understand how local populations from various socio-economic groups and interests perceive water management and the performance of community-based WMOs, 57 semi-structured Focus Group Discussions (FGDs) and 92 KIIs were conducted in the southwest coastal zone. This qualitative work was conducted from January 2012 to September 2012 in five Bangladesh Water Development Board polders: P3 (19,430 hectares [ha]), P31 (14,831 ha), P30 (7209 ha), P24G (25,856 ha), P43-2F (5622 ha), and four Local Government Engineering Department sub-projects: Jainkathi (31 ha), Jabusha-Beel (1211 ha), Bagachra-Badurgacha (385 ha), and Latabunia (168 ha). These nine study areas were purposively selected from three different agro-ecological zones in coastal Bangladesh in order to capture differences in terms of environmental constraints (salinity, waterlogging) and their differing institutional backgrounds for water management (small scale vs. large scale; managed by different government implementing agencies). In each selected area, FGDs were first conducted with a general group of community members and then separately with the executive committees of WMOs and with Labor Contracting Societies consisting of male or female day laborers. KIIs were held with local government officials (male and female, respectively), project field staff, the executive chairs of WMOs, women WMO members, paddy farmers, shrimp farmers, women household heads and the landless (men and women, respectively). Ultimately, eight FGDs were conducted with female only groups and 12 key women informants were interviewed. The resulting 2000 pages of transcripts were then coded and entered into the Atlas Ti qualitative analysis software. Queries were generated on perceptions of participation, ability to influence water management and the state of the infrastructure, and were disaggregated based on the type of respondents.

Third, descriptive statistics from a quantitative survey conducted in a subset of the study areas (P3, P30, P43-2F, Latabunia, Jabusha and Jainkathi) were used in order to illustrate qualitative findings. The survey drew a sample of 1000 representative households from 44 villages randomly selected in the study areas.

3. Water policies in Bangladesh: Participation in theory

3.1 History of water projects: From top-down engineering to small-scale interventions

The current practice of CBNRM in the water sector of Bangladesh is closely tied to a long-standing discourse of people's participation and the perceived top-down mentality of government engineering departments. For example, the BWDB held key responsibility for irrigation, flood control, and drainage in Bangladesh from the 1950s to the late 1990s. It constructed over 100 embankments across the coastal zone in the 1960s to protect coastal communities from flooding, established irrigation systems and employed local gatemen called *khalashis* for the operation of sluice regulators. This initial construction was seen as an infrastructural investment in the hands of engineers, without any participation from, or consultation with, local communities. Nevertheless, the embankments, known as polders, with their canals and sluice gates became fundamental in the struggle against flooding and salinity intrusion while they simultaneously established themselves as a key source of water for agriculture, aquaculture, and other productive activities.

In the 1970s and 1980s, donors focused on projects that moved from top-down mega constructions to small-scale local interventions. Donors such as the Swedish International Development Agency (Sida) and the Embassy of the Kingdom of Netherlands (EKN) introduced and financed participatory projects to be implemented by the Bangladesh Water Development Board. They were to use social mobilization NGOs to organize excluded and marginalized groups to take part in income-generating maintenance work through local groups named 'Target Groups' for the poor and 'Landless Contracting Societies'. This trend continued until the early 1990s and includes the Early Implementation Project (1972-1995), the Land Reclamation Project (1978-1991) and the Delta Development Project (1981-1991) (Dutta, 1997; Duyne, 1997). It was further emphasized that the landless and the poor were to become active in the decision-making processes of water management. The emphasis on social equity and challenging power inequalities through focusing on the poor reflected a wider movement of participation at the time. The 1970s and 1980s saw a proliferation of social mobilization NGOs that promoted women’s empowerment and the strengthening of the rights of the landless. Notable NGOs were *Nijera Kori* ('We do it ourselves') and *Gono Shahajjo Sangstha* (GSS, 'People’s Help/Aid Organization') that effectively encouraged their members to compete in local government elections and/or engage in local politics (Hashemi, 1996; Thörlind, 2000). These examples illustrate the early interest in participation emerging in the 1980s within the NGO community, strongly influenced by Robert Chamber’s (1983) idea of 'putting the last first' to promote a power shift among stakeholders (Williams, 2004).

3.2 Paradigm shift in the 1990s: Participation as maintenance

Swedish and Dutch donors were funding both social empowerment NGOs and participatory water management projects, where the politicized participation in the former affected the discourse of participation in the latter. However, as Mollinga (2008) points out, 'participation' is a central theme in water policy discussions and has obtained several different meanings over time. There are thus divergent views on participation, how it is defined, whom it is expected to involve, what it is expected to achieve and how it is to be brought about (Agarwal, 2001). Over the 1990s and 2000s, a depoliticized concept of participation consolidated in the donor community, who came to prefer service delivery to social mobilization as the latter became too politically contentious (Wood, 1994; Hashemi, 1996; Edwards and Hulme, 1997; Holloway, 1998; Sogge, 2002; Rahman, S., 2006; Dewan, 2009). By the 1990s, participatory discourse rapidly became part of the official aims and objectives of governments and international development agencies (Williams, 2004).

However, the shift away from social mobilization changed the meaning of participation to one that increasingly obscured power inequalities. Depoliticized terms such as 'stakeholder consultation' replaced the use of 'Target Groups' that had explicitly focused on the poor and the use of 'Labor Contracting Societies' removed the focus on the landless from 'Landless Contracting Societies'. The early 1990s saw a growing tension between these competing meanings of participation. On the one hand, civil society and NGOs promoted participation as 'an end in itself', reflecting the legacies of the 1970s and 1980s (Dutta, 1997; Duyne, 1997; Hanchett, 1997). On the other hand, donor-funded projects began to increasingly advocate participation as a means to an end, the end being involving communities for maintenance and upkeep of water infrastructures. In the latter, participation was relegated to public consultation, while it was used as an excuse for transferring responsibilities without delegating actual decision-making power (Hanchett, 1997: 278; Cornwall and Gaventa, 2001). Williams (2004) also suggests that enlisting and demonstrating 'popular participation' became a crucial measure of scheme success and a key condition of donor approval in development projects. Critics argue that policy labeled as 'participatory' or 'community-driven' provides more effective instruments to advance external interests and agendas while further concealing the agency of outsiders, or political manipulations of local elites (Cook and Kothari, 2001; Mosse, 2001). The problem of water management is inherently political and as such attempts to keep politics out of it is futile and even counterproductive. As Mollinga (1998: i) aptly put it: "water management and use are contested at all these levels, that is, that water control needs to be understood as a political process".

Considering the different meanings and uses of 'participation', Arnstein's (1969) ladder of participation (Figure 1) will be used to differentiate between the different levels of politicized and depoliticized participation in which water management organizations operate.

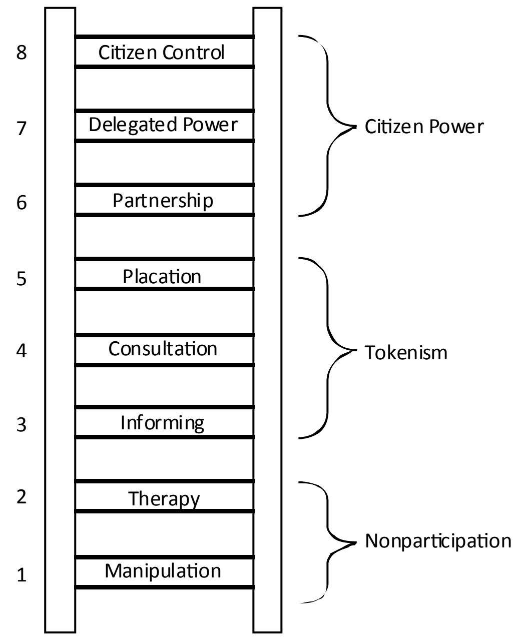


Fig. 1. Arnstein's ladder of participation (source: Arnstein 1969).

The top of the ladder envisages participation similar to that of the empowerment work of social mobilization NGOs of the 1970s and 1980s, where the redistribution of power enables citizens presently excluded from the political and economic processes ('have-nots') to be deliberately included in decision-making. This is directly tied to discussions of citizen power, where Ribot et al. (2006) define citizenship as the right and ability of people to be politically engaged and shape the fate of their polity. As such, high levels of citizen power may therefore also correlate with democratic participation. The lower half of the ladder reflects a depoliticized approach to participation, or 'tokenism', where participation is limited to information, consultation, and placation. In Bangladesh, the depoliticized and 'mainstreamed' version of participation came about in a context of a wider decentralization agenda, where 'community participation' included the devolution of responsibility over O&M from the state to communities, while state agencies such as the BWDB were being simultaneously weakened. For example, in 1992, the World Bank recommended that the Land and Water User Directorate would be closed, ending the unit that provided BWDB with the staff and expertise to interact with local water users and farmers (MoWR, 2005). The BWDB Act of 1998 reduced staff size from 24,000 to 8000, replacing government-employed gate operators with operators who were to be appointed and paid by communities, while many of the staff that had worked with the empowerment projects of the 1980s retired and were not replaced. The National Water Policy of 1999 formally transferred responsibility over O&M to WMOs (MoWR, 1999). Despite a considerable reduction in size and the closure of Land and Water User Directorate, BWDB was now required to engage with communities on matters of water management (MoWR, 2000). As a result, both the BWDB and the Local Government Engineering Department (LGED) have relied heavily on donor funding to implement participatory projects in order to comply with the National Water Policy and the Guidelines for Participatory Water Management (GPWM) (MoWR, 2001).

Despite the National Water Policy's attempt towards decentralization, in the GPWM no formal mention is made of local government institutions beyond that they 'raise awareness' of water management issues and supporting, facilitating and coordinating assistance to the concerned WMOs (MoWR, 2001). It frames a decentralization agenda where the central government transfers powers to private actors, in this case WMOs, rather than democratically elected local institutions (Larson, 2003). As will be discussed later in the article, local governments are nevertheless highly active in water-related issues and coordinate various development projects and social programs in local areas. The creation of water management organizations in order to implement projects may therefore, as Summers (2001) points out, duplicate the functions of local government in a way that detracts funding and legitimacy away from existing democratically elected local institutions. The next section discusses how the GPWM with its depoliticized framework and limited conceptualization of participation is prone to tokenism.

4. Participation in practice: Top-down blue prints

Figure 2 illustrates the key participatory stages of the GPWM that implementing agencies BWDB and LGED must follow when executing new water projects. The GPWM aims to ensure community ownership and involvement in water management, both in planning, decision-making, and financial and physical participation.

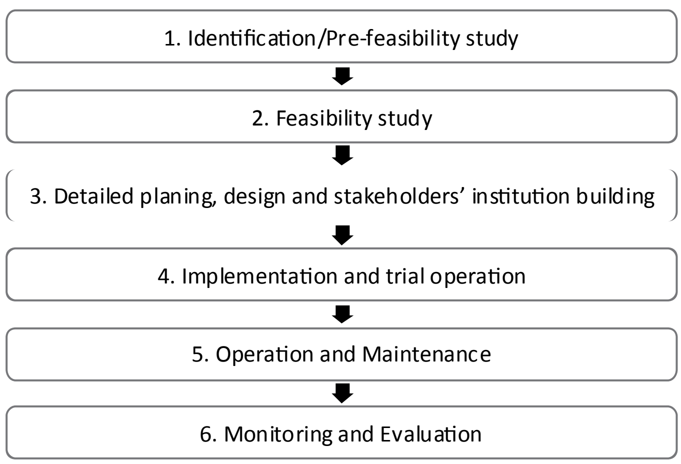


Fig. 2. Guidelines for participatory water management (source: Ministry of Water Resources 2001).

4.1. Lack of efficacy: Top-down and sub-optimal planning of infrastructures

The first three stages in the GPWM (Figure 2) aim to ensure that local stakeholders have ample opportunities to provide feedback and shape water management projects. The GPWM requirement of feasibility studies sought to address the perceived top-down planning associated with BWDB and place the decision-making power in the hands of local stakeholders through the WMO. This component was integrated into the methodologies of LGED's Small-Scale Water Resources Development Sector Project (SSWRDSP) for sub-projects under 1000 hectares and BWDB's Integrated Planning for Sustainable Water Management (IPSWAM) for larger projects.

IPSWAM is seen as one of BWDB's most successful examples of participatory water management and was implemented in nine out of 123 polders.[15] For IPSWAM and other BWDB polder communities a key constraint arose with the requirement of WMOs; they must create community organizations 50 years after the initial construction of polders in order to receive government assistance for maintenance and rehabilitation. BWDB polders struggle with the lack of resources needed to create and sustain the WMOs required for accessing rehabilitation and maintenance funds.[16] G3's fieldwork found that without a project budget to create and support WMOs in the local communities, BWDB field engineers would rarely consult communities on periodic maintenance, e.g. where to excavate canals or repair the embankment.[17] Instead, BWDB tend to use use external contractors rather than hiring local people, a practice seen as removing rural employment opportunities[18].

[15] Two of the five BWDB study areas (P30 and P43-2F) were included in IPSWAM.
[16] FGDs in P3, P31, P30 and P24G from February to August 2012.
[17] KIIs with BWDB Upazila field engineers in Khulna and Satkhira Districts, February to August 2012.
[18] FGDs from P3, P31, P30, P43-2F and P24G, February to September 2012.

The difficulty of incorporating local feedback was also evident in LGED's SSWRDSP sub-projects. The data collected revealed several examples of inadequate technical solutions. These include an unsatisfactory number of regulators, too low or weakly constructed embankments, flawed sluice gate shutters, and superficial canal re-excavation. The inability to incorporate local needs was further respondents in these sub-projects stating that their request for a larger, wider, and more robust embankment had been ignored, resulting in the embankment now being in poor condition.[19] A striking example of poor design can be found in Badurgacha-Bagachra where the gate is operated provisionally using bamboos and rope, a consequence of LGED s disregard of local residents' request for a steel shutter rather than a now-broken wooden shutter. Similarly, respondents in the Jainkathi sub-project stated that they had warned LGED about placing regulators on private land. The result was that the landowner took control over the infrastructure; consequently, only one out of two regulators in Jainkathi is active and the second canal in the sub-project has become silted and unproductive. The emerging picture from LGED sub-projects is that the final decision-making power over physical construction also remains largely in the hands of the implementing agency rather than those of the WMO or community, a finding supported by an evaluation of the LGED project (ADB, 2003). LGED has been able to institutionalize community engagement (local contact at sub-district level, permanent coordinating unit at headquarters). However, even with such institutionalized support, the sub-projects still suffer from flawed technical problems.

The experiences of IPSWAM and SSWRDSP provide a case to question the efficacy of the feasibility studies and formation of WMOs made mandatory by GPWM. Rather than providing a high degree of citizen power, the current arrangement seems to fit on the lower end of Arnstein's ladder, near 'tokenism' through placation, consultation, and informing. The degree of citizen power, i.e. to exert control in decision-making, at this stage seems to be that of participation that is limited to a specific project intervention and then only through the channel of an externally initiated non-functional water management organization. Though the GPWM attempts to involve and empower local communities in implementing agencies, the current guise of participation is perhaps used as a 'tool' to give a 'human face' to depoliticized and technocratic projects (Palmer-Jones et al., 2010). This may reflect a mismatch of incentives between project implementers and stated goals of the projects, where more tangible and measurable goals like physical construction of infrastructure can easily take precedence over longer-term goals like participation and empowerment (Mosse, 2001; Araral, 2005). This type of CBNRM is therefore arguably ineffective in involving local stakeholders in decision-making.

4.2 Lack of equity: WMO obscuring power differences within communities

4.2.1 Elite capture of WMOs

The GPWM stipulates broad involvement of local stakeholders from all cross-sections of society. In all study sites, WMO members had internalized the rhetoric of participation and broad stakeholder involvement where statements such as, "The water management committee is formed with equal emphasis to all classes of people, nobody is excluded from the committee" were common.[20] However, in practice the WMO composition often consisted of teachers, local politicians, and businessmen who in some instances were either not directly involved in using water for productive uses, or could benefit greatly from deciding the distribution of water. These findings are corroborated by other studies that found frequent domination of rural male elites in WMO executive committees in Bangladesh preventing participation of general people (MoP, 2005; Rahman et al., 2007; ADB, 2007a, 2008; BIDS, 2008; Nowreen et al., 2011).

[19] Code: 'Q3. Embankment_condition_poor'. Frequency: 48 total in the four small LGED sub-projects.

[20] FGDs in P31, P30, P43-2F, Latabunia, Bagachra-Badurgacha, Jainkathi and Jabusha, February to June 2012.

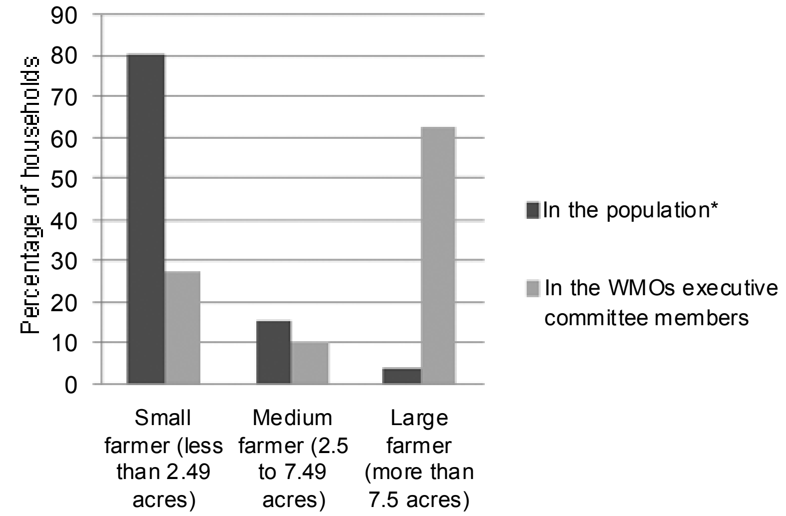


Fig. 3. Elite frequency in executive committee composition (source: CGIAR Challenge Program on Water and Food G3 quantitative survey (IWMI, 2013)).

Note: * From 1000 representative households selected in polders and sub-projects; 1 acre = 0.405 ha.

Figure 3 illustrates how the WMO executive committee does not reflect the composition of the local community. One of the most common perceptions in the qualitative survey was that the ability to participate is defined by power and economic status,[21] where non-elites are excluded from participation in water management.[22] In particular, the majority of poor and women respondents stated that they did not have any information on the activities of the WMOs, WMOs were not seen at platforms where voices of ordinary men and women are heard. This confirms findings from the anthropological literature on CBNRM in general, that though community participation is meant to involve and benefit all sections of the community, they can effectively exclude significant social segments, such as women (Agarwal, 2001; Sultana, 2009), while masking power dynamics and inequality (Kothari, 2001; Mosse, 2001, Bandiaky, 2008).

4.2.2 Quotas and tokenism: Exclusion of women and landless

Coastal water infrastructure projects in the coastal zone of Bangladesh have aimed at flood control and at supporting the most visible productive uses of water, e.g.; irrigation for paddy cultivation and water supply for shrimp farming. This latter focus has often ignored other uses of water, where women use a variety of water sources, such as ponds, rivers, canals for productive (kitchen garden, livestock) and domestic purposes. WMOs are solely in charge of the productive uses of water and rarely consider other water uses that are particularly important for women: drinking water, bathing, sanitation, livestock and homestead garden irrigation (Crow and Sultana, 2002; Faisal and Kabir, 2005; MoWR and EKN 2008; Clement, 2012). For example, Crow and Sultana (2002) in their case study of coastal Bangladesh found that the neglect of the multiple uses of water in polder management can adversely affect women – shrimp farming affects them through loss of ponds and salinization of water. For women, this has increased time to fetch water and find suitable places for bathing, poorer nutrition due to decreased vegetable cultivation and increased reliance on the cash economy for food items such as rice and fish. The expanding use of groundwater for irrigation has caused many hand pumps used for drinking and domestic water to run dry, worsening women's tasks to fetch safe water especially in arsenic-contaminated areas (ibid). A major rationale for women's participation in WMOs is therefore that it can improve the integration of their needs within water management and therefore improve their livelihoods (Clement, 2012).

[21] Atlas Ti code: 'Participation:power_economic_status'. Frequency: 109. Top 3rd code.
[22] Atlas Ti code: 'Participation:exclusion_general'. Frequency: 89. Top 5th code.

Equity is a key aim of CBNRM as communities are perceived as able to manage resources for the common interest. In order to ensure 'women's participation', the guidelines (GPWM) stipulate that one-third of the executive committee members must be women. However, household surveys in the study sites reveal that 80% of executive committee members are male and less than 20% are women. Previous project evaluations have argued that women WMO representatives are often token members with no real power in WMO decision-making processes (ADB, 2003; MoP, 2005). During the data collection for the qualitative survey, it was difficult to locate women WMO members for KIIs in the majority of sites. FGDs revealed that though women are formally included in the WMOs, they are not notified of, or involved in, water management meetings. This appears to be connected to an inherent bias against women's involvement in water management expressed both explicitly, "Women should not be involved in this work [water management]",[23] and implicitly through the formation of WMOs consisting of only male elites who used their spouses to complement the quota requirement of the project. A majority of women respondents emphasized the importance of drinking water and water for food, yet would still state that formal water management and WMOs belonged to the male domain. "No, I am not involved in any water management organization. I am a woman, why will I be involved there"?[24]

The above findings of women being marginalized in the participation process are corroborated with other studies on gender and CBNRM (Cornwall and Gaventas, 2001; Agarwal, 2001; Sultana 2009). Agarwal (2001) argues that participatory institutions can exclude people through 'participatory exclusions' that can individually or interactively constrain a woman's participation in natural resources management. She identifies these exclusionary mechanisms as rules of entry (e.g. only one member for each household in WMOs), social norms of women's behavior and actions (meetings held in public spaces deemed inappropriate for women), social perceptions of women's abilities (unknowledgeable, 'illiterate'), all of which are exclusions expressed by our respondents.

Some exceptions were found in IPSWAM's polders 30 and 22, where gender awareness training of both male and female WMO members was perceived to have increased the confidence in women engaging as active executive committee members in the WMOs (BARD, 2009; EKN and BWDB, 2011). This was further facilitated by long-term empowerment activities taking place during the 1980s Delta Development project implemented by the social mobilization NGO *Nijera Kori*.[25] The women executive committee members in both these polders were vocal and proactive in the WMO and its water management decisions. Nevertheless, in both cases these women were married. In Polder 22 respondents stated that "women without husbands have nothing, no food, no clothes",[26] indicating that the gendered issue in water management is further divided along socio-economic lines. As Agarwal (2001) points out, by having quotas for women, the differences between women in a locality may become obscured, and institutionalize exclusions and privilege where rich or elite women hold the nominal memberships. Women-headed households revealed a sense of exclusion from most institutions due to their marital status as divorcees or widows. In addition, women who are landless, poor and/or of religious minorities often expressed that they lack the social standing to participate in decision-making processes. When asked why they were not members of a WMO frequent replies were: "[w]e are women, poor and Hindu, why would they listen to us? Nobody hears us, nobody cares about us (…). We only go to meetings to provide our signature".[27]

Furthermore, adding women to a project does not necessarily address power issues between men and women, and does not capture that many poor and marginalized men are excluded (Agarwal, 2001). The guidelines (GPWM) recognize the particular vulnerability of those without landholding by requiring at least one landless representative in the WMO executive committees. This recognition is important because, though they do not own the land on which they work, they are also local stakeholders who are affected in various ways by issues of water management. For example, it may inhibit their right to fish for themselves in public canals or reduce or increase their chance of employment depending on whether aquaculture or agriculture is pursued.[28] However,

[23] KII, Shrimp farmer, Tildanga Union, P31, 12 March 2012.
[24] KII, Woman household head, Kaliganj Union, P3, 16 February 2012.
[25] KIIs, Former BWDB consultants to the Delta Development Project, Dhaka, February 2012.
[26] FGD, WMO executive committee in Dumuria Union, P22, 8 December 2011.
[27] FGDs, Women day labourers' earthwork groups (LCS) in P3 and P31, also the most conflicted aquaculture areas.
[28] FGDs with day labourers' earthwork groups (LCS) and KIIs with landless respondents in P3, P31, Bagachra-Badurgacha and Latabunia.

a majority of the WMOs lacked landless representatives in both the general and executive committees and when landless members have been found in these committees, they have always been male, thus ignoring the particular social exclusion of women of the poorest class.

A key weakness of the CBNRM's focus on 'community' is that by viewing the WMO as capable of representing the interests of a homogenous 'community', it ignores the various levels of conflict of interest among rural populations. The mechanism of quotas as they have been implemented thus far generally fails to empower these target groups in the decision-making processes of WMOs.

4.2.3 Rural inequalities and conflict: Operation for competing water uses

The inability of implementing agencies and of the GPWM to address social inequalities and competing interests is further revealed by the conflicts between different water users in the operation of sluice gates that regulate the water entering the polders and the usage of canals that distribute the water inside the polders. With the creation of polders in the 1960s, BWDB employed government-funded gatemen to operate the gates according to set protocols and through local requests. Since 1999, local communities have to fund and operate sluice gates themselves. The study found that sluice gate committees were created regardless of the presence of a WMO, where local operators would be paid through rice or fishing rights in the canal. This was the case even where LGED's WMOs still continued to formally exist ten years after they had first been created. Figure 4 below illustrates the various ways in which operators for different gates may be appointed in the different polders.

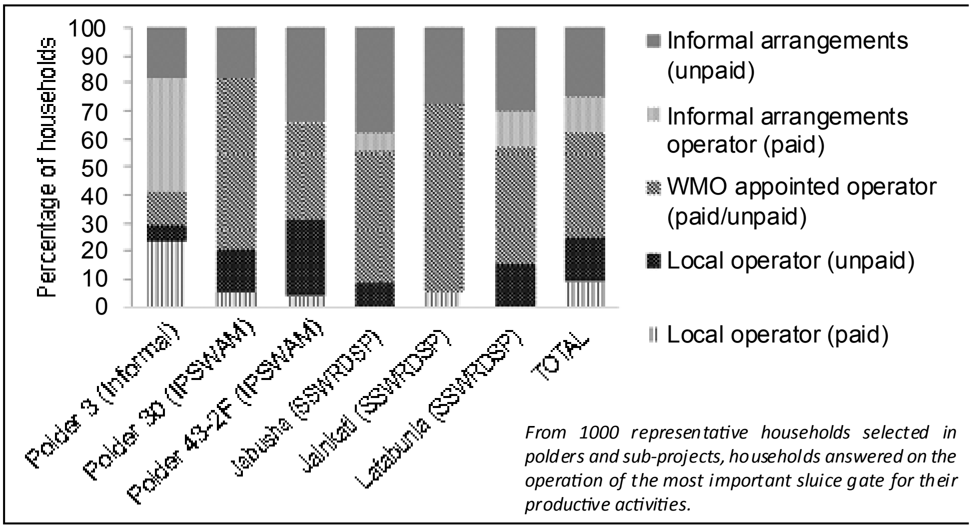


Fig. 4. Distribution of different modes of operation of sluice gates across six case study polders.

Source: G3 quantitative survey (IWMI, 2013).

For all SSWRDSP sub-projects, the WMO is responsible for a limited number of gates in a small area (less than 1000 ha). Figure 4 establishes that only a minority of the gates is operated through the WMOs, with a considerable number of informal arrangements. Through our qualitative study, we found that even in an area as small as Jainkathi, the WMO can only control one of the two gates due to a land dispute. In Latabunia, shrimp farmers have created private gates and pipes that they regulate unilaterally, rendering the WMO powerless. In Jabusha, factions in the WMO have led to leasing and blockage of the canals used for aquaculture, which disrupts irrigation through the main canal. The qualitative survey revealed how water management is affected by a leasing system dominated by influential elites. Due to their autocratic use of canals and their domination over operation of sluice gates, existence of a gate committee becomes redundant. Instead, the canals are drying up, often as a deliberate attempt to increase landholding size.[29] For regular farmers, the slow annihilation of the canals is detrimental as their main source of irrigation is removed. As such, 'canal grabbing' impedes effective, equitable, and sustainable water management.

[29] FGDs and KIIs from BWDB polders P31, P3, P30, 24G and P43-2F and LGED sub-projects Bagachra-Badurgacha, Jabusha, Patuakhali, Jainkathi, February to September 2012.

Some canals are possessed by powerful peoples through corruption. They use these canals as they wish. We cannot excavate, repair canals, or maintain water drainage. These privately possessed canals cannot retain water. So there is no way for us to cultivate our crops.[30]

The informal pipes, gates and incisions to the embankment by aquaculture interests increase the risk of flooding during disasters and reduce agricultural yields by increasing the salinity level of the land. A group of day laborers in Bagachra voiced their feeling of exclusion from any real 'participation'.

If they would listen to our voice, they could stop aquaculture and stop drawing in saltwater. All of the influential people are practicing aquaculture using saltwater. Actually, they get much benefit from this, but we are not getting anything. We are going from poor to poorer.[31]

The problems outlined above are arguably related to the depoliticized view of water management in the CBNRM inspired GPWM. Our respondents did not equate participation with a water management organization. Instead, the qualitative findings suggest that the WMO is an external idea that prompts polder populations to create committees as a condition to receive project funding. Without a working mechanism to ensure that power differences and the needs of marginalized stakeholders are taken into account, CBNRM cannot be truly considered participatory and equitable, rather the use of 'community' in the Bangladeshi context is based on a flawed assumption of shared common interests.

4.3 Lack of sustainability: The panacea of financial cost-sharing

With the debate on 'participation' in the 1990s, there was an increasing focus on 'participation' as a means of local stakeholders financially contributing to O&M. With the GPWM, communities were now encouraged to contribute financially; fully for minor maintenance costs and partially for periodic maintenance defined as canal excavation and embankment repair, while being active in the regular upkeep and maintenance of infrastructure. In addition to transferring the full responsibility of operation of the gates from a state-employed gatekeeper to 'communities', the National Water Policy of 1999, also stipulates that WMOs takes full responsibility for 'minor', or day-to-day, maintenance. Therefore, given the new discourse on participation, its outcomes have to be measured not only in terms of empowerment of communities or their voices in decision-making, but in terms of state of maintenance of infrastructure. Below, we assess to what extent this decentralization to communities has supported maintenance of the coastal water infrastructure.

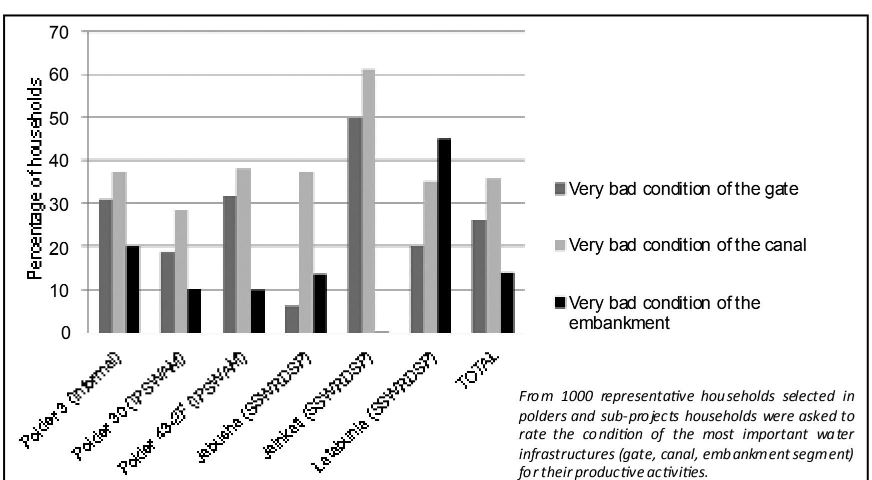


Fig. 5. Households' perception of the quality of water infrastructures across six study polders (source: CGIAR Challenge Program on Water and Food G3 quantitative survey (Buisson et al., 2013)).

[30] FGD General, Khona village, Pankhali Union, P31, 10 March 2012.
[31] FGD, Male earthwork group, East Bagachra, Shobhona Union, Bagachra-Badurgcha sub-project, 24 March 2012.

Figure 5 highlights a poor state of maintenance. Arguably, WMOs have not only performed sub-optimally in terms of processes of community mobilization through elite capture and marginalization of the voices of the poor and the women, but also in their results and outcomes (O&M).

The problems of maintenance are also seen in the LGED's flagship participatory water management projects, the SSWRDSP. LGED's division of labor between units is well defined since major donors have promoted standardization through long and comprehensive technical assistance. A permanent unit has been created within LGED to promote coordination of water management cooperative associations from various phases (there are currently four successive SSWRDSP projects running), while institutionalizing cooperation with several different agencies (BWDB, departments of cooperatives, agricultural extension, and fisheries) (Fujita, 2011). According to our key informants, LGED's success is often attributed to its 'water-plus' approach that combines water management with micro-credit and income-sharing activities, a financial incentive perceived to facilitate the longevity and continuity of their WMOs. In LGED's WMOs, local stakeholders contribute a monthly fee to be a member of the WMO, seen as a means to increase their sense of ownership over the water infrastructure, while providing funds for local micro-credit. The accrued interest will then be used for WMO savings and maintenance funds (LGED, 2012). The 'water-plus' approach proved popular among other donors and was at the time of fieldwork being incorporated into the planning of BWDB's Dutch-funded Blue Gold project.[32] WMOs created by all LGED sub-projects that we studied were still active in one form or another even up to ten years after their creation, while a majority of those created by BWDB in Polders 31 (Fourth Fisheries Project, World Bank) and Polder 24G (Khulna-Jessore Drainage Rehabilitation Project, Asian Development Bank) are conspicuous by their absence.

However, even though LGED-created WMOs are still active, this does not necessarily mean that they have carried out their mandated tasks of O&M. In fact, the amount spent by WMOs on maintenance is less than micro-credit amounts disbursed (LGED, 2009). Rather, respondents across the study sites reported high levels of default of micro-loans. Despite having active WMO cooperatives, the state of the embankment, canals, and gates tended to be poor in the four LGED sub-projects reviewed. When the WMO-financial incentive leads to higher default than repayment without contributing to effective water management, it is unlikely that micro-finance in itself is key to a sustainable WMO and warrants caution for promoting micro-finance as a sustainable practice for CBNRM.

It is equally doubtful that current cost-sharing arrangements are realistic given maintenance demands in the coastal zone. The two most frequently mentioned issues from the qualitative survey was that increased excavation of canals is necessary[33] and that the canals are heavily silted in a way that disrupts their function to retain and distribute water: [34] "The Bhadra River is now the Mora (dead) Bhadra".[35] The high frequencies of both responses were prevalent throughout the study sites and were followed by problems relating to damaged embankments and inactive sluice regulators. In Bagachra-Badurgacha, despite funds from leasing out canals, the WMO funding was insufficient and required additional amounts from LGED that, in turn, found itself requesting funds from the current donor. This is an example of how WMO funding from membership collection was insufficient to pay for half of the periodic maintenance costs. Moreover, GoB itself lacks the funding required for maintenance, as illustrated by Figure 6.

[32] KII, Embassy of the Kingdom of Netherlands to Bangladesh. Dhaka, 28 February 2012.

[33] Atlas Ti code: 'SUG:maintenance_re-excavation of canal'. Frequency: 218.

[34] Atlas Ti code: 'Khal_condition:silted'. Frequency: 163.

[35] FGD, Male earthwork group, Shobhona Union, Bagachra-Badurgacha sub-project, 24 March 2012.

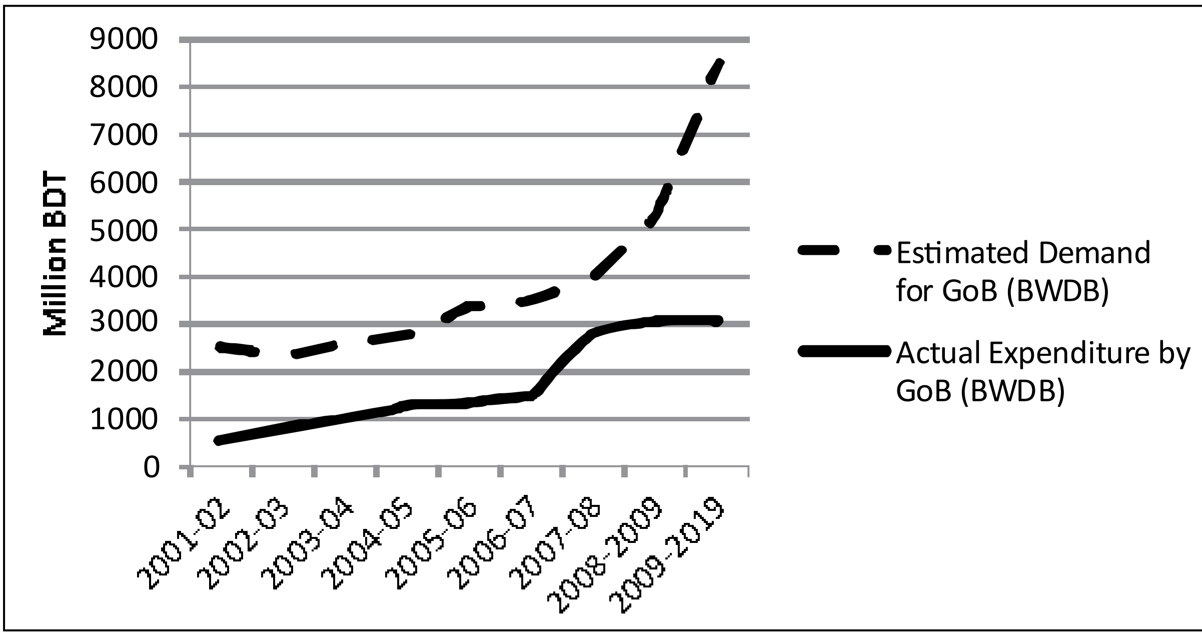


Fig. 6. Funding gap in maintenance (source: Adapted from BWDB data[36]).

LGED suffers from a similar problem, but on a much lower scale, and often fails to finance its part of the cost-sharing arrangements (LGED 2009). This funding gap in maintenance has therefore led to an oversubscription to LGED's Emergency Fund and BWDB's Non-Revenue Development Budget as a financial source for additional maintenance costs. The reality of financial decentralization is that the concept has remained alien to local stakeholders, who state that it is unrealistic for them to contribute half of the required maintenance costs given the problems of continuous and extensive siltation that congests both rivers and canals, while river erosion and cyclones regularly damage and weaken embankments. This regular need for major repairs is costly, time-consuming and beyond the capacity of WMOs and local communities.

A significant weakness of the GPWM is therefore that it does not take into account the considerable hydrological challenges in the coastal zone, the consequent funding deficiency or the means by which WMOs can generate such large funds. Instead, donors tend to attribute blame for deferred maintenance to communities, who they argue are unwilling to contribute financially (ADB, 2007a). In contrast, others have argued that donors are to blame, as they prefer 'visible projects' (Araral, 2005). Instead of providing continuous maintenance support, donors have let maintenance lapse after the project intervention is concluded, effectively resetting the entire rehabilitation process.[37] Arguably, the cost-sharing approach has not been able to ensure the sustainability of community-based water management organizations or their contribution to water management.

In addition, the 'flagship' examples of successful participatory water management projects only take place in a limited number of polders in the coastal zone. These projects also require substantial funding for mobilizing and sustaining WMOs. LGED's SSWRDSP project has seen consistent funding from 1994 to 2017; arguably, the LGED project has never really ended. This makes it difficult to compare it with BWDB polders where project funding has terminated. Most BWDB WMOs tend to collapse within two years of the end of a project intervention. In the case of IPSWAM, WMOs were in limbo from 2011 to 2012, awaiting additional project funding. Furthermore, though IPSWAM is deemed a 'successful' participatory project, most of its polders reviewed are less than 7,000 ha. With difference in size comes difference in size of communities and number of villages that must be mobilized. Many LGED projects span just one village, making community mobilization relatively easier than in most BWDB polders that are above 5000 ha spread across ten or more villages. Furthermore, since the late 1990s BWDB has undergone institutional reforms that have significantly reduced its manpower,

[36] Email correspondence. Planning Wing, Bangladesh Water Development Board. Dhaka, 13 April 2012.
[37] KIIs with project consultants for BWDB's IPSWAM and LGED's SSWRDSP, Dhaka, February 2012 as well as LGED, 2010.

community participation expertise and local field presence. To both create sustainable WMOs in a true participatory process and to be able to respond to the various requests and needs of these communities with over 1.21 million ha of land, BWDB requires a large number of multidisciplinary manpower, which they cannot hire without substantial and long-term external funding. To quote an ex-BWDB official: "[w]e are engineers. We cannot promote community ownership. We cannot manage these things, nor can we hire the people that can. They [donors] just forced community participation on us".

Lack of sustainability is a key reason to question the validity of the current model of WMOs, where examples of successful participatory water management projects are represented by costly processes that are difficult to replicate, a finding which matches those of a global review of participatory water projects (Mukherji et al., 2009). The use of WMOs is particularly unsustainable given their record of being unable to address the acute maintenance challenges facing the coastal zone, making local communities increasingly vulnerable to cyclones and rising sea levels. The CBNRM model in Bangladesh's coastal water management is unsustainable for two key reasons. One is that this form of decentralization does not equip WMOs financially or structurally to deal with an ongoing and accelerating water management crisis. Second, it is a costly and time-consuming process to create and sustain these WMOs, resources that could have been allocated to state and local government institutions to better equip them with the acute issues of periodic maintenance.

5. Filling the gap: The role of existing institutions

Local government institutions (LGIs) are not formally acknowledged in the GPWM, but play an important role in water management. For example, the Union Parishad (UP) arranges for evacuation when alerted to cyclones, while it also organizes immediate repair in the face of embankments breaking during disasters. Similarly, when the WMO system fails to address acute maintenance needs, the Upazila Parishad responds to the requests of its constituents by using rural employment schemes such as KABHIKA (Food for Work), KABITA (Cash for Work) and 40-day Work Order allocated from the to maintain roads, embankments, and canals. It does so through either sub-contracting it to the Union Parishad, NGOs or LGED, who then organize the formation of Labor Contracting Societies consisting of the rural and disadvantaged poor. Such rural employment schemes are popular and a majority of respondents suggested that permanent funding should be made available to these schemes to address siltation and river erosion. However, even in these schemes, there were problems with the canals not being properly excavated and respondents have suggested that there is an independent body that measures the depth of canals before and after an intervention and that it will have the authority to pay the sub-contracting party only after the work has been successfully completed.

In BWDB polders where the WMOs have become inactive after the project has ended, such as in P24G in Jessore, P31 in Dacope and P30 in Khulna, and in areas without formal participatory projects, e.g. in P3 Satkhira, the local governments in the form of UPs are active members of gate committees. They are often the first point of contact for water management issues, "If we face any problem, we inform the Union Parishad",[38] and are part of the decision-making process relating to gate operations and coordination of different requests. Since the UP representatives are democratically and locally elected, this arrangement is seen as generally favorable in managing disputes of operation, though incidences of elite capture have also been mentioned.[39]

In contrast to the lack of confidence in externally initiated WMOs, respondents from various categories voiced that they perceived the UP as locally accessible, accountable and working for the local community. The second most frequently mentioned suggestion in the qualitative survey, after canal excavation, was that the role of UP in water management should increase.[40] The data collected generally depict the UPs as having a unique position as grassroots representatives situated within the local government system. This allows them to further coordinate between various sectors, from drinking water to agriculture, fisheries, infrastructure and health,

[38] Atlas Ti code: 'Union Parishad:perception_First point of contact', Frequency: 82. Top 9th code.

[39] A key exception to this was found in P3, where the UP officials tend to be part of the system of influential elites/shrimp farmers. This is discussed in-depth by De Silva (2012). Similar criticims and allegations of corruption and collusion were voiced in Polder 31's Tildanga Union, Latabunia and Jabusha, where financial interests from the aquaculture industry are meshed with local politics.

[40] Atlas Ti code: 'SUG: increase_role_water_management_UnionParishad'. Frequency: 91. Top 2nd code.

and thus help avoid the replication and duplication that otherwise tend to occur in a 'project' approach. This is in stark contrast to the isolated task of the WMO. Figure 7 below illustrates the gap between participation as seen by the GPWM versus participation as seen by the local Bangladeshi people themselves. In total, more than 70% believed that the Government (BWDB, UP, LGED) should be responsible for water management, with a majority favoring the UP.

Figure 7 illustrates that respondents preferred the UP to act in water management questions (35%) over temporary project entities such as WMOs (2%).

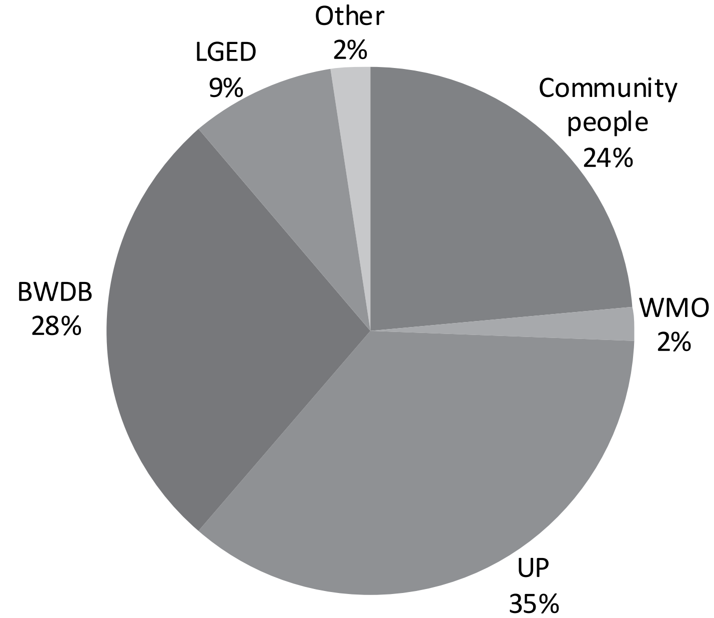


Fig. 7. Perception of the responsibility for water management (source: CGIAR Challenge Program on Water and Food G3 quantitative data (IWMI 2013)). From 1000 representative households selected in polders and sub-projects, households were asked who should act to solve the water-management problems.

Any institution situated in a context of deep inequalities and social strife is prone to elite capture (Bardhan, 2000). Local government institutions such as the UP in Bangladesh and *Gram Panchayat* in India are just as prone to elite capture as WMOs and are as likely to be corrupt and exclude the voices of the poor and the marginalized (Bardhan, 2000; Khan, 2004; Lewis and Hossain, 2008). Increasing the role of local government institutions in water management is not a panacea. They have their own share of problems ranging from several factors that impede their responsiveness and accountability to the people (As-Saber and Rabbi, 2009). This encompasses role confusion and a lack of authority and accountability between local politicians (the UP) and local bureaucrats (at Upazilla/district level) (Toufique and Turton, 2002) to being weak and constrained by the central government through regulations and inadequate local resources (Toufique and Turton, 2002; As-Saber and Rabbi, 2009).

However, there are several points that favor inclusion of UPs in water management.

First, chairmen and members of UPs are already involved in water management and other local development activities, including local employment generating earthwork activities. Second, unlike WMOs, whose funding is restricted through specific donor projects, UPs can access wider arrays of developmental funds from the Upazila level that they can deploy more effectively for water-management-related work.

Finally, Union Parishads are subjected to regular local elections. As elected representative of the people, the local residents demand these services from them and given the nature of electoral politics, UP members feel obliged to meet these demands. Thus, the polls might exert a positive pressure on the UP members in favor of their electorates needs and in favor of accountability. The deficient electoral process of the WMOs and the lack of long-term vision prevent this pressure to work in the case of the community organizations.

While there is considerable change required to strengthen LGIs to become more accountable and effective (As-Saber and Rabbi, 2009), each successful local election means that local governments, their power and authority are validated by the electorate. Strengthening of grassroots democracy through regular elections and inherent competition for votes in a multi-party democracy is likely to lessen chances of elite capture and exclusion (Lewis and Hossain, 2008). Moving beyond the CBNRM model could involve more focus on democratic decentralization of water management through local governments. Though it must be noted that this is not a 'silver bullet', it could, however, contribute towards a democratic decentralization that is (a) *more efficient* as they can coordinate between various departments at the local level while using existing channels for maintenance; (b) *more equitable* as they face re-election and are therefore held accountable to their voters to a greater extent than the WMO executive committees where elections are exclusive to those with economic or social power; (c) *more sustainable* as it would involve a shift away from temporary projects to strengthening existing government channels such as Food/Cash for Work schemes, and in the process give focus on making these institutions more responsive and accountable to their citizens. Yet, despite their merits and performance in water management, local governments are neglected in favor of WMOs. Arguably, one key weakness with the CBNRM model is that it acts as an alternative decentralization working in parallel with existing local government institutions, while simultaneously enabling capture of resources.

6. Conclusion

The GPWM were established to ensure that local people from all segments of society could influence water decisions that affected them, with a particular emphasis on the control of gates and canals. At the same time, it departed from previous discourses of people's participation by focusing on decentralizing responsibility to local stakeholders, rather than mobilizing their degree of decision-making on development outcomes. Furthermore, it imposed participation and CBNRM on the main implementing state agency, the BWDB, while having removed its Land and Water User Directorate and reduced staff who had the expertise to engage and consult with local communities. It was also apolitical in its nature by limiting representation of local stakeholders to externally created community-based water management organizations, thus obfuscating deep inequalities embedded in society. The GPWM model of quotas has resulted in high degrees of tokenism among women and landless representatives, two groups that are rarely involved in decision-making processes. As externally initiated committees, these WMOs tend to lack both transparency and accountability through their artificial elections, and instead become resources for elites. This model is unable to address underlying conflicts tied to socio-economic inequalities, evidenced by the prevalence of illegal salinity intrusion and the misappropriation of public canals. It has therefore proven unsuccessful in ensuring equitable water management.

In addition, the model has proved ineffective, as engineering design remains top-down. Participation is limited to consultation while decision-making power remains in the hands of the implementing agency. The WMO model is also unsustainable, as its unrealistic cost-sharing requirements do not take into account the periodic maintenance challenges posed by siltation, river erosion, canal grabbing and illegal cuts/pipes in the embankment further contributing to deferred maintenance. Rather, millions of dollars are spent on each individual donor-funded project in order to create and sustain WMOs, yet these often collapse within two years. In addition, WMOs are disassociated from the local government structure and established channels for maintenance, and instead rely heavily on temporary project funding. In contrast, the UP is perceived as embedded in the local government institutional structure, with access to rural employment schemes from the Upazila office along with NGOs and LGED. If donors and the Government of Bangladesh were to establish a permanent maintenance funds and allocate it through the Upazila Office, this would arguably be a more sustainable system to address the severe hydrological and socio-economic challenges facing the coastal zone of Bangladesh This, in turn, would lead to support for real and democratic decentralization, rather than for the limited effectiveness of CBNRM in the water sector. Considering the prevalence of inadequate canal excavation independent of sub-contractor, a strengthening of rural employment work schemes should also be accompanied by the establishment of an independent quality assurance body that would approve payment after satisfactory completion of maintenance work.

Acknowledgements

This paper presents findings from G3 'Water Governance and Community-based Management in Coastal Bangladesh ', a part of the Ganges Basin Development Challenge funded by the CGIAR Challenge Program on Water and Food. The authors wish to thank colleagues from the International Water Management Institute, in particular Mark Giordano, Sanjiv De Silva, Floriane Clement, and Ravinder Malik for their feedback and support. They also wish to thank all their G3 project partners, including Shushilan for their qualitative and quantitative data collection throughout the southwest costal zone of Bangladesh. Last, a special thanks to the government officials, donors and project staff who gave access to valuable information on water management in Bangladesh.

The original version of this paper was published in Water Alternatives 7(2) and should be cited as: 'Dewan, C.; Buisson, M.-C. and Mukherji, A. 2014. The imposition of participation? The case of participatory water management in coastal Bangladesh. *Water Alternatives* 7(2): 342-366'.

References

ADB (Asian Development Bank). 2003. External evaluation. Small-scale water resources development sector project. Final Report. Dhaka, Bangladesh: ADB.

ADB. 2007a. Project performance evaluation report. Small scale water resources development sector project (Loan 1381-BAN). Dhaka, Bangladesh: ADB (Operations and Evaluation Department).

ADB. 2007b. Project performance evaluation report, Bangladesh: Khulna Jessore Drainage Rehabilitation Project. Dhaka, Bangladesh: ADB (Operations and Evaluation Department).

ADB. 2008. Operation and maintenance study: Final report. Incremental support to TA-7041-BAN: Participatory small-scale water resources project. Dhaka, Bangladesh: ADB.

Agarwal, B. 2001. Participatory exclusions, community forestry, and gender: An analysis for South Asia and a conceptual framework. *World Development* 29(10): 1623-1648.

Agrawal, A. and Gibson, C.C. 1999. Enchantment and disenchantment: The role of community in natural resource conservation. *World Development* 27(4): 629-649.

Araral, E. 2005. Bureaucratic incentives, path dependence, and foreign aid: An empirical institutional analysis of irrigation in the Philippines. *Policy Sciences* 38(2-3): 131-57.

Arnstein, S.R. 1969. A ladder of citizen participation. *Journal of the American Institute of Planners* 35(4): 216-24.

Arntzen, J.W.; Molokomme, D.L.; Terry, E.M.; Moleele, N.; Tshosa, O. and Mazambani, D. 2003. *Main findings of the review of CBNRM in Botswana.* Occasional Paper No. 14. Gaborone: IUCN/Netherlands Development Organisation (SNV) CBNRM Support Programme.

As-Saber, S. and Rabbi, M. 2009. Democratisation of the Upazila Parishad and its impact on responsiveness and accountability: Myths versus realities. *Journal of Administration and Governance* 4(2): 53-71.

Bandiaky, S. 2008. Gender inequality in Malidino biodiversity community-based reserve, Senegal: Political parties and the village approach. *Conservation & Society* 6(1): 62-73.

BRAC (Bangladesh Rural Advancement Committee). 1983. *The net: Power structure in ten villages*. Dhaka: BRAC.

BARD (Bangladesh Academy of Rural Development). 2009. *Review of the socioeconomic impact assessment report on IPSWAM project in Southern and South-western zones of Bangladesh.* Comilla, Bangladesh: BARD.

Bardhan, P. 2000. Irrigation and cooperation: An empirical analysis of 48 irrigation communities in South India. *Economic Development and Cultural Change* 48(4): 847-866.

BIDS (Bangladesh Institute of Development Studies). 2008. *Impact evaluation study: Report of selected 10 sub-projects, SSWRDSP-I, Benefits monitoring and evaluation (BME) study, GoB, LGED, IWRM.* Dhaka, Bangladesh: Local Government Engineering Development, Government of Bangladesh.

Blaikie, P. 2006. Is small really beautiful? Community-based natural resource management in Malawi and Botswana. *World Development* 34(11): 1942-57.

Boyce, J. 1987. *Agrarian impasse in Bengal: Institutional constraints to technological change*. Oxford: Oxford University Press.

Buisson, M.-C.; Mitra, A. and Kenia, N. 2013. Report from Households and Water Management Organizations Quantitative Surveys. Dhaka, Bangladesh: Challenge Program on Water and Food

Chambers, R. 1983. *Rural development: Putting the last first*. London: Longman.

Chambers, R. 1997. *Whose reality counts? Putting the first last*. London: Intermediate Technology Publications.

Clement, F. 2010. Analysing decentralised natural resource governance: Proposition for a 'politicised' institutional analysis and development framework. *Policy Sciences* 43(2): 129-56.

Clement, F. 2012. *Literature review: Gender and water management organisations in Bangladesh.* Dhaka, Bangladesh: Challenge Program on Water and Food.

Cooke, B. and Kothari, U. 2001. *Participation: The new tyranny?* London and New York: Zed Books.

Cornwall, A. and Gaventa, J. 2001. Bridging the gap: Citizenship, participation and accountability. *PLA Notes* 40(February): 32-5.

Crook, R.C. and Manor, J. 1998. *Democracy and decentralization in South Asia and West Africa: Participation, accountability and performance.* New York, US: Cambridge University Press.

Crow, B. and Sultana, F. 2002. Gender, class and access to water: Three cases in a poor and crowded delta. *Society and Natural Resources* 15(8): 709-724.

Custer, P. 1993. Bangladesh's flood action plan: A critique. *Economic and Political Weekly* July (17-24): 1501-03.

De Silva, S. 2012. *G3 situation analysis report: Polder 3, Satkhira, Bangladesh.* Colombo, Sri Lanka: International Water Management Institute. Mimeo.

Devas, N. and Grant, U. 2003. Local government decision-making citizen participation and local accountability: Some evidence from Kenya and Uganda. *Public Administration and Development* 23: 307-16.

Dewan, C. 2009. Piper calls the tune query: A case study of power-dynamics between Northern donors and Southern recipients in Bangladesh. MA dissertation, University of Edinburgh, Edinburgh, UK.

Dutta, A. 1997. *Planning and management of water resources – Lessons from two decades of early implementation projects, Bangladesh.* Dhaka, Bangladesh: University Press Limited.

Duyne, J. 1997. Local initiatives and national projects in Bangladesh. In Dutta, A.K. (Ed), *Planning and management of water resources – Lessons from two decades of early implementation projects, Bangladesh.* Dhaka, Bangladesh: University Press Limited.

Edwards, M. and Hulme, D. 1997. *Beyond the magic bullet: NGO performance and accountability in the post-cold war world.* West Hartford, Connecticut, US: Kumarian Press.

EKN (Embassy of the Kingdom of Netherlands) and BWDB (Bangladesh Water Development Board). 2011. *Integrated planning for sustainable water management (IPSWAM): Evaluation report.* Dhaka, Bangladesh: EKN and Government of Bangladesh.

Faisal, L.M. and Kabir, M.R. 2005. An analysis of gender-water nexus in rural Bangladesh. *Journal of Developing Societies* 21(2): 175-194.

FAO (Food and Agriculture Organization of the United Nations). 1985. *Report on tidal area study.*: FISHERIES RESOURCES SURVEY SYSTEM, FAO/UNDP-BGD/79/015.

Fariba, A. 2010. *Contested waters, conflicting livelihoods and water regimes in Bangladesh.* Hague, The Netherlands: International Institute of Social Studies.

Fox, W.F. and Menon, B. 2008. *Decentralization in Bangladesh: Decentralization has been elusive*. International Studies Program Working Paper Series 0829. Atlanta, Georgia, US: International Center for Public Policy, Andrew Young School of Policy Studies, Georgia State University.

Fujita, Y. 2011. *What makes the Bangladesh Local Government Engineering Department (LGED) so effective? Complementarity between LGED capacity and donor capacity development support.* Tokyo: JICA Research Institute.

Hanchett, S. 1997. Participation and policy development: The case of the Bangladesh Flood Action Plan. *Development Policy Review* 15(3): 277-95.

Hardin, G. 1968. The tragedy of the commons. *Science* 162(3859): 1243-1248.

Hashemi, S. 1996. NGO accountability in Bangladesh: Beneficiaries, donors and the state. In Hulme, D. and Edwards, M. (Eds), *Beyond the magic bullet: NGO performance and accountability in the post-cold war world,* pp. 123-31. West Hartford, Connecticut, US: Kumarian Press.

Holloway, R. 1998. *Supporting citizens initiatives: Bangladesh s NGOs and society.* London, UK: Intermediate Technology Publication.

Hossain, M. A. 2004. *Administrative decentralization: A framework for discussion and its practices in Bangladesh*. Rajshahi, Bangladesh: University of Rajshahi.

Hulme, D. and Murphree, M. 2001. *African wildlife and livelihoods: The promise and performance of community conservation.* Oxford, UK: James Currey.

Ingham, B. and Kalam, A. 1992. Decentralization and development: Theory and evidence from Bangladesh. *Public Administration and Development* 12(4): 375-85.

IWMI (International Water Management Institute). 2013. Results from G3 quantitative survey. Project report. Colombo: IWMI (Mimeo).

Khan, M. M. 2004. Corruption: Concepts, comparative experiences and Bangladesh case. A paper prepared for Transparency International – Bangladesh Chapter.

http://unpan1.un.org/intradoc/groups/public/documents/APCITY/UNPAN019105.pdf (accessed 13 April 2014)

Kothari, U. 2001. Power, knowledge and social control in participatory development. In Cooke, B. and Kothari, U. 2001. *Participation: The new tyranny?, pp. 148.* London and New York: Zed Books.

Larson, A. 2003. Decentralisation and forest management in Latin America: Towards a working model. *Public Administration and Development* 23(3): 211-226.

Larson, A. 2008. Indigenous peoples, representation and citizenship in Guatemalan forestry. *Conservation and Society* 6(1): 35-48.

Larson, A.M. and Ribot, J.C. 2007. The poverty of forestry policy: Double standards on an uneven playing field. *Sustainability Science* 2(2): 189-204.

Leach, M.; Mearns, R. and Scoones, I. 1999. Environmental entitlements: Dynamics and institutions in community-based natural resource management. *World Development* 27(2): 225-247.

Lewis, D. and Hossain, A. 2008. A tale of three villages: Power, difference and locality in rural Bangladesh. *Journal of South Asian Development* 3(1): 33-51.

LGED (Local Government Engineering Department). 2012. *Inception report: Support to Department of Cooperatives under participatory Small Scale Water Resources Sector Project.* Dhaka, Bangladesh: LGED (Mimeo).

LGED (Local Government Engineering Department). 2009. *Operation and maintenance strategy development for small scale water resources sub-projects: Small scale water resources support strategy and O&M manual.* Dhaka, Bangladesh: LGED and Asian Development Bank.

Mansuri, G. and Rao, V. 2003. *Evaluating community-based and community-driven development: A critical review of the evidence.* Development Research Group. Washington, DC: The World Bank.

Molle, F. 2008. Nirvana concepts, narratives and policy models: Insights from the water sector. *Water Alternatives* 1(1): 131-56.

Mollinga, P. M. 1998. Editorial introduction. In Mollinga, P.M.; Merrey, D.J.; Hvidt, M. and Radwan, L.S. 1998. *Water control in Egypt s canal irrigation: A discussion of institutional issues at different levels, international institute for land reclamation and improvement.* Wageningen, the Netherlands: Wageningen Agricultural University.

Mollinga, P. 2008. Water, politics and development: Framing a political sociology of water resources. *Water Alternatives* 1(1): 7-23.

MoP (Ministry of Planning). 2005. *Evaluation study on small scale water resources development sector project at Upazila and Union level 1996-2002.* Dhaka, Bangladesh: MoP, Government of Bangladesh.

Mosse, D. 1999. Colonial and contemporary ideologies of 'community management': The case of tank irrigation development in South India. *Modern Asian Studies* 33(2): 303-38.

Mosse, D. 2001. 'People's knowledge', participation and patronage: Operations and representations in development. In Cooke, B. and Kothari, U. (Eds), *Participation – The new tyranny?,* pp. 16-35. London: Zed Books.

Mosse, D. 2004. Is good policy unimplementable? Reflections on the ethnography of aid policy and practice. *Development and Change* 35 (4): 639-71.

Mosse, D. 2005. *Cultivating development: An ethnography of aid policy and practice. Anthropology, culture and society.* London, UK: Pluto Press.

MoWR (Ministry of Water Resources). 1999. *National Water Policy*. Dhaka, Bangladesh: MoWR, Government of Bangladesh.

MoWR. 2000. *Bangladesh Water Development Board Act 2000.* Dhaka, Bangladesh: Government of Bangladesh.

MoWR. 2001. *Guidelines for participatory water management.* Dhaka, Bangladesh: Government of Bangladesh.

MoWR. 2005. *Technical report no 2: Report of the institutional analysis study. Integrated Planning for Sustainable Water Management (IPSWAM).* Dhaka, Bangladesh: Government of Bangladesh.

MoWR and EKN (Embassy of the Kingdom of the Netherlands). 2008. *Integrated Planning for Sustainable Water Management (IPSWAM). Gender in IPSAWM.* Dhaka, Bangladesh: Government of Bangladesh.

Mukherji, A.; Fuleki, B.; Shah, T.; Suhardiman, D.; Giordano, M. and Weligamage, P. 2009. *Irrigation reforms in Asia: A review of 108 cases of irrigation management transfer.* Colombo, Sri Lanka: International Water Management Institute.

Nowreen, S.M.; Khan, S.A. and Huq, H. 2011. Development of an operational IWRM framework in a selected small scale water resources development sector project in Bangladesh. *South Asian Water Studies* 2(2): 6-26.

Ostrom, E. 1990. *Governing the commons: The evolution of institutions for collective action.* New York, Cambridge University Press.

Poteete, A. and Ribot, J. 2011. Repertoires of domination: Decentralization as process in Botswana and Senegal. *World Development* 39(3): 439-49.

Palmer-Jones, R.; Arvidson, M and Mandal, S. 2010. *Whatever happened to the water sellers?* Draft paper presented at festschrift for Geoff Wood, University of Bath, 13-14/9/2010.

www.uea.ac.uk/~d280/other/bangladesh/water%20sellers%207%20Sept.pdf (accessed 4 May 2014)

Rahman, A. 1981. *Rural power structure: A study of local leaders in Bangladesh*. Dhaka: Bangladesh Books International.

Rahman, A.; Rahman, T. and Rahman, T. 2007. *The role of organizations in the growth of the rural non-farm sector in Bangladesh: The case of LGED.* University of Manchester Discussion Paper Series No. 11. Manchester, UK: Improving Institutions Pro-Poor Growth (IPPG) Programme Office, Institute for Development Policy and Management, University of Manchester.

Rahman, S. 2006. Development, democracy and the NGO sector: Theory and evidence from Bangladesh. *Journal of Developing Societies* 22(4): 451-73.

Rasul, G. and Chowdhury, A. 2010. Equity and social justice in water resource management in Bangladesh. *Gatekeeper Series International Institute for Environment and Development (IIED)* 146(July): 1-20.

Ribot, J.; Agrawal, A. and Larson, A. M. 2006. Recentralizing while decentralizing: How national governments reappropriate forest resources. *World Development* 34(11): 1864-86.

Ribot, J.; Chhatre, A. and Lankina, T. 2008. Introduction: Institutional choice and recognition in the formation and consolidation of local democracy. *Conservation and Society* 6(1): 1-11.

Shackleton, S. and Campbell, B. 2001. Devolution in natural resources management: Institutional arrangements and shifts – A synthesis of case studies for Southern Africa. Report to USAID SADC NRM Project no. 690-0251.12. 79. Mimeo.

Shackleton, S.; Campbell, B.; Wollenberg, E. and Edmunds, D. 2002. Devolution and community based management: Creating space for local people to participate and benefit? *Natural Resources Perspectives (ODI)* 76: 1-6.

Sogge, D. 2002. *Give and take: What s the matter with foreign aid?* London; New York: Zed Books.

Sultana, F. 2009. Community and participation in water resources management: Gendering and naturing development debates from Bangladesh. *Transactions of the Institute of British Geographers* 34(3): 346-63.

Sultana, P. and Thompson, P. 1997. Effects of flood control and drainage on fisheries in Bangladesh and the design of mitigating measures. *Regulated Rivers: Research and Management* 13(1): 43-55.

Summers, L. 2001. Speech at World Bank Country Director's Retreat – 2001, June 2001.

Thörlind, R. 2000. *Development, decentralization and democracy: Exploring social capital and politicization in the Bengal region.* Copenhagen, Denmark: Nordic Institute of Asian Studies.

Toufique, K.A. and Turton, C. 2002. *Hands not land: How livelihoods are changing in rural Bangladesh.* Dhaka, Bangladesh: Bangladesh Institute of Development Studies.

Wester, P. and Bron, J. (n.d.). *Coping with water: Water management in flood control and drainage systems in Bangladesh*. http://edepot.wur.nl/78392 (accessed 24 April, 2014)

Williams, G. 2004. Evaluating participatory development: Tyranny, power and (re)politicisation. *Third World Quarterly* 25(3): 557-578.

Wittayapak, C. and Vandergeest, P. 2009. *The politics of decentralization: Natural resource management in Asia.* Chiang Mai, China: Mekong Press.

Wood, G.D. 1994. *Bangladesh: Whose ideas, whose interests?* Dhaka, Bangladesh: University Press Limited.

World Bank. 1988. *World development report.* New York, US: Oxford University Press.

Predicting success in community-driven water infrastructure maintenance: Evidence from public goods games in coastal Bangladesh

A. Das[1], M.-C. Buisson[2] and A. Mukherji[3]

[1]Center for Public Affairs and Critical Theory, Shiv Nadar University, India, arijitdas22@gmail.com
[2]International Water Management Institute, India, m.buisson@cgiar.org
[3]International Centre for Integrated Mountain Development, Nepal, amukherji@icimod.org

Abstract

The policy of the Government of Bangladesh requires local communities to organize themselves into Water Management Organizations (WMOs) and contribute to 'minor' maintenance of water infrastructure. For this purpose, WMOs are required to collect contribution from their members. This paper is an in-depth analysis of the conditions under which these contributions are collected from the communities to serve the sustainability of the water infrastructure. This paper uses an experimental game, a public good game, replicating on-the-ground realities of coastal areas of Bangladesh, which was played in 14 different places across coastal Bangladesh to understand group cooperative behavior towards infrastructure maintenance. Here we analyze the determinants of the success or failure of the game regarding group contribution to maintenance and further simulate the results for predicting success under different scenarios. The results highlight the role of institutions in building cooperative behavior toward sustainable management of the infrastructure as well as proportional sharing of the benefits. These results argue for a stronger involvement of local stakeholders at a smaller scale while transferring water management responsibilities to communities, and for strengthening group incentives for community contributions.

Keywords: Experimental games, water management, contribution, simulation

1. Introduction

The entire coastal belt of Bangladesh is one of the most active deltas of the world. Every day millions of ton of silt floats through the Ganges and Brahmaputra rivers to this newly formed land, continuously forming and destroying it. Other features including daily tidal surges and occurrence of seasonal cyclones and floods make for a harsh and uncertain life in the coastal area.

During the 1960s a major geophysical intervention took place in the coastal areas of Bangladesh. The Dutch government along with Bangladesh Water Development Board (BWDB) started building embankments along the riversides. These embankments (called polders) were to serve a dual purpose: first, to protect the coastal communities from daily tidal surges, flooding, and natural calamities, and; second, to increase agricultural productivity in the coastal regions. Over the years polder infrastructure, with its embankments, canals and sluice gates, became a key source of water for multiple uses like irrigation, aquaculture, domestic use and drainage. The embankments also became useful for transportation. For forty years the embankments served their initial purpose and the regular minor maintenance of the water infrastructures was undertaken by central agencies (BWDB). The second round of intervention started in the year 1990, when the Local Government Engineering Department (LGED) built embankments in smaller areas that were earlier left out from the main polders. Developed by a different agency, the LGED sub-projects have a different governing structure than that of the polders.

Under the current water policy, polders of 1000 hectares and more are supervised by BWDB and managed jointly by BWDB and community-led water management organizations (WMOs). WMOs are comprised of all water users in the area. Those of less than 1000 hectares (called sub-projects to distinguish them from polders) are under the jurisdiction of local governments, built by LGED and jointly managed by LGED, WMOs and local governments. Policies regarding operation and maintenance of polders have changed over time (see

Dewan et al. 2014; Dutta 1999). The Government of Bangladesh's current policy framework asks local communities to organize themselves into WMOs and to contribute towards 'minor' maintenance of water infrastructure. This is embodied in the National Water Policy of 1999 (MoWR 1999) and in the Guidelines for Participatory Water Management (MoWR 2001). For this purpose, WMOs are required to create a maintenance fund and collect contribution from their members. Interestingly, not all WMOs maintain such funds; some WMOs keep some funds that are sometimes used for emergencies. Similarly, a series of focus group discussion revealed that some WMOs/Water Management Cooperative Associations are successfully repairing their water infrastructures while others are not.

The purpose of this paper is to understand the factors that may explain variations in success of 'minor' maintenance in water infrastructure in coastal Bangladesh. We use experimental games to understand success in multiple simulated environments. Our participants are drawn from coastal communities – more specifically from BWDB polders and LGED sub-projects. We consequently try to understand how institutional mechanisms are important for water infrastructure management. This study further tries to simulate the results in real life conditions and predict success in simulated conditions. Based on the predictions, our objective is to prescribe policies for 'minor' water infrastructure management in coastal areas.

To answer these research objectives an *arte-factual* public goods game is used as the analytical framework in this study. Most common-pool resource experiments are inspired by the groundbreaking work of Ostrom, Gardener and Walker (1994). A pure public good is characterized by non-excludability and non-rivalness in consumption. The current maintenance problem in the polder areas of Bangladesh replicates similar common pool problems. This paper consequently uses the typical framework of a public goods game, which essentially replicates on-the-ground conditions in coastal areas of Bangladesh. The principal of the WMO maintenance fund is contributions, which are dependent on the agent's choice. No institutional pressure or directive is imposed on the agents to contribute to the common fund. This situation is therefore exactly similar to a public goods game.

2. Literature

Neo-classical literature posits that since these goods are non-rival and non-excludable in consumption, any attempts to elicit a user's willingness to voluntarily pay for such goods will inevitably fail. This is known as a free riding problem. To test this neoclassical free riding problem, experimental work using voluntary contribution mechanism games has been designed to replicate public goods situations. These studies have revealed that a large fraction of experimental cohorts do not play rational Pareto dominated equilibrium (i.e. zero contribution for public goods provisions) (Baland et al. 1996). Indeed, this paradox of rationality has led to a large number of experimental studies in both economics and psychology that have explored this deviation from neo-classical free rider assumptions (Andreoni et al. 1993). Similar deviation from free-riding principle is also observed in real-life examples (Baviskar 1994; North 1990; Ostrom 1992), which in the process avoids occurrence of the 'tragedy of the commons' (Hardin 1968).

Numerous experiments have made significant contributions to studying the behavioral particularities of the human psychology that may affect environmental governance. Fehr et al. (2000) show that costly punishment can deter free-riding and maintain cooperation among agents, but its excessive use lowers the total surplus. Studies also indicate that communication among participants improves cooperation (Janssen et al. 2013; Shah 1996).

Extensive research has been done in the direction of economic valuation and discounting of future benefits and costs with alternative behavioral paradigm (see Kahnemann et al. 1990; Horowitz et al. 2002; and Shogren 2004 for a survey). Another branch of experimental work deals with the study of how incentives and institutions affect decisions and outcomes. Experimentalists have used experimental designs to study how incentives can influence water management systems (Cummings et al. 2003; Ward et al. 2006) and network markets for resource allocation (e.g. energy network markets, Denton et al. 2001). A third group of experimental economists work on the typical problem of externalities or social dilemmas associated with common-pool resources and public goods. Ledyard's survey (1995) of voluntary contribution mechanism games revealed the behavioral and institutional foundations of why would people, despite the clear incentives to free ride, engage in cooperative behavior and refrain from over-exploiting a common-pool resource or contribute voluntarily to the provisioning of a public good. Field experiments in this area include Velez et al. (2008), Cardenas et al. (2000, 2004) and Rodrigues et al. (2008).

Numerous experiments have been conducted to understand not only the contribution to public goods, but also how cooperation can be increased by punishments. Fehr et al. (2000) carried out seminal work in this direction. The work of Fehr et al. (2002) and others shows that costly punishment can deter free riding and maintain cooperation among agents. Though costly punishments are effective, they are seen as socially wasteful, thus their excessive use lowers the total surplus. Communication and informal punishment are both seen to have an impact on augmenting contribution behavior. Pre-play communication between subjects is one such tool for maintaining cooperation. Issac et al. (1988) found that communication fosters cooperation. Ostrom et al. (1992) corroborated this finding in a common pool extraction game. Various types of pre-play communications have been explored in the literature (Isaac and Walker 1988; Bochet et al. 2009). Botchet et al. (2006) found that communication, both face-to-face as well as anonymously through a chat room, allowed subjects to cooperate efficiently.

Important theories consider social preference as a root cause for the pro-social behavior in public goods game. They posit that social preference is a function of social capital. Social capital is seen as a medium to reduce transaction costs of monitoring contracts, and negotiating and enforcing contracts. Dasgupta (2008) argues that trust is the key to cooperation and what scholars meant by social capital is just one of the ways to channel trust. He further argues that social capital means some kind of social network and social network developed on the basis of caste, religion or race. Bouma et al. (2008) use a trust game (an NPD: N-Player Prisoner's Dilemma) experiment combined with a household survey in rural India to explore the linkages between social capital, community characteristics, and the provision of a semi-public good: investment in soil and water conservation maintenance. They find that cooperation in the trust game is positively correlated with community participation in the provision of the public goods and social homogeneity.

It is found from the earlier discussion that game design and socio-cultural backgrounds influence the results of the games. Moreover, institutional setup sometimes shapes players preference of cooperation and contribution or division of wealth. Henrich et al. (2004) compiled a large number of field experiments to argue that people's decisions are not uniform across continents or societies. The outcomes of simple Dictator Games, Ultimatum Games and Public Goods Games vary widely across societies. Travers et al. (2011) find institutional set up to be significant for resource extraction from common property in Cambodia.

Mitra and Gupta (2009) also observed the effects of institution on human decision in the Indian context. They ran a non-computerized, single-period voluntary contribution mechanism game. The subjects are from different social backgrounds. The first group consists of undergraduate students from colleges. The subjects in the second and third groups have a similar socio-economic background and are members of Community Based Organizations (CBO). But the players in the second group belong to the same CBO, while players in the third group are pooled from different CBOs. They found that the members in the second group made the highest contribution to public goods in all the treatments, with an average contribution rate of above 85% of endowment. They argue that weak bonds between the members of different CBOs could be the reason for lower contribution in the third group. According to the authors, the primary cause for lower contribution in the first group could be attributed to the player's urban backgrounds and exposure to western culture, which promotes individualistic behavior. In a different example for Thye et al. (2009), it is observed that subjects coming from collectivist societies behave more pro-socially compared to those who come from individualist societies. These results clearly indicate how being in a specific institutional structure can change human behavior.

Few studies show how information about social donation pattern affects individual contribution. Croson and Shang (2008) used a voluntary contribution mechanism game to explore the effect of social influence on contribution behavior. Frey and Meier (2004) studied the behavior of students from the University of Zurich with respect to contribution to two separate funds. They found that students are willing to contribute more, if others contribute more in accordance to conditional cooperation theory.

Heterogeneity in wealth and preference has shown an ambiguous effect on contribution. Both positive and negative effect of heterogeneity has been registered in the literature. Ostrom (1992) found the importance of homogeneity of social and individual capital for people to craft successful institutions and Oslon (1993) suggested that homogeneity in preference and income may "increase welfare and reduce conflict". Other researchers (Marwell et al. 1988; Heckathorn 1993) described scenarios in which the impact of wealth heterogeneity in preferences and incomes may lead to increased collective action.

Some studies found more cooperative behavior in same-sex groups than in mixed-sex groups (Nowell and Tinkler 1994; Greig et al. 2009). Others obtained the opposite results with women being more cooperative in mixed-sex than in same-sex groups (Sell 1997; Carpenter et al. 2004). Several other studies however provide no evidence of sex or sex composition differences in the voluntary provision of public goods (Sell et al. 1993).

In a nutshell, game design as well as socio-economic background and particularly institutional background (Travers et al. 2011) of the subjects can have a strong impact on the outcome of the experiment. Factors such as ethnic group, gender, and the societal norms that the subjects bring with them can significantly alter their decisions. The game and the subsequent analysis then build on the learning from the literature.

3. Game Design

An *arte-factual* field experiment (hereafter referred to as field experiment) gave us an opportunity to study decisions in the field, in controlled situations, involving subjects who would be difficult to get to a laboratory in an urban setting (see Binswanger 1981 for an early field experiment; Harrison et al. 2004 and and Chakravarty et al.2011 for comprehensive reviews). Contribution dilemma in coastal Bangladesh could be replicated through a public goods game environment. A public goods game creates an environment where players choose to contribute to a common pool. A similar voluntary contribution mechanism is followed in coastal areas of Bangladesh for minor maintenance works. This paper uses a particular variant of a public goods game and calibrated treatments according to the ground conditions.

3.1. Selection of game venues and players

Our public good games were played 18 times in 14 different villages in the coastal zone of Bangladesh. Of these villages, five were located in LGED sub-projects and 9 were located in BWDB polders. In each village, we designated households into different wealth strata: poor, rich and intermediate. Five players were then randomly selected from these three strata. Stratified selection ensured a subject pool of diverse economic backgrounds. The players are users and beneficiaries of the same water infrastructure. This also means that they are people who may have to make decisions together in real life.

3.2. Rules of the game

The game is a public goods game and the design follows Issac et al. (1984), however, changes have been incorporated to satisfy local context and research focus. One control and four treatment sessions are played. The treatment rules are designed to capture three separate effects: publicly available information, unequal endowment, and differences in redistribution of benefits. Each set of rules (or sessions) was played for five rounds of replication. Rules were explained to the players by reading out a written text before the start of every new treatment. Players were instructed not to talk to each other during the rounds.

The first session was the control session. Each player received 20 tokens and had to decide how much to contribute to the common maintenance fund. Contributions were made in secret so that other players did not know who contributed how much, but the total collection in the common fund is declared after every round. The threshold of total contribution to the common fund is fixed at 50 tokens. Total contribution of less than

50 tokens was forfeited, but contributions above 50 tokens were rewarded by an additional contribution of 25 tokens or 75 tokens depending on toss of a coin. This amount represents government contribution and mimics the real life situation when the government tops up community contribution for repair and maintenance work. The common fund so created (minimum 50 tokens, plus either 25 or 75 additional) was then equally re-distributed among the five players. At the end of the round, each player was informed of individual earnings. The earnings of the players were the sum of tokens kept with them plus the gains received from the sharing of the common fund if any. In these five rounds both the individual contribution to the common fund and the individual earnings were kept secret from the other players.

Thus, a player's payoff at the end of each round was:

$$\Pi_i = \frac{E(25|75) + \sum_{j \neq i} x_j + x_i}{5} + (20 - x_i)\ if \sum_{j \neq i} x_j + x_i \geq 50$$

$$\Pi_i = (20 - x_i)\ if \sum_{j \neq i} x_j + x_i < 50$$

The first treatment session was similar to the control session in that every player started with 20 tokens; the only difference was that information on individual contribution to the common fund was made public.

The second treatment remained identical to first treatment, except that the common fund was redistributed in the same proportion as the contributions.

In the third treatment, the initial endowment (or tokens) received by the players became unequal; two players were considered "rich" and received 35 tokens, whereas three "poor" players received 10 tokens each. Poor and rich players were decided by drawing of a lottery at the beginning of each round. The threshold level of success remained the same (50 tokens) and the collective fund was equally divided among the players, irrespective of their contribution to the common fund – akin to Treatment 1.

The fourth treatment incorporated inequalities in endowment (similar to Treatment 3) and redistributed common funds in the same proportion as contribution to the common fund (similar to Treatment 2). Put in real life context, this is somewhat akin to a situation when farmers with more landholding contribute more to maintenance funds and receive more benefits from upkeep of the water infrastructure.

The rounds in which the players were able to reach the threshold of 50 tokens were considered to be successful. However, when players failed to accumulate half of their endowment in the public pool we consider the round a failure. The success or failure of each round will here be considered as our variable of interest.

We also collected demographic, socio-economic and perception related data from each player at the end of the game using a structured questionnaire. In addition, we generated discussion among participants about their behavior at the end and kept notes of those discussions to inform our results qualitatively.

4. Descriptive statistics

Here we describe the average success rate in 25 rounds that are divided into five sessions. We can observe the changes in success due to changes in the rules of the game. Information introduced in Treatment 1 had a negative effect on success and, moreover, success declined over rounds. A sudden jump in success can be seen in Treatment 2, where benefit progressed with contribution. This clearly indicates that incentive has a dominant effect on contribution. Indeed both Treatment 2 and Treatment 4 show exactly the same pattern. The commonality between these two rounds is proportional division of benefits. Irrespective of initial endowment, the success rate rises as the game proceeds during these two rounds, confirming that incentive is a primary driving force both in homogeneous and heterogeneous setups.

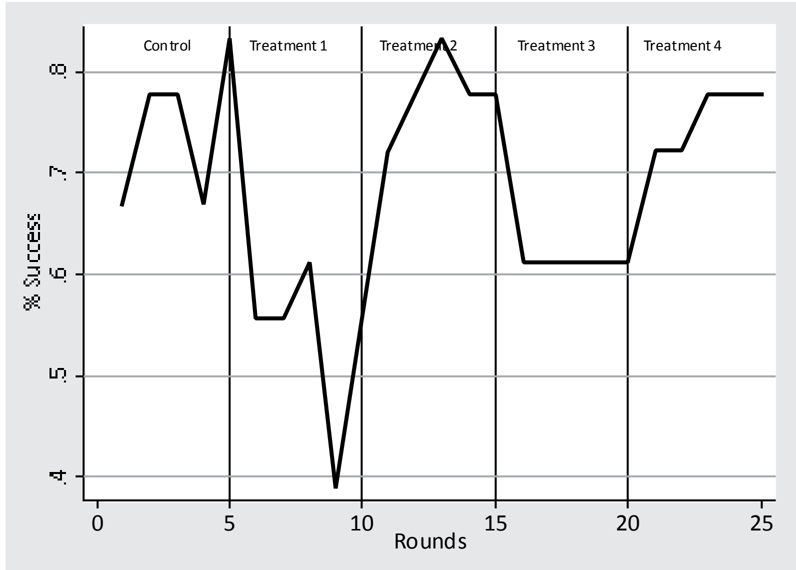


Fig. 1. Percentage of success across the rounds.

5. Econometric modeling

5.1 Empirical model

We derived a simple logistic model to explain the variation in 'success'. Based on the existing findings and literature review we assume that success in each round depends on specific game design as well as external group characteristics. The basic model is as follows:

$$X_{ij} = \alpha + \beta_1 G_i + \beta_2 U_j + \beta_3 L_{ij} + I_j + \epsilon_{ij}$$

Xij is a binary variable with two values 0 and 1 where 0 and 1 indicates failure and success respectively. *i* stands for rounds and *i* = 1, 2, 3, 4……, 25. *j* stands for group and *j* = 1, 2, 3, …,18. G is the vector of game variables and varies over the rounds. Game-specific characteristics like information, unequal endowment and proportional division are included in this category. U stands for the group's characteristics. This vector includes group characteristics like average education level of the group, average age of the group, gender and religious heterogeneity of the group and the number of WMO and other local body members within the group. We also tried to capture the learning that occurred during the gaming process. The learning effects are represented by L in the equation and try to capture how the groups coordinate among themselves through their initial contribution pattern in the common pool. This learning vector also captures how the last two rounds explain the success in the current round. Most importantly we have incorporated a binary variable, *I,* which represents the specific institutional environment in order to capture the effect of institution on cooperation and coordination.

The descriptive statistics of the variables used in the regression are given in Table 1. There is a comfortable level of variation in the variables making them significant to explain variation in success.

Coming back to the regression model, the variation in success is estimated by five distinct models. The first and second models are estimated through logistic regression with and without clustering, respectively. The third and fourth models are akin to model one and two; the only difference is that we dropped the learning variables from the model. Model 5 is more interesting and distinct from the other models. This model is focused on the treatment-specific effect on success, controlling other covariates whereas the other four models looked into effects of information, wealth heterogeneity and unequal sharing on success keeping all other covariates the same. The results are presented in Table 2.

Finally, robustness checks were conducted. Results from a test for specification of the errors in the model highlight that there are no specification errors. We also ran goodness-of-fit tests for all five models and found that model two is the one explaining the highest variation in success. The ROC curve displayed in Appendix 1 confirms that the second model has the maximum explanatory power.

Table 1. Descriptive statistics of the variables

Variable	Definition	Obs.	Mean	Std. Dev.	Min	Max
Success	1 if collected sum ≥50, otherwise 0	450	0.68	0.47	0	1
Institution	1 if location is at LGED area, otherwise 0	450	0.33	0.47	0	1
Information	1 if information about contribution and earning is publicly available	450	0.80	0.40	0	1
Unequal endowment	1 if initial endowment is not equal, 0 if initial endowment is equal (i.e. 20 BDT)	450	0.40	0.49	0	1
Proportional distribution of common pool	1 if division of common pool is proportional to individual contribution, 0 otherwise	450	0.40	0.49	0	1
Average age of the group	Average age of the 5 players	450	39.88	5.59	26	47
Variation in Age	Standard deviation of age of 5 players	450	10	3.48	5	16
Avg. education level of the group	Average education level of the group	450	8	1.97	4	11
Variation in Education	Standard deviation of education level of 5 players	450	2.72	1.28	1	5
Sex homogeneity	1 if all the players are from same sex, 0 otherwise	450	0.33	0.47	0	1
Religion homogeneity	1 if all the players are from same religion, 0 otherwise	450	0.61	0.49	0	1
Occupation	No of players engaged is aquaculture or agriculture	450	4.06	1.08	2	5
Majority WMCA/WMO members	1 if more than 3 players are member of WMCA/WMO, 0 otherwise	450	0.28	0.45	0	1
Majority member of other local bodies	1 if more than 3 players are member of other local bodies, 0 otherwise	450	0.28	0.45	0	1
Avg. contribution in first 5 rounds	Average contribution by the five players in first five rounds	450	11.45	3.38	2.32	16.16
S.D. of contribution in first 5 rounds	Standard deviation of five players of the average contribution in first five rounds	450	3.95	2.22	1.40	8.75
Success in previous round	1 if previous round is a successful round i.e. sum of contribution is ≥50	432	0.68	0.47	0	1
Success in second last previous round	1 if previous two rounds are successful , 0 otherwise	414	0.61	0.49	0	1

5.2 Econometric results

5.2.1 Institutions

We will start explaining variation in success with the covariate 'institution'. This is a characteristic that players bring with them to the game (Dasgupta 2008; Mitra and Gupta 2009). Through this binary variable we capture how exposure to particular governance setup can influence coordination as well as success. Institution is significant in all five models. The coefficient of institution is positive and significant. Taking all variables at their mean, the probability of success is 40%when the game is played at a LGED sub-project, meaning that LGED polder areas have 40% higher probability of success than BWDB polders. The result shows positive and significant influence of institution on success. It is an indication that certain governance structures can help some communities to coordinate more effectively than others. A related policy recommendation could be to improve water governance by replicating the LGED governance module at the community scale in larger polders.

5.2.2 General rule variables

Treatment variables show very consistent results in four models. This study shows that information has a negative and significant effect on success. The coefficients of information dummy are significant and negative in the four models. This result confirms that disclosing contribution amount to other stakeholders of water management could result in backlash. The reason could be mismatch of expected contribution on the part of other players results into lower contribution and coordination in later rounds. This fact is corroborated by declining success in later rounds in the Treatment 1 session in model 5.

Heterogeneity in initial endowment is not significant in all the models. This result indicates that in-built heterogeneity does not have any influence on success (Oliver et al. 1950; Marwell et al. 1988; Heckathorn 1993). In a real life context this means no significant difference is expected in homogeneous villages and heterogeneous villages. Proportional distribution of the common pool has a positive and significant influence on success rate. The coefficients are positive and significant in all the models, which confirms the results obtained by Buisson et al. (2013). On the ground, this result indicates that locals would able to manage 'minor' maintenance more successfully if repair work was linked with water use or canal use.

5.2.3 Group characteristics

We assume that the players carry some inherent characteristics while making decisions. This section describes the effects of such characteristics. Average age of the group as well as variation in the age among the players is not important for achieving success. Education level seems important in achieving success. Average education level of the group is significant for model 2, which was the best fitted model among others, though variation in education level does not have any effect.

The coefficient for sex homogeneity is positive and significant for all models. Hence, gender-wise homogeneous groups are more likely to achieve success than mixed sex groups. This result aligns with other findings where researchers found lower contributions from mixed sex groups.

Social capital also has interesting effects. If social capital is defined as participation in the local community organization then we see a very interesting result. The fact that a majority of players are associated with WMOs does not have any influence on success, but a greater association with other local organizations significantly increases the success rate. This indicates that socialization and social capital does have a significant influence on coordination, even if it is not specifically related to water management.

Interestingly, the occupation variable comes out as negative and significant. As more and more players are associated with agriculture and aquaculture the success rate goes down. This is quite surprising and contrary to the findings of Buisson et al. (2013) who considered individual occupations and obtained a positive effect on contributions for being farmers. In that case, it might be that even if individually the agriculturist or aqua-culturist is contributing more to the 'minor' maintenance fund, when it comes to a group strategy, players practicing agriculture and aquaculture play more strategically, preventing them from reaching the required threshold. Hence, successful water management policy would promote participation of different stakeholders with different interests.

5.2.4 Learning effect

The same group played the game for 25 consecutive rounds. Hence, a lot of learning took place at the player and group levels. This analysis focuses at the group level and we hence concentrate more on group level learning. Controlling such learning is always challenging. In this regression we considered multiple levels of learning: learning from initial contribution behavior, learning from immediate past experiences and learning over time.

On the first case we use average contribution in the first five rounds to determine the cooperative nature of the group. The average of the first five rounds is considered as it is least affected by game design and leaning bias. The coefficient of average contribution is 0.898 and significant, which means that higher contribution in the initial rounds predicts higher probability of success. Interestingly, variation in the contribution is also positively related to success. Success in immediate previous rounds shows significant and positive influence on next round's success. If the group experiences success in one round probability of success increases in the next round. But if the group is experiencing success for two consecutive rounds then that does not have any significant influence over the third round. Finally round learning variable, designed to capture linear round-wise learning, is insignificant. Due to regular changes in the rules of the game, no specific round-wise linear learning happened in this game.

Table 2. Regression results

VARIABLES	(1) Success	(2) Success	(3) Success	(4) Success	(5) Success
Institution	1.169	1.169*	1.603***	1.603*	1.201*
	(1.142)	(0.636)	(0.489)	(0.867)	(0.654)
Information	-2.388***	-2.388***	-1.602***	-1.602***	
	(0.873)	(0.790)	(0.473)	(0.567)	
Unequal endowment	-1.157	-1.157	0.242	0.242	
	(1.363)	(1.220)	(0.301)	(0.299)	
Proportional distribution of common pool	1.516*	1.516*	1.700***	1.700***	
	(0.799)	(0.874)	(0.311)	(0.445)	
Treatment 1					-2.510***
					(0.871)
Treatment 2					-0.528
					(1.322)
Treatment 3					-3.375**
					(1.708)
Treatment 4					-2.291
					(2.496)
Average age of the group	0.038	0.038	-0.007	-0.007	0.044
	(0.129)	(0.099)	(0.067)	(0.133)	(0.099)
Variation in Age	0.168*	0.168	-0.0655	-0.0655	0.166
	(0.0986)	(0.114)	(0.0443)	(0.119)	(0.115)
Avg. education level of the group	1.092	1.092**	0.528	0.528	1.129**
	(0.811)	(0.551)	(0.370)	(0.559)	(0.551)
Variation in Education	-0.0622	-0.062	0.923***	0.923*	-0.044
	(0.679)	(0.644)	(0.337)	(0.533)	(0.647)
Gender homogeneity	2.688**	2.688***	2.250***	2.250*	2.771***
	(1.299)	(0.903)	(0.621)	(1.257)	(0.919)
Religion heterogeneity	-1.077	-1.077	1.737***	1.737	-1.174
	(1.644)	(0.890)	(0.663)	(1.394)	(0.882)
Occupation	-1.442***	-1.442***	-0.968***	-0.968***	-1.460***
	(0.548)	(0.340)	(0.207)	(0.353)	(0.353)
Majority WMCA/WMO members	1.555	1.555***	2.513***	2.513**	0.903***
	(1.022)	(0.577)	(0.492)	(1.015)	(0.153)
Majority member of Other local bodies	6.517***	6.517***	5.919***	5.919***	0.669***
	(1.523)	(1.251)	(0.674)	(1.283)	(0.218)
Avg. contribution in first 5 rounds	0.898***	0.898***			1.593***
	(0.128)	(0.150)			(0.594)
S.D. of contribution in first 5 rounds	0.659**	0.659***			6.552***
	(0.331)	(0.216)			(1.278)
Success in previous round	1.710***	1.710***			1.713***
	(0.625)	(0.430)			(0.445)
Success in second last previous round	-0.046	-0.046			-0.087
	(0.645)	(0.469)			(0.471)
Round learning	0.141	0.141			0.139
	(0.134)	(0.128)			(0.127)
Constant	-21.48*	-21.48**	-4.427	-4.427	-22.04**
	(12.91)	(9.090)	(6.328)	(10.79)	(9.130)
Observations	414	414	450	450	414

Note: Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

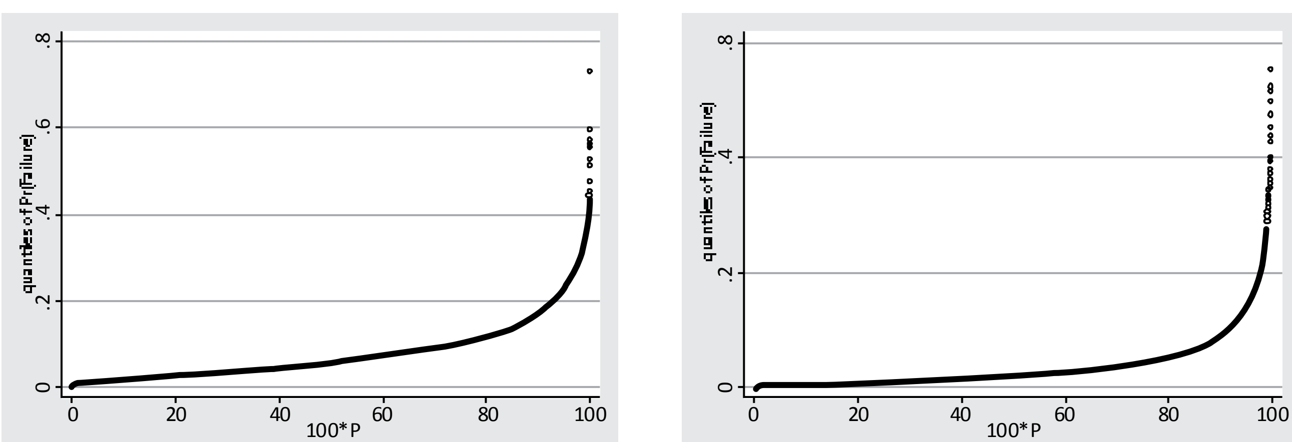
6. Predictions and simulations

This particular section is very important with respect to the focus of this study as well for policy formulation. This section will simulate the best-fitted model (in this case model 2) and replicate real life conditions into the model results to predict probability of success. Such an exercise enables us to simulate probable scenarios that could help policy makers get a hands-on policy prescription.

These simulations are based on different assumptions from which the different scenarios in terms of failure or success for community cooperation toward contributions for water infrastructure maintenance are derived. Specifically, the probability of failure is predicted under different assumptions. The simulations are repeated 10,000 times in order to check the consistency of the coefficients and the robustness of the results.

6.1. Observed effect of institutions

Community water management in coastal Bangladesh is under two types of governance structures: Water Management Groups created and supported by donors and projects in BWDB-led polders and Water Management Cooperative Associations established by LGED programs in sub-projects. Stark differences are visible between these two bodies in their formation, involvement with locals, fundraising activities and outreach (Dewan 2012). Previous regression analysis also indicates that the differences between these two institutional structures has significant effect on the probability of success. The simulation again confirms these results (Figure 2). The figures indicate that in a large number of events LGED water management bodies would have more prolonged success than BWDB polders. The probability of failure is higher under the BWDB institutional framework and increased much faster while progressing over the number of replications than under the LGED assumption. The LGED-type of community level institutions are consequently more likely to support effective community contributions for maintenance and sustained infrastructure.

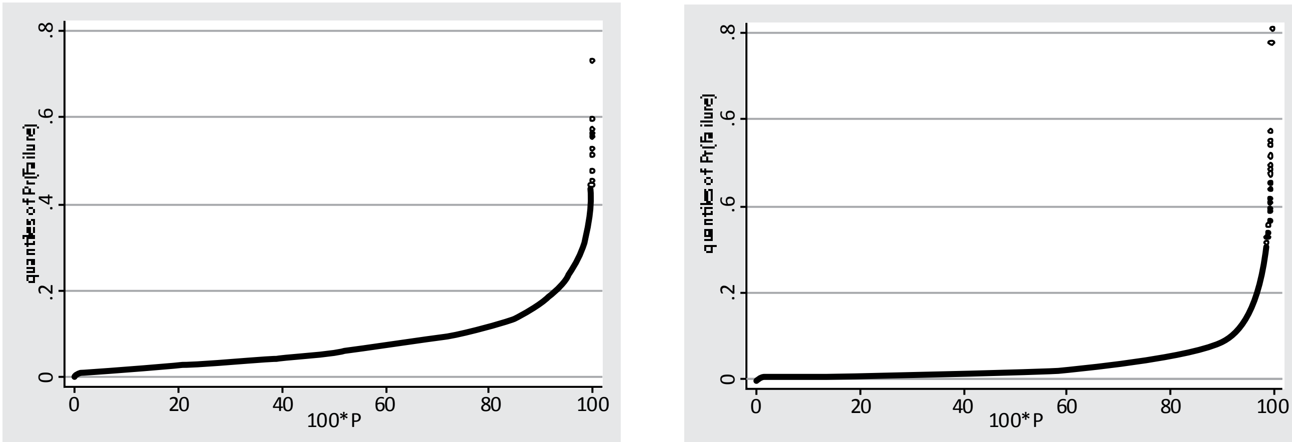


BWDB **LGED**

Fig. 2. Simulation with institutional variation.

6.3 Observe effect of proportional sharing

The second important finding of the regression analysis is the positive and significant impact of proportional distribution of benefits on the probability of group success. We simulated two scenarios: one with proportional sharing of benefits and one with equal sharing of benefits (Figure 3). Figure 3 indicates that the probability of failure is minimal for a large number of replications under the scenario with proportional sharing of benefits. On the contrary, when benefits are equally divided among the stakeholders the probability of failure is much higher and increases more rapidly over the replications. Efforts made by the community members for the maintenance of water infrastructure are consistent with access to benefits. This should be used as a tool to improve contributions from different stakeholders.



Equal sharing of benefits **Proportional sharing of benefits**

Fig. 3. Simulation with equal or proportional sharing rules.

7. Conclusion

Based on an experimental game played with coastal communities, this analysis aimed to understand how such communities can undertake cooperative behavior to keep their water infrastructures, here a public good, well kept and regularly maintained with contributions from community members.

Using regression analysis and simulations we established that in this setting, success in collective action varied across institutions and with the rules of the game. The simulation exercise shows that proportional sharing of benefits is a strong tool for positively influencing the cooperative behavior of a group and for prolonging success. This result is consistent with Buisson et al. (2013), who demonstrated a positive and significant effect of proportional sharing of benefits on individual contributions toward maintenance of water infrastructure. The second most important result relates to institutions; the probability of success and cooperation is higher in communities within LGED projects and where Water Management Cooperative Associations have been created than in BWDB polders where Water Management Groups exist. To understand the scope of this result, the differences between these two institutional settings have to be understood. The first difference is the scale. In LGED sub-projects, water management organizations are organized at a small scale; with less than 1000 hectares in a sub-project, usually only one village is included. In contrast, in BWDB-administered communities, the resources of several villages were commonly considered together. The second difference is more subjective and highlights the participatory processes followed during the creation of these community-led water management organizations (Dewan et al. 2014).

From these results, the policy recommendations that emerge highlight the need to reconcile the contributions from the communities and the benefits they are granted. Due to the deferred maintenance cycle, too often infrastructure is so damaged that even if communities contribute, they will hardly see any benefit. If the Government of Bangladesh and donors were able to cover major maintenance costs as mentioned in the policy, then community members would have an incentive to contribute as they would ultimately be able to enjoy the benefits of the water infrastructure. Secondly, the results in relation to institutions underline the need to mobilize communities at a small scale and to strengthen the ownership they may have over water infrastructure through a long term participatory process rather than through technical rehabilitation works.

Acknowledgements

This article is based on data collected for the project ‘G3: Water Governance and Community-based Management in Coastal Bangladesh’, part of the Ganges Basin Development Challenge of the CGIAR Challenge Program on Water and Food and the CGIAR Research Program on Water, Land and Ecosystems (WLE). The authors wish to thank the players involved in these games as well as Dr. Anannya Dasgupta and anonymous referees for their comments on the manuscript.

References

Andreoni J. and J. H. Miller. 1993. Rational cooperation in the finitely repeated prisoner's dilemma: Experimental evidence. *The Economic Journal* 103**:** 570-585.

Asian Developement Bank. 2008. External Evaluation. Small-Scale Water Resources Development Sector Project – I. Final Report. Asian Development Bank, Dhaka.

Baland J. M.and J. P. Platteau. 1996. *Halting degradation of natural resources: is there a role for rural communities?.* Oxford: FAO and Clarendon Press.

Bangladesh Institute of Development Studies. 2008. Impact Evaluation Study Report, Selected 10 Subprojects, SSWRDSP-I.

Baviskar A. 1994. Fate of the forest: Conservation and tribal rights. *Economic and political weekly* 29(38): 2493-2501.

Binswanger, Hans P. 1981. Attitude Toward Risk, Theoretical Implications of an Experiment in Rural India. *Economic Journal* 91: 867-90.

Bochet, O., T. Page, and L. Putterman. 2006. Communication and punishment in voluntary contribution experiments. *Journal of Economic Behavior & Organization*, *60*(1): 11-26.

Bochet O. and Putterman, L. 2009. Not just babble: Opening the black box of communication in a voluntary contribution experiment. *European Economic Review* 53**:**309-326.

Bouma J., E. Bulte, and D. van Soest, 2008. Trust and cooperation: Social capital and community resource management. *Journal of Environmental Economics and Management* 56**:** 155-166.

Buisson, M-C., Das, A., and Mukherji, A. 2013. What determines contribution to a common fund for upkeep of water infrastructures? Evidence from experimental game in Coastal Bangladesh. Poster. Colombo, Sri Lanka: CPWF.

Cardenas, J. C., and Ostrom, E. 2004. What do people bring into the game? Experiments in the field about cooperation in the commons. *Agricultural System 82*(3): 307-326.

Cardenas, J. C., Stranlund, J., and Willis, C. 2000. Local environmental control and institutional crowding-out. *World Development 28*(10): 1719-1733.

Carpenter J. P., A. G. Daniere, and L. M. Takahashi, 2004. Social capital and trust in South-east Asian cities. *Urban Studies* 41**:**853-874.

Chakravarty, S., D. Friedman, G. Gupta, N. Hatekar, S. Mitra, and S. Sunder. 2011. Experimental economics: a survey. *Economic and Political Weekly* 46(35): 39-78.

Croson, R., and J. Y. Shang. 2008. The impact of downward social information on contribution decisions. *Experimental Economics 11*(3): 221-233.

Cummings, R. G., C. A. Holt, and S. K. Laury. 2004. Using laboratory experiments for policymaking: An example from the Georgia irrigation reduction auction. *Journal of Policy Analysis and Management 23*(2): 341-363.

Dasgupta P. 2005. Economics of Social Capital. *Economic Record* 81**:**S2-S21.

Datta A. K. 1999. *Planning and management of water resources: lessons from two decades of early implementation projects, Bangladesh.* Dhaka: University Press Ltd.

Denton, M. J., S. J. Rassenti, and V. L. Smith. 2001. Spot market mechanism design and competitivity issues in electric power. *Journal of Economic Behavior & Organization 44*(4):435-453.

Dewan, C., M.-C. Buisson, and A. Mukherji. 2014. The imposition of participation? the case of participatory water management in coastal bangladesh. Water Alternative 7(2): 342-366

Dewan, C. 2012. Literature Review: Review of the Historical Evolution of Policies and Institutions of Community Based Management in Coastal Bangladesh. Dhaka, Bangladesh: CPWF.

Fehr, E. and S. Gächter. 2000. Cooperation and punishment in public goods experiments. *The American Economic Review* 90 **:**980-994.

Fehr, E., and S. Gächter. 2002. Altruistic punishment in humans. *Nature 415*(6868): 137-140.

Frey B. S. and S. Meier, 2004. Social comparisons and pro-social behavior: Testing "conditional cooperation" in a field experiment. *The American Economic Review* 94**:**1717-1722.

Greig, F., and I. Bohnet. 2009. Exploring gendered behavior in the field with experiments: Why public goods are provided by women in a Nairobi slum. *Journal of Economic Behavior & Organization* 70(1): 1-9.

Hardin G. 1968. The Tragedy of the Commons. *Science* 162**:**1243-1248.

Harrison, Glenn W. and J. List. 2004. Field Experiments. *Journal of Economic Literature* 42(4) :1009-55.

Heckathorn, D. D. 1993. Collective action and group heterogeneity: voluntary provision versus selective incentives. *American Sociological Review* 58(3): 329-350.

Henrich J., R. Boyd, S. Bowles. 2004. *Foundations of human sociality: Economic experiments and ethnographic evidence from fifteen small-scale societies*. Oxford: Oxford University Press.

Horowitz, J. K., and K. E. McConnell. 2002. A review of WTA/WTP studies. *Journal of Environmental Economics and Management* 44(3): 426-447.

Isaac R. M. and J. M. Walker. 1988. Communication and free riding behavior: The voluntary contribution mechanism. *Economic Inquiry* 26**:** 585-608.

Isaac R. M. and J. M. Walker. 1998. Nash as an organizing principle in the voluntary provision of public goods: Experimental evidence. *Experimental Economics* 1**:** 191-206.

Isaac, R M, J. M. Walker, and S. Thomas. 1984. Divergent Evidence on Free Riding: An Experimental Examination of Possible Explanations. *Public Choice* 43 (1) : 113-49.

Janssen M. A., F. Bousquet, J. C. Cardenas, D. Castillo, and K. Worrapimphong. 2013. Breaking the elected rules in a field experiment on forestry resources. *Ecological Economics* 90:132-139.

Kahneman, D., J. L. Knetsch, and R. H. Thaler. 1990. Experimental tests of the endowment effect and the Coase theorem. *Journal of political Economy 98(6)*: 1325-1348.

Kleemeier E., 2000. The Impact of Participation on Sustainability: An Analysis of the Malawi Rural Piped Scheme Program. *World development* 28**:** 929-944.

Ledyard J. 1995. 'Public goods: a survey of experimental research'. in J. Kagel and A. Roth (eds). The Handbook of Experimental Economics, Princeton, NJ: Princeton University Press: 111-194.

Mahmud M., G. Gupta, P. Maitra, and S. Mitra. 2013. Religious identity, Minority Status and Trust: Evidence from Field Experiment.

Mailath G. J., 1998. Do people play Nash equilibrium? Lessons from evolutionary game theory. *Journal of Economic Literature*, 36**:**1347-1374.

Marwell G., P. E. Oliver, and R. Prahl. 1988. Social networks and collective action: A theory of the critical mass. III. *American Journal of Sociology* 94(3): 502-534.

Ministry of Water Resources G. o. B., 1999. National Water Policy.

Ministry of Water Resources G. o. B., 2001. Guidelines for Participatory Water Management.

Mitra S. and G. Gupta, 2009. The logic of community participation: experimental evidence from West Bengal. *Economic and political weekly*, 44(20): 51-57.

Mosse D., 2006. Collective action, common property, and social capital in South India: An anthropological commentary. *Economic Development and Cultural Change*, 54**:**695-724.

North D. C., 1990. *Institutions, institutional change and economic performance*. Cambridge university press.

Nowell C. and S. Tinkler, 1994. The influence of gender on the provision of a public good. *Journal of Economic Behavior & Organization*, 25**:**25-36.

Olson M., 1993. Dictatorship, democracy, and development. *American Political Science Review* 87(3): 567-576.

Ostrom E., 1990. *Governing the commons: The evolution of institutions for collective action.* Cambridge University Press, Cambridge.

Ostrom E., 1992. Community and the endogenous solution of commons problems. *Journal of Theoretical Politics* 4**:**343-351.

Ostrom E., R. Gardner, J. Walker. 1994. *Rules, Games, and Common-pool Resources*. Ann Arbor: University of Michigan Press.

Rodriguez-Sickert, C., R. A. Guzmán, and J. C. Cárdenas. 2008. Institutions influence preferences: Evidence from a common pool resource experiment. *Journal of Economic Behavior & Organization* 67(1), 215-227.

Sell, J., 1997. Gender, strategies, and contributions to public goods. *Social Psychology Quarterly* 60: 252–265.

Sell, J., Griffith, W.I., and R. K. Wilson. 1993. Are women more cooperative than men in social dilemmas. S*ocial Psychology Quarterly* 56: 211–222.

Shah T. 1996. *Catalysing co-operation: design of self-governing organisations*. New Delhi : Sage Publications.

Shogren, K. A., M. N. Faggella-Luby, S. J. Bae, and M. L. Wehmeyer. 2004. The Effect of Choice-Making as an Intervention for Problem Behavior A Meta-Analysis. *Journal of Positive Behavior Interventions* 6(4), 228-237.

Thye, S. R., and E. J. Lawler. 2009. *Altruism and prosocial behavior in groups*. Emerald Group Publishing.

Travers H., T. Clements, A. Keane, and E. J. Milner-Gulland, 2011. Incentives for cooperation: The effects of institutional controls on common pool resource extraction in Cambodia. E*cological Economics* 71:151-161.

Wade R., 1988. *Village Republics: Economic conditions for collective action in South India. South Asian Studies.* Cambridge: Cambridge University Press.

Ward J., J. G. Tisdel, T. Straton, and T. Capon. 2006. An empirical comparison of behavioural responses from field and laboratory trials to institutions to manage water as a common pool resource. IASCP procedings, Bali, Indonesia.

Velez, M. A., J. J. Murphy, and J. K. Stranlund. 2010. Centralized and decentralized management of local common pool resources in the developing world: experimental evidence from fishing communities in Colombia. *Economic Inquiry 48*(2): 254-265.

Determinants of contract choice in groundwater irrigation markets in Bangaldesh

M. Saidur Rahman[1], M. A. Sattar Mandal[1] and Humnath Bhandari[2]

[1] Dept. of Agricultural Economics, Bangladesh Agricultural University, Bangladesh, saidurbau@yahoo.com, asmandal11@gmail.com
[2] Agricultural Economist, International Rice Research Institute, Bangladesh, h.bhandari@irri.org

Abstract

Boro rice accounts for 57% of Bangladesh's total annual food grain production of 33 million tonnes. It is produced under irrigated condition using mainly groundwater (80%). Many small farmers buy groundwater from neighbours to irrigate their *boro* rice. One-fourth crop sharing has been the dominant payment system for irrigation since the 1970s but in recent years new payment systems for irrigation have emerged. This study aims to analyze factors influencing the choice of a particular payment system in groundwater irrigation markets in Bangladesh. To examine this objective, ninety-six villages were randomly selected from five divisions of Bangladesh and primary data were collected from those villages through focus group discussions. A multinomial probit model was used to determine the factors influencing the choice of a particular payment system in groundwater irrigation. Results show that crop share, fixed charge and two-part tariff are the major payment systems in groundwater irrigation markets in Bangladesh. The probability of choosing these systems was estimated to be 0.58 for fixed charge, 0.25 for crop share, and 0.18 for two-part tariff. Years in irrigated farming, interest rate of loans, access to electricity, drought, and lowland endowment are the factors that strongly influence the choice of crop share payment scheme. The same factors also significantly affect the choice of fixed charge payment. Drought problems and lowland endowment are the factors that significantly affect the choice of two-part tariff payment scheme. This study concludes that two-part tariff and fixed charge cash payment methods are more preferred by the water buyers than the traditional crop share scheme. The newly emerging two-part tariff system should be promoted among irrigator farmers since it is economically beneficial to both buyers and sellers of water and it encourages saving irrigation water in rice farming.

Key message: Crop share, fixed cash charge and two-part tariffs are the major payment systems in groundwater irrigation water markets in Bangladesh. The payment systems are shifting from traditional crop share to fixed cash charge and two-part tariff. Policies should promote a two-part tariff payment system to increase economic gains and to save irrigation water in rice farming.

Keywords: Crop share, cash payment, two-part tariff, groundwater irrigation, water markets, multinomial probit

1. Introduction

Groundwater irrigation technologies, mainly shallow tubewells (STWs) and deep tubewells (DTWs), play a crucial role in accelerating food grain production (mainly rice and wheat) in Bangladesh. In the 1980s and the 1990s groundwater irrigation increased rapidly, leading to a rapid expansion of paddy cultivation in the dry season, known as the *boro* paddy. In 2010/2011, groundwater irrigation accounted for 80 percent of the total irrigated area. In the same year, 1.55 million STWs accounted for 67 percent of groundwater irrigated area and about 66 percent of total area irrigated in the dry season (BBS 2010; BER 2010).

The markets for groundwater irrigation technologies have been largely liberalized and privatized since the early = 1980s. With the expansion of STW irrigation, a relatively competitive market for irrigation water has evolved. The main characteristic of the market is that the STW owner irrigates his/her own land and partners' land[41] and sells excess water to irrigate the plots of their neighboring farmers, not only for their neighbor's interest but

[41] Ownership of a STW may have more than one person i.e. a group of farmers from same family kinship may buy a STW to irrigate their land together. They are treated as partner of that STW.

also for their own benefit. Payment for irrigation water is made in cash per unit of land, one-fourth crop-share or different modes of rental arrangements. As the irrigation water market matures with an increased number of pumps, different pump owners are attempting different strategies for running their water selling business profitably. For example, it has been observed that some farmers jointly own STW enterprises and collectively raise capital for the purchase and operation of irrigation equipment (Mandal 1993). The number of irrigation technologies has increased significantly in the past three decades in Bangladesh (Gill 1983; Mandal 1993; BBS 2009; BER 2009; Ali 2010; DAE 2011; Rahman et al. 2011; Majumder et al. 2011). At the initial stage of groundwater irrigation development when the number of tubewells were few, the seller had a monopoly to sell water to the buyer. The payment system and the water rate proposed by the seller were executed directly. The seller's preference was stronger than that of the buyer in determining the irrigation contract. As the number of irrigation technologies—particularly STWs—increased exponentially over the years, the ability of buyers to select payment systems for irrigation water has become stronger. It has also been observed that some tubewell owners are entering this market only for selling water as a business (Rahman et al. 2011). They mostly agree with the preferences of the users.

Past studies and field observations show three types of payment systems in groundwater irrigation markets in Bangladesh: crop share, fixed charge payment and two-part tariff (Majumder and Rahaman 2011; Rahaman et al. 2011). In the crop share contract, the water seller provides the required amount of irrigation water for rice production and receives one-fourth of the crop output in return. Higher risk in crop production causes water buyers to prefer a crop share contract (Kajisa and Sakurai 2005). In this system the water buyer gets as much water as required without extra payment and s/he has less incentive to invest in production because part of the production goes to the water seller. This contract system discourages saving irrigation water and leads to economic loss due to sub-optimal production. In a fixed charge payment, the water seller provides required irrigation water for rice production and receives a fixed amount of cash or non-cash commodity. This system also discourages saving irrigation water but it improves economic gain because the water buyer does not share his/her output with water seller and hence s/he is likely to invest maximum resources to attain maximum production. In the two-part tariff system, the seller only provides the machine, which is paid for either in cash or in kind. The buyer then buys the fuel himself. This system encourages saving irrigation water because the farmer/buyer will minimize the use of fuel and it also improves economic gain as all output is kept by the buyer.

Thus, the use of different contract payment systems in water markets has implications for water saving and production efficiency. It is therefore important to understand the dynamics of contract choice in irrigation water markets. The identification of determinants of contract choice will help in understanding more about the irrigation water markets and develop strategies to popularize appropriate contract systems that benefit buyers, sellers, and society as a whole. Studies on the dynamics of contract choice in groundwater irrigation markets in Bangladesh are limited. This study aims to bridge this knowledge gap. The main objective of this paper is to document the major payment systems and determine factors influencing the choice of a particular payment system in irrigation water markets in Bangladesh. Shallow tubewell irrigation is not common in the coastal zone of Bangladesh but the payment systems for irrigation and its determining factors are similar and important for coastal zone irrigation as well.

2. Methods

2.1 Data

This study uses village-level primary data collected from boro rice farmers located across 96 villages in Bangladesh. The unit of analysis is a boro rice farming village. The sample village consists of both water buyer and water seller. Ninety six villages were selected from five divisions— i.e. Rajshahi, Rangpur, Dhaka, Khulna, and Chittagong— of Bangladesh following a multi-stage stratified random sampling technique. Boro rice production, use of groundwater irrigation and prevalence of water markets were the main basis for designing the sampling framework and selecting study sites. Data were collected from 96 villages using Focus Group Discussions (FGD). The village-level data were derived based on group consensus and the data represent the average situation of the sample villages. The data collected from 48 upazillas of 31 districts of Bangladesh broadly represent the whole country (Figure 1). A computer assisted personal interview (CAPI) method and Surveybe software was used to collect the data. The collected data include biophysical and socioeconomic characteristics of the village, boro rice yield and details of irrigation water use and the payment system. The survey was conducted from April to September 2013 and the data were collected for the crop year 2013.

Fig. 1. Map of the locations of the 96 sample villages with GPS coordinates (prepared by GIS lab, IRRI).

2.2 Multinomial Probit Model Specification

A discrete choice model is used when a decision maker is confronted with choosing among a set of alternatives (Train 2007). To fit within a discrete choice framework, the set of alternatives – the choice set – needs to exhibit three characteristics: (a) alternatives need to be mutually exclusive, (b) alternatives must be exhaustive, and (c) the number of alternatives must be finite. Binomial logit or probit discrete choice model is used when the choice set consists of two alternatives. Multinomial logit or probit model is used when the choice set consists of more than two alternatives. In our case, the decision maker (the water buyer) is confronted with the choice of three alternative payment methods (crop share, fixed charge and two-part tariff) for irrigation. Therefore, multinomial logit (MNL) or multinomial probit (MNP) model is appropriate in our case[42]. The MNL or MNP models differ slightly in terms of distributional characteristics but both models give similar parameter estimates. Both MNL or MNP models assume Independence of Irrelevant Alternatives (IIA) and errors are uncorrelated, i.e. cov(ε_j, ε_i)=0. This basically means choice probabilities in the models are estimated using a technique involving random draws and Monte Carlo estimation. The MNP model estimation with the "asmprobit" command in Stata software uses the simulated Maximum Likelihood technique known as the Geweke-Hajivassiliou-Keane (GHK) algorithm to satisfy IIA assumptions and it produces highly reliable parameter estimates (Geweke 1991; Keane 1990; Keane 1994; Hajivassiliou and MacFadden 1998; Hajivassiliou et al. 1996; StataCorp 2007; Kropko 2008). Therefore, MNP model is used in our case to examine the choice of alternative payment methods for irrigation. The technical details of the multinomial probit model are presented in Appendix 1.

---

[42] See Green (2008) for detailed specification of logit and probit models.

2.3 Empirical specification of the multinomial choice model

The multinomial probit model used to select the payment systems in groundwater irrigation is specified below.

$Y^*_{i,0} = X_{i,0}\beta_0 + \varepsilon_{i,0}$

$Y^*_{i,1} = X_{i,1}\beta_1 + \varepsilon_{i,1}$ ε_i~ type-1 extreme value distribution of their error term

$Y^*_{i,2} = X_{i,2}\beta_2 + \varepsilon_{i,2}$

$$Y_i = \begin{cases} 0 \text{ if crop sharing; } & Y^*_{i,0} > Y^*_{i,1} \ \& \ Y^*_{i,0} > Y^*_{i,2} \\ 1 \text{ if cash payment (fixed charge); } & Y^*_{i,1} > Y^*_{i,0} \ \& \ Y^*_{i,2} > Y^*_{i,2} \\ 2 \text{ if cash payment (two part tariff); } & Y^*_{i,2} > Y^*_{i,0} \ \& \ Y^*_{i,2} > Y^*_{i,1} \end{cases}$$

Y_i = Dependent variable (payment systems or contract choices)

X_i = Vector of independent explanatory variables including the biophysical and socio-demographic factors of the sample villages

Table 1. List of dependent and independent variables for empirical multinomial probit model.

Dependent variable (Y_i)	Independent variables (X_i)	
Contract choices: 0 = Crop share 1 = fixed charge 2 = two-part tariff	X_1	Yield (kg/ha)
	X_2	Frequency of user's plot visit by the seller (no.)
	X_3	Relation between water seller and water buyer (no. of talks between the seller and the buyer)
	X_4	Chance of denied irrigation by the seller (%)
	X_5	Irrigation cost (Tk./ha)
	X_6	Years of using groundwater irrigation (no.)
	X_7	Interest rate on NGOs loan (Tk.)
	X_8	Flood duration in the last 10 years (days)
	X_9	Electricity dummy (1= village has electric, 0=otherwise)
	X_{10}	Drought dummy (1=village is prone to drought, 0=otherwise)
	X_{11}	Lowland dummy (1=most land in the village is a lowland, 0=otherwise)
	X_{12}	Distance from *Upazila* dummy (1= less than or equal to 10 km, 0=otherwise)

A multinomial probit model was used to estimate factors influencing the choice of a particular payment system in groundwater irrigation. The dependent variable consists of three alternative systems of contracts: crop share, fixed charge or two-part tariff. The independent variables included in the model are described in Table 1.

The relationship between the contract choice and yield as well as between the contract choice and the irrigation cost are likely to be endogenous. Theoretically, this endogeneity problem can be solved using an instrumental variable approach. But finding exogenous instruments might be tricky in this case and hence correcting the endogeneity problem in the specified model is beyond the scope of this paper. Therefore, the potential endogeneity problem in the model is left uncorrected and it is acknowledged as a limitation of the model.

The estimated coefficients of the multinominal probit model are interpreted relative to the reference group. The standard interpretation of the multinomial probit model coefficients is that for a unit change in the predictor variable, the relative probability of choosing a particular payment system, as compared to the reference payment system, is expected to change by its respective parameter estimate, *ceteris paribus*.

2.4 Inclusion of socio-demographic variables in the model

By definition, attributes of the decision maker do not vary over the alternatives. As a result, they can only enter in the model in ways that create differences in utility over the alternatives. This can be seen by using three alternatives:

$U_0=\alpha X_0 + \beta X_0 + \vartheta_0 Z+ \varepsilon_0$

$U_1=\alpha X_1 + \beta X_1 + \vartheta_1 Z + \varepsilon_1$

$U_2=\alpha X_2 + \beta X_2 + \vartheta_2 Z + \varepsilon_2$

Where Z is a vector of some socio-demographic variables and ϑ_0, ϑ_1 and ϑ_2 capture the effect of this variable on the utility of alternatives 1 (u_1) and 2 (u_2), respectively. We might expect that $\vartheta_0 \neq \vartheta_1$, i.e., the effect of the variable differs across alternatives. The problem is that only differences in utility matter and so we cannot estimate the absolute levels of ϑ_0, ϑ_1 and ϑ_2. Again we need to normalize one of these parameters to 0. Now the model becomes:

$U_0=\alpha X_0 + \beta X_0 + \varepsilon_0$

$U_1=\alpha X_1 + \beta X_1 + + v^*_1 Z + \varepsilon_1$

$U_2=\alpha X_2 + \beta X_2 + v^*_2 Z + \varepsilon_2$

Where $\vartheta_1 = \vartheta_1 - \vartheta_0$ and $\vartheta_2 = \vartheta_2 - \vartheta_1$. It is possible to interpret ϑ_1 as the differential impact of the variable on the utility of alternative 2 (v^*_2) compared to alternative v^*_1.

3. Water markets in Bangladesh

3.1 Characteristics of water markets

The water market is an emerging market all over the world. Recognizing irrigation as a main input in agriculture, water markets have become a focal point of discussion. The term "water market" refers to localized, village level informal arrangements through which owners of modern wells sell irrigation services to other members of the community (Shah 1989). It is also noted that once the owner finishes irrigating his own plots, it is to his advantage to sell the surplus water to as many buyers as possible, as long as s/he can cover costs (Kajisa et al. 2005; Shah 1993). The term water market is a general term as water may be lifted from open or tube wells; deep or shallow wells; or from canals, tanks, rivers, drains or other surface sources. It may be transported to the buyer's field through unlined field channels, plastic pipes, or underground pipeline networks. Where land holdings are fragmented, most sellers of water are also buyers of water from other owners. Most farmers sink wells in one or two of their largest and the best parcels. They often purchase water for irrigating their own fields that cannot be irrigated from their own tubewells and also sell water to other farmers under various payment systems. Water markets started as natural oligopolies but large expansion of irrigation equipment markets and support services is leading to increasing competition in water markets. Nevertheless, a number of specific characteristics of water inhibit smooth operation of water markets (Tsegabirhan 2004).

3.2 Mode of existing payment systems for irrigation water

The payment system for water significantly influences water use and, hence, the performance of STWs and DTWs. As the irrigation water market is maturing with an increased number of pumps different pump owners pursue different strategies in order to run their water selling business profitably. Use of different payment systems for irrigation water is one strategy. In Bangladesh two modes of payments for water are practiced under DTW and STW: crop share payment and fixed cash payment (Table 2). In the early stage of groundwater irrigation development, choice of a payment system was determined by whether the machine was operated by diesel or electricity. Usually, crop share payment was used for diesel operated machines and fixed cash payment was used for electricity operated machines. Although diesel operated irrigation is more expensive than electricity operated irrigation, farmers are compelled to use diesel pumps due to lack of electricity in the villages (Mukherji 2007).

The share of resources for irrigation water supply between the seller and the buyer, flexibility and reliability of water supply, and the amount of money paid for water differ between crop share and fixed charge payment systems. In crop share systems, the tubewell owner supplies water to the user's plot for the entire irrigation season and receive 25 percent of the harvested crop. STW owners collect their share from the buyer after the harvesting of *boro* rice. The cost of *boro* rice irrigation for water buyers was estimated to be Bangladesh Taka (BDT)18,000–25,000/season/ha for both diesel or electricity operated machines. The seller has an incentive to provide timely and adequate quantity of water to his buyers because the seller will receive a good share of harvest if the crop is well irrigated, holding other factors the same. It should be noted that the yield also depends on the users' practices regarding weeding, seedlings, fertilizer and insecticides. Climatic factors such as rainfall, flood, and drought also effect yield.

Table 2. Existing contracts in irrigation water markets

Sl. No.	Operating system	Mode of payment	Rate of payment	Timing of payment	Price range (BDT)	Input provider	Popularity	Trend
1.	Diesel	Crop	¼ share of harvest	After harvest	18000-25000	Seller	Popular	Old
2.	Diesel	Cash	Fixed/ha/ season	Beginning the season	15000-18000	Seller	Not so popular	Emerging
3.	Diesel	Cash	Fixed/ha/ season	Beginning the season	12000-13000	Buyer	Most popular	Most emerging
4.	Electricity	Cash	Fixed/ha/ season	Beginning the season	14000-16000	Seller	Popular	Emerging
5.	Electricity	Crop	¼ share of harvest	After harvest	18000-25000	Seller	Not so popular	Old

Source: Rahman et al. 2011

In fixed charge systems, the seller provides water for the whole crop season and receives a fixed amount of cash or non-cash commodity. Fixed cash payment per unit of land or time is usually determined based on the average cost of supplying water including fuel, management and supervision. Payment is made partly prior to and partly after harvesting rice. Two types of fixed cash payment systems are practiced in Bangladesh. In the first, the STW owner provides water to the user for the whole season and receives a fixed amount of cash per unit of land. The cash amount that the STW owner receives depends on local arrangements between owner and user, time of payment, soil type and elevation of the plot, distance from the STW, and relation with the owner. In this system, the cost of boro rice irrigation for the water buyer was estimated to be BDT15,000–18,000/ season/ha for diesel operated machines and BDT14,000–16,000/season/ha for electricity operated machines. In the second system, users pay a service charge for using the STW but provide their own diesel and other irrigation needs. The service charge varies depending on location and contract between the owner and the user. This system is practiced only with diesel operated machines and the cost of boro rice irrigation for water buyers was estimated to be much lower (BDT12,000–13,000/season/ha) than the other payment system. This system is newly introduced in the country and it is gradually replacing the traditional crop share system and the previously mentioned fixed cash per unit of land system. This payment system emerged due to the high price of diesel and engine oil, lack of commitment to agreements by owners and better access to financial resources by owners. The STW owners take less responsibility in this system and transaction cost are also reduced(Rahman et al. 2011; Aggarwal 2007).

The irrigation water payment contract systems in Bangladesh are similar to that of other South Asian countries (Bhandari and Pandey 2006; Kajisa and Sakurai 2005). Kajisa and Sakurai (2005) found three types of contracts in irrigation water markets in India: fixed charge per season, flat charge per application of water and output sharing. In a fixed charge contract, a water buyer pays a fixed amount of cash once per season for specified irrigation acreage for the entire season. In a flat charge contract, a buyer irrigates as much as he wants at a given price per acre and pays each time he applies the water. In an output sharing contract a buyer pays for the water by providing a certain portion of his product after the harvest of the crop.

3.3 Groundwater irrigation payment options available at village level

The results of the descriptive analysis show that farmers in 68% of the sample villages have only one payment system option in groundwater irrigation markets, and farmers in the remaining 32% of the sample villages have more than one payment system option (Figure 2).

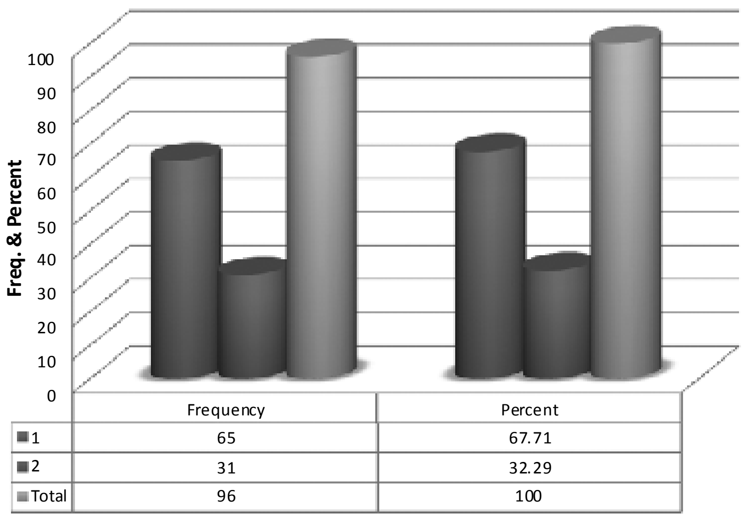


Fig. 2. Percentage distribution of available payment options at the village level, 2013.

3.4 Frequency distribution of payment options

Table 3 shows that the single choice payment option is available in 65 sample villages and more than one payment option is prevailing in 31 sample villages. It is interesting to look into the existing payment combinations in the villages. Out of 31 villages with more than one payment system, seven villages have crop share and fixed charge payment systems, one village has crop share and two-part tariff payment systems, and the remaining 23 villages have fixed charge and two-part tariff payment systems. Figure 3 provides a clear picture of the prevailing scenario of payment options for irrigation water in rural areas of Bangladesh. Fixed charge is the dominant payment option (51%) in villages with a single payment option, while a combination of fixed charge and two-part tariff is dominant (74%) in villages with two options. The results also show that two forms of cash payment prevail in the sample villages: fixed charge and two-part tariff (Fig. 3).

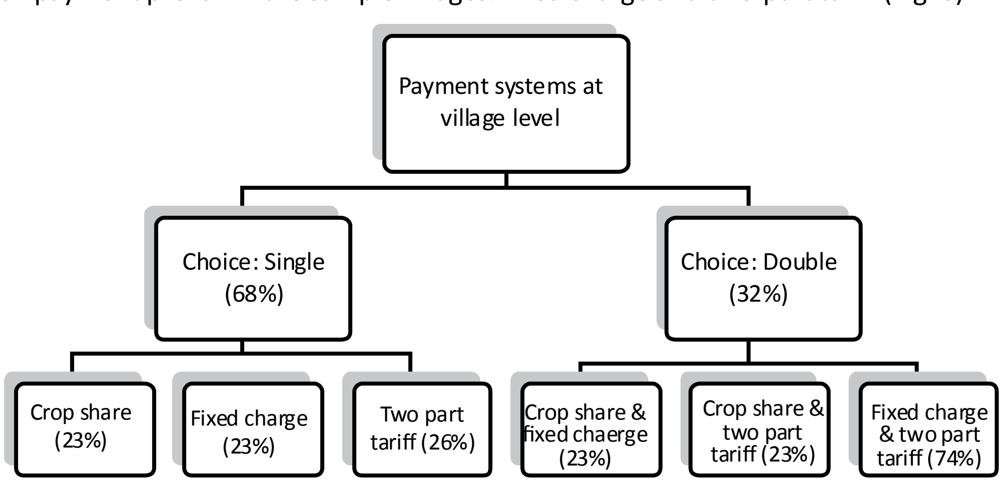


Figure 3. Payment system options at the village level.

Table 3. Frequency distribution of prevailing alternative payment contract options in the sample villages, 2013

Payment option	Payment types			Payment combinations		
	Crop share	Fixed charge	Two part tariff	Crop share & fixed charge	Crop share & two part tariff	Fixed charge & two part tariff
Single=65	15	33	17	-	-	-
Double=31	-	-	-	7	1	23

Source: Field survey, 2013

4. Results and discussion

Table 4 presents the summary results of the estimated multinomial probit model. The reference group in the model is crop share payment system. Thus, the results are interpreted in terms of fixed charge payment system versus crop share payment system and two-part tariff payment system versus crop share payment system. A relatively large likelihood ratio and the statistically significant Chi square value indicate that the estimated multinomial model equation is well fitted to the data.

Table 4. Summary results from multinomial probit model estimation, 2013

Number of observations = 96		
Wald chi^2 (24) = 34.73		
Probability > chi^2 = 0.0725		
Log likelihood = -58.438289		
0	Base outcome = Crop share	
Payment system	Coefficients	Std. Err.
1	Fixed charge	
Paddy yield	0.00108^{***}	0.00044
Frequent visit to the user's plot by the seller	-0.01912	0.01998
Relation between the seller and the buyer	0.00011	0.02269
Chance of denied irrigation by the seller	0.11020	0.07384
Irrigation cost	-0.00010^{**}	0.00005
Years of using groundwater irrigation	-0.13750^{***}	0.04389
Interest rate of NGOs loans (Tk.)	-0.07803^{*}	0.04276
Flood duration	-0.02760^{**}	0.01236
Electricity dummy	1.91391^{**}	0.94990
Drought dummy	-2.07133^{***}	0.72280
Low land dummy	1.57627^{***}	0.62687
Distance from village to *upazila* headquarters dummy	0.45375	0.54716
Constant term	2.51065	3.01869
2	Two part tariff	
Paddy yield	0.00070	0.00046
Frequent visit to the user's plot by the seller	-0.04767^{**}	0.02295
Relation between the seller and the buyer	0.05144^{**}	0.02616
Chance of denied irrigation by the seller	-0.03440	0.08295
Irrigation cost	-0.00007	0.00005
Years of using groundwater irrigation	-0.02453	0.04666
Interest rate of NGOs loans (Tk.)	-0.02196	0.04773
Flood duration (day)	-0.00132	0.01327
Electricity dummy	-0.19003	0.77525
Drought dummy	-0.17991	0.76776
Low land dummy	-0.21757	0.77941
Distance from village to *upazila* headquarters dummy	0.37720	0.62261
Constant term	-0.80239	3.53152

Note: ***, **, * indicate the level of significance at 1%, 5% and 10%, respectively.

4.1 Determinants of fixed charge payment relative to crop share

The maximum likelihood estimates of the multinomial probit model show that the relative probability of choosing a fixed charge payment system versus a crop share system is positively related to paddy yield, access to electricity and having lowland. It is negatively related to cost of irrigation, years of using groundwater irrigation, interest on loan, longer duration of floods and drought problems. The relationships with the rest of the variables are insignificant (Table 4). The estimated coefficients indicate that the relative probability of choosing a fixed charge payment versus crop share payment increased by 0.001 units for one unit increase in yield, by 1.91 units for those villages with access to electricity as compared to those without electricity, and by 1.58 units for lowlands villages as compared to other villages. The relative probability of choosing a fixed charge payment versus crop share payment decreased by 0.0001 units for one unit increase in irrigation cost, by 0.14 units for one unit increase in the years of using groundwater irrigation, by 0.08 units for one unit increase in the interest rate of a loan, by 0.03 units for each unit increase in flood duration and by 2.07 units for villages affected by drought as compared to those that are not affected.

4.2 Determinants of two-part tariff payment relative to crop share

The model estimates show that the relative probability of choosing a two-part tariff payment system versus crop share system is positively related to the relation between the seller and the buyer and negatively related to the frequency of visit to the buyer's plot by the seller, while the relationship with the rest of variables was insignificant. The estimated coefficients indicate that the relative probability of choosing a two-part tariff payment versus crop share payment increased by 0.05 units for one unit increase in the relationship between the seller and the buyers and it decreased by 0.05 units for one unit increase in the frequency of seller's visit to the buyer's field.

4.3 Determinants of choosing a crop share payment system

Table 5 presents the marginal effect coefficients of different variables in choosing a crop share payment system for groundwater irrigation. The parameter estimates of the probit model show that the probability of choosing a crop share system is positively related to cost of irrigation, years of using groundwater irrigation, flood problems, and drought problems. It was negatively related to paddy yield and having lowland area. The variables that have a relatively large effect in choosing a crop share payment are drought dummy and lowland dummy. The marginal effect coefficient of a variable indicates the effect of that variable on the probability of choosing a crop share payment system. The marginal effect coefficient of -0.0002 for paddy yield indicates that a 1 t/ha increase in paddy yield will decrease the probability of choosing a crop share payment method by 0.02%, *ceteris paribus*. The marginal effect coefficient -0.21723 for the lowland dummy indicates that the villages with lowlands have a 22% higher probability of choosing a crop share payment than those without lowlands, *ceteris paribus*. The coefficients of other variables can be interpreted in the same fashion.

Table 5. Marginal effects of the predicted payment system (crop share), 2013

Variables	y = Pr(Payment method=0) (predicted outcome of Crop share) = .18634181		
	dy/dx	Std. Err.	Expected value (X)
Yield (kg/ha)	-0.00020***	0.00008	6286.90
Frequent visit (no.)	0.00515	0.00374	45.66
Good relation (no.)	-0.00232	0.00423	28.62
Chance of denied irrigation (%)	-0.01586	0.01345	5.62
Irrigation cost (Tk./ha)	0.00002**	0.00001	19348.70
Years of using irrigation (year)	0.02280***	0.00841	31.96
Interest rate of NGOs (Tk.)	0.01330	0.00831	29.77
Flood duration (day)	0.00442*	0.00234	15.13
Electricity dummy	-0.27838	0.20389	0.86
Drought dummy	0.25437***	0.08115	0.73
Low land dummy	-0.21723**	0.09457	0.42
Distance from upazila dummy	-0.09292	0.10988	0.68

Note: ***, **, * indicate the level of significance at 1%, 5% and 10%, respectively.

4.4 Determinants of choosing a fixed charge payment system

Table 6 presents the marginal effect coefficients of different variables in choosing a fixed charge payment system for groundwater irrigation. The factors that significantly affect the probability of choosing a fixed charge payment system are yield, chance of denied irrigation by the seller, irrigation cost, years of using groundwater irrigation, interest rate on NGO loans, duration of floods, access to electricity, occurrence of drought, and land type under *boro* rice. The probability of choosing a fixed charge payment system is positively related to yield, chance of denied irrigation, access to electricity, and endowment of lowland. It is negatively related to irrigation cost, years of using groundwater irrigation, interest rate on NGO loans, longer flood duration and occurrence of drought. The variables that have a relatively large effect on choosing a fixed charge payment are chance of denied irrigation, years of using groundwater irrigation, access to electricity, occurrence of drought and endowment of lowlands. The marginal effect of 0.0337 for chance of denied irrigation indicates that a one percent increase in refusing to provide irrigation by the seller will increase the probability of choosing a fixed charge payment system by 3.37%. Likewise, the marginal effect of -0.4138 for the drought dummy indicates that villages prone to drought have a 41.38% lower probability of choosing a fixed charge payment than those villages not prone to drought. The coefficients of other variables can be interpreted in the same fashion.

Table 6. Marginal effects of the predicted payment system (fixed charge)

Variables	y = Pr(Payment method=1) (predicted, outcome of fixed charge) = .68922906		
	dy/dx	Std. Err.	Expected value (X)
Yield (kg/ha)	0.00021**	0.00010	6286.90
Frequent visit (no.)	0.00020	0.00468	45.66
Good relation	0-.00576	0.00553	28.62
Chance of denied irrigation (%)	0.03367*	0.01760	5.62
Irrigation cost (Tk./ha)	-0.00002*	0.00001	19348.70
Years of using irrigation (year)	-0.03442***	0.01075	31.96
Interest rate of NGOs (Tk.)	-0.01863*	0.01075	29.77
Flood duration (day)	-0.00732**	0.00317	15.13
Electricity dummy	0.55805***	0.19105	0.86
Drought dummy	-0.41381***	0.09850	0.73
Low land dummy	0.40726***	0.11397	0.42
Distance from upazila dummy	0.08361	0.13574	0.68

Note: ***, **, * indicate the level of significance significant at 1%, 5% and 10%, respectively.

4.5 Determinants of choosing a two-part tariff payment system

Table 7 presents the marginal effect coefficients of different variables in choosing a two-part tariff payment system for groundwater irrigation. There are fewer variables that significantly influence the probability of choosing a two-part tariff payment system. These variables are user's plot visits by the water seller, conversation between user and seller, drought problems and land type. The probability of choosing a two-part tariff payment system increased by 0.80% for each increase in conversations between the seller and user and by 15.94% for villages prone to drought. In contrast, the probability of choosing a two-part tariff payment system decreased by 0.54% for each increase in visits by seller to users' plots and by 19.00% for villages located in low lands.

Table 7. Marginal effects of the predicted payment system (two-part tariff)

Variables	y = Pr(Pay_method1=2) (predicted outcome of two part tariff) = .12442913		
	dy/dx	Std. Err.	Expected value (X)
Yield (kg/ha)	-0.00001	0.00006	6286.90
Frequent visit (no.)	-0.00535*	0.00323	45.66
Good relation	0.00808**	0.00394	28.62
Chance of denied irrigation (%)	-0.01781	0.01206	5.62
Irrigation cost (Tk./ha)	0.00000	0.00001	19348.70
Years of using irrigation (year)	0.01161	0.00716	31.96
Interest rate of NGOs (Tk.)	0.00533	0.00717	29.77
Flood duration (day)	0.00290	0.00208	15.13
Electricity dummy	-0.27967	0.18668	0.86
Drought dummy	0.15944**	0.07003	0.73
Low land dummy	-0.19002**	0.08602	0.42
Distance from upazilla dummy	0.00931	0.08740	0.68

Note: ***, **, * indicate the level of significance significant at 1%, 5% and 10%, respectively.

4.6 Aggregate probability of choosing a payment system from the model

The multinomial probit regression model shows that the probability of choosing fixed charged payment is highest (0.58), followed by crop share (0.25) and two-part tariff (0.18). The estimations from the specific multinomial probit model are similar to the existing payment methods actually practiced by farmers for groundwater irrigation in Bangladesh (Table 8).

Table 8. Probability of choosing payment methods for groundwater irrigation markets

Payment methods	Observation	Mean	Std. Dev.	Min	Max
Crop share, p_0	96	0.24588	0.242514	1.39E-05	0.958907
Fixed charge, p_1	96	0.578376	0.341866	0.001017	0.999854
Two-part tariff, p_2	96	0.175743	0.201567	3.65E-09	0.817899

The village level survey data show some changes in payment methods during the last 10 years but these changes are not significant. Farmers observed that changes in the payment systems in the short- to medium-term future will be small as users have limited payment options to choose. Only a few villages have more than one payment method. The individual household survey data also show that only one payment option exists in a particular tubewell command area, thus, no providing no option to choose.

Table 9. Payment methods in irrigation water markets from multinomial probit model

Payment systems	Frequency	Percent	Cumulative percent
Crop share (0)	23	23.96	23.96
Fixed charge (1)	56	58.33	82.29
Two part tariff (2)	17	17.71	100
Total	96	100	-

It can be seen from Tables 3 and 9 that the predicted values and survey-based values do not differ radically. So the effect on the estimated parameters is fairly modest. We can confidently use these parameter estimates to forecast future payment systems based on the significant coefficients from the model estimation.

4.7 Alternative-specific multinomial probit: some limitations

In this analysis, the mprobit model is used to examine why farmer choose a specific payment system and practice it over the years. Why do they think that the method is somehow good for them? Why do they change their payment methods? What were the reasons behind the change? What are the characteristics of the village that determine the choice? Theoretically, there are three options for farmers but in a particular village, there are few options. And our collected dataset does not have all relevant information, like rice yield of households within the villages for different payment systems. It is therefore not possible to test the asmprobit command. This is considered to be one of the limitations of the study—limited data due to the prevailing groundwater irrigation system.

Asmprobit fits the multinomial probit model by using maximum simulated likelihood (MSL) implemented by the Geweke-Hajivassiliou-Keane (GHK) algorithm. By estimating the variance-covariance parameters of the latent-variable errors, the model allows us to relax the independence of irrelevant alternatives (IIA) property that is a characteristic of the multinomial logistic model. *Asmprobit* requires multiple observations for each decision, where each observation represents an alternative that may be chosen. The cases are identified by the variable specific to the case option, whereas the alternatives are identified by the variable specified in the alternative option. The outcome or chosen alternative is identified by a value of 1 for the dependent variable, indicating the alternatives chosen; only one alternative may be chosen for each case. It allows for two types of independent variables: alternative-specific variables and case-specific variables. Alternative-specific variables vary only across cases and are specified in the case variable option.

5. Conclusions and recommendations

There are three payment systems that exist in the groundwater irrigation market in Bangladesh. In the 1970s and 1980s, only a crop share payment system existed. After the import market liberalization of small scale STW engines in the late 1980s, farmers of Bangladesh increased the cultivation of irrigated HYV *boro* rice. Small and cheap irrigation technologies enabled farmers to invest more on tubewells, leading to more land under irrigation. After years of experience in irrigation, some farmers adopted other payment systems, i.e. fixed-charge cash payment and two-part tariff payment. The latter is the latest payment scheme wherein the farmer will only pay a service charge for the use of the tubewell. Fuel and other needs are borne by the farmer/buyer himself.

The descriptive analysis shows that the number of fixed charge and two-part tariff are payments have increased over the years and the crop share system has decreased. Depending on the nature of the irrigation water market, users have choices but not full freedom to choose a particular payment. It is also seen that the seller and the user face some disputes in water transactions. They have introduced self resolution protocol at the village level. Sellers and buyers rarely go to court to resolve their disputes regarding irrigation contracts. After 30 to 40 years of experience in irrigation transactions they have adopted a sustainable, village-based resolution system that is unique to the market. There are fewer disputes reported with the use of a two-part tariff payment system compared to the fixed-charge system, which is however more commonly found among farmers.

A crop share payment system does not promote water conservation and discourages water users from saving irrigation water because they get as much water as they requires without extra cost. Also, this system provides less incentive for water users to invest resources in rice production and achieve maximum yield because part of the production will be shared with the water seller. This production behavior leads to an economic loss. The irrigation cost per unit area for the water user is higher in crop share systems than other payment systems. Therefore, crop share payment systems are less economically beneficial to the seller, the buyer and society as a whole. Compared to crop share systems, fixed charge payment systems are economically beneficial but also do not encourage the water user to save irrigation water. On the other hand, two-part tariff systems are not only economically beneficial to both the buyer and the seller, but also provides incentives to the user to save irrigation water. Therefore, proper policies and a concerted effortsare needed to change the payment system in irrigation water markets from crop share to fixed charge or two-part tariff payment, depending on the local context.

Rural electrification is one of the significant factors that increases the probability of choosing a fixed charge payment method. The very high price of paddy in 2007 and 2008 is also believed to be a major cause for the expansion of fixed charge and two-part tariff payment systems. If output price increases without proportionate increase in irrigation cost, that reduces the popularity of crop share payment systems and presents strong economic reasons for shifting to any other payment system. Expansion of electrification in rural areas and continuous and regular supply of electricity is one way of expanding fixed charge payment systems. If the village is dominated by diesel operated tubewells, promotion of a two-part tariff payment system would be a best bet.

It is also noted that cash and credit availability are major issues. It has been observed that credit availability is increasing in rural areas over times due to the proliferation of micro-finance institutions. The interest rate of credit from money lenders is also decreasing because more NGOs and micro-finance institutions are operating in rural areas. Commercial bank loans are also becoming increasingly more accessible and cheaper for the farmers who are living closer to the *upazila* main towns and in villages with good transport and communication infrastructure. Farmer are also becoming more conscious about their ability to access resources through media support, with the exception of those farmers living in remote areas.

Higher education, awareness and trainings, opportunities to diversify income sources and changing livelihoods make farmer more careful about choosing their agricultural practices and other activities for improving their welfare. Recently, the government of Bangladesh has provided facilities for loans without collateral, especially for tenant farmers. NGOs provide loans to smallholder farmers and the rural poor without collateral. Grameen Bank and other small-scale credit providers are coming forward to support the agricultural and small-scale business activities of rural poor farmers. Such positive efforts makes farmers more capable of bearing irrigation expenses on their own and give them more flexibility to choose a suitable payment system for irrigation water. Additional tubewell owners are entering into the water selling business and they are providing more options to the users for expanding their tubewell command area. More research is needed to study these emerging options and promote a competitive water market that not only benefits both buyers and sellers but also saves irrigation water by increasing water productivity.

Groundwater is not widely used in south Bangladesh due to salinity problem. But there are some pocket areas in the coastal and inland coastal zone of south Bangladesh where farmers are using non-saline groundwater to irrigate their crops using tubewells. As the adoption of water-intensive improved agricultural technologies gradually increases in coastal and inland coastal zones, farmers are also increasing investment in irrigation, including pumping of groundwater where it is not saline and purchasing irrigation machines to pump surface water from ponds, canals and *khals*. These changes are likely to expand water markets in south Bangladesh in the future. Different strategies are needed for efficient use of scarce freshwater resources and for increasing water productivity in south Bangladesh. This study indicates that the promotion of a two-part tariff payment system is one simple and effective strategy to save irrigation water in rice production and will increase water productivity. This two-part tariff can be promoted in south Bangladesh for efficient use of freshwater resources.

Acknowledgements

This paper has been derived from IRRI's Village Dynamics in South Asia (VDSA) Project, which funded the first author's PhD dissertation research on "Determinants of water price, contract choice and rice production efficiency in groundwater irrigation markets in Bangladesh." The authors are thankful to IRRI and the VDSA Project for funding this research work. The authors would also would like to thank Valerien O. Pede of IRRI for providing valuable inputs to this paper.

References

Aggarwal, RM. 2007. Role of risk sharing and transaction costs in contract choice: Theory and evidence from groundwater contracts, Journal of Economic Behavior & Organization, 63: 475–496.

Ali, M. H. 2010. Fundamentals of Irrigation and On-farm Water Management, volume 1, No. XXII, 556P, 89 illus, 29 in color, Hardcopy, ISBN: 978-1-4419-6334-5.

BADC, 2008. Minor Irrigation Survey Report 2007–08. Bangladesh Agricultural Development Corporation, Ministry of Agriculture, GOB, Dhaka, Bangladesh, p 122.

Bangladesh Agricultural University, 1986. *Water Markets in Bangladesh: Inefficient and Inequitable?* 285p, Mymensingh.

BBS (Bangladesh Bureau of Statistics), 2001. Yearbook of Agricultural Statistics of Bangladesh. Ministry of Planning, The Government of the Peoples Republic of Bangladesh (GOB).

BBS, 2009. Statistical Year book of Bangladesh, Ministry of Planning, GOB, Dhaka, Bangladesh.

BBS, 2009. Statistical Year book of Bangladesh, Ministry of Planning, GOB, Dhaka, Bangladesh.

BBS, 2010. Statistical Year book of Bangladesh, Ministry of Planning, GOB, Dhaka, Bangladesh.

BER, 2009. Ministry of Finance, Government of the People's Republic of Bangladesh, Dhaka.

BER, 2010. Ministry of Finance, Government of the People's Republic of Bangladesh, Dhaka.

Bhandari H, Pandey S., 2006. Economics of groundwater irrigation in Nepal: some farm-level evidences. Journal of Agricultural and Applied Economics, 38 (1): 185-199.

DAE, 2011. Annual Report 2010. Department of Agricultural Extension (DAE), Ministry of Agriculture, GoB, Bangladesh.

EPADC (East Pakistan Agricultural Corporation). 1968. Annual report 1966–67, East Pakistan Agricultural Corporation, Dhaka.

Gill, G.J. 1983. The Demand for Tube Well Equipment in Relation to Groundwater Availability in Bangladesh. AERSS Paper No. 13. Bangladesh Rural Advancement Committee, Dhaka.

Green, W. H., 2008. Econometric analysis, 6th ed., N.J. (USA): Prentice Hall.

Hajivassiliou, V. and D. McFadden, 1998. The Method of Simulated Scores for the Estimation of LDV Models. Econometrica. 66: 863-896.

Hajivassiliou, V., D. McFadden and P. Ruud, 1996. Simulation of Mulltivariate Normal Orthant Probabilities: Methods and Programs. Journal of Econometrics, 72:85-134.

IBRD (International Bank for Reconstruction and Development), 1972. Land and Water Sector Study, The World Bank.

Kajisa, K. and Sakurai, T. 2005. Efficiency and equity in groundwater markets: the case of Madhya Pradesh, India. Environment and Development Economics*, 10(6): 801-819.*

Keane, M. P. 1990. Four Essays in Empirical Macro and Labor Economics. PhD Dissertation. Brown University.

Keane, M. P. 1994. A Computationally Practical Simulation Estimator of Discrete Choice Models. Econometric Theory. 11:437-483.

Kotz, S. and Nadarajah, S. 2000. *Extreme Value Distributions: Theory and Applications*. London: Imperial College Press.

Kropko, J. 2008. Choosing Between Multinomial Logit and Multinomial Probit Models for Analysis of Unordered Choice Data. MS thesis submitted to the faculty of The University of North Carolina at Chapel Hill.

Majumder, M. K. and S. Rahman. 2011. Impact of Introducing LLP on Improving Income of Farm Households in Some Areas of Bhola District in Bangladesh. J. Bangladesh Agril. Univ., 9(2): 233-240.

Mandal, M. A. S. 1993. Groundwater Irrigation in Bangladesh: Access, Competition, and Performance. Friedrich Kahnert and Gilbert Levine edited book on Groundwater Irrigation and the Rural Poor: Options for Development in the Gangetic Basin, The World Bank, Washington, D.C.

Mc Fadden, D. 1973. Conditional Logit Analysis of Qualitative Choice Behavior. In Frontiers of Economitrics, Ed. P. Zarembka, Ney Work: Academic Press.

Michler, J. D. and Wu, S. 2013. Contracting for Groundwater Irrigation: A Principal-Agent Based Approach to Determining Contract Effectiveness. Paper presented in the AAEA & CAES joint annual meeting, Washington, DC, August 4-6, 2013.

Mukherji, A. 2004. Groundwater Markets in Ganga-Meghna-Brahmaputra Basin: Theory and Evidence. Economic and Political Weekly, 30(31):3514-3520.

Mukherji, A. 2007. The Energy-Irrigation Nexus and Its Impact on Groundwater Markets in Eastern Indo-Gangetic Basin: Evidence from West Bengal, India, Energy Policy, 35(12):6413–6430.

Rahman, M. S. and A. Angelsen. 2011. Comparison between Irrigation Payment Systems and Probability of Using Water Saving Technology. Journal of Economics and Sustainable Development, ISSN 2222-1700 (Paper) ISSN 2222-2855 (Online) www.iiste.org, Vol.2, No.10.

Sattar M. A. 1999. Irrigation Development and Management in Bangladesh. Oxford & IBH, New Delhi, p 120.

Shah, T. 1993. Groundwater markets and irrigation development: Political economy and practical policy, Oxford University Press, Bombay.

StataCorp. 2007. Stata Statistical Software: Release 10. College Station, TX: StataCrop LP.

Train, K. E. 2007. Discrete Choice Models with Simulation. New York: Cambridge University Press.

Tsegabirhan, W. 2004. Estimating Willingness to Pay for Irrigation Water: A Contingent Valuation Case Study on Small Scale Irrigation Schemes, A.A.U., FBE, Department of Economics, Ethiopia.

Appendix 1. Technical details of the multinomial probit model

The detailed technical specifications of the multinomial probit model are discussed below.

We can say 'Y' denotes a random variable taking on the values {0; 1; ...; J} for J a positive integer, and let 'X' denote a set of conditioning explanatory variables (NxK vector including a constant).

In our irrigation water market case, 'Y' would be {j=0: crop share; j=1: fixed charge and j=2: two part tariff} and 'X' would be commitment, supervision, good relation, age, education level, rice area, number of tubewell, farm size, etc. It is also assumed that the variables are independent and identically distributed (i.i.d.).

Here we are interested in how *ceteris paribus* changes in the elements of x after the response probabilities, P(y=j|x), j=0, 1, ..., J. Since the probabilities must sum to unity (1), P(y=0|x) will be determined once we know the probabilities for j=1, ..., J.

It is assumed here on the multinomial model as a series of binary models. That is, the probability of the alternative j against alternative i for every i≠j is evaluated. The model started by considering the binary model, which is as follows:

$P(y = j \| y \in \{i,j\}, x)$:

$$\frac{P(y = j|x)}{P(y = i|x) + P(y = j|x)} = \frac{P_j}{P_i + P_j} = F(X\beta_j)$$

We can derive from the above equation:

$P_j = F(X\beta_j)(P_i + P_j)$

$$\frac{P_j}{P_i} = F(X\beta_j)\frac{P_i + P_j}{P_i} = \frac{F(X\beta_j)}{\frac{P_i}{P_i + P_j}} = \frac{F(X\beta_j)}{1 - \frac{P_j}{P_i + P_j}} = \frac{F(X\beta_j)}{1 - F(X\beta_j)} = G(X\beta_j)$$

It needs to be mentioned here that:

$$(x + a)^n = \sum_{j \neq i} \frac{P_j}{P_i} = \frac{\sum_{j \neq i} P_j}{P_i} = \frac{1 - P_i}{P_i} = \frac{1}{P_i} - 1$$

$$\frac{1}{P_i} = 1 + \sum_{j \neq i} \frac{P_j}{P_i}$$

So we can get the following by using the expression for P_i / P_i from above:

$$\frac{1}{P_i} = 1 + \sum_{j \neq i} G(X\beta_j)$$

$$P_i = \frac{1}{1 + \sum_{j \neq i} G(X\beta_j)}$$

For P_j:

$$P_j = \frac{G(X\beta_j)}{1 + \sum_{i \neq j} G(X\beta_i)}$$

To find an explicit form for P_i we only have to substitute the G(.) by exp(.), and then we obtain the multinomial probit/logit model:

$$P(y = j|x) = \frac{G(X\beta_j)}{1 + \sum_{i \neq j} G(X\beta_i)}, j = 1, \ldots, J$$

We know that the response probabilities must be sum to 1, we set the probability of the reference response (j=0) to the following:

$$P(y = 0|x) = \frac{1}{1 + \sum_{i \geq 1} G(X\beta_i)}$$

The multinomial probit (MNP)/multinomial logit (MNL) is obtained through maximum-likelihood estimation which we can express as:

$$L(\beta) = \prod_{i-1}^{n} \prod_{j-0}^{J} P(y_i = j|x)^{1[y_i=j]}$$

Mc Fadden (1974) has shown that the log-likelihood function is globally concave, which makes the maximization problem straightforward. The partial effects for this model are complicated. For continuous X_k, we can express the following equation:

$$\frac{\delta P(y = j|x)}{\delta x_k} = P(y = j|x)[\beta_{jk} - \frac{\sum_{i \geq 1} \beta_{ik} \exp(X\beta_i)}{1 + \sum_{i \geq 1} \exp(X\beta_i)}]$$

Where β_{ik} is the k-th element of β_i even the direction of the effect is not entirely revealed by β_{ik}.

Deriving probit/logit based models from the random utility model where we consider the basic utility equation:

$U_{ij}=V_{ij}+ \varepsilon_{ij}$

It is known that the logit model is obtained by assuming that each ε_{ij} is distributed iid extreme value. This distribution is also called the Gumbel distribution or a Type-I extreme value distribution. The density for each unobserved component of utility is:

$f(\varepsilon_{ij}) = exp^{-\varepsilon ij} exp(-exp^{-\varepsilon ij})$

This is shown in Figure 1.

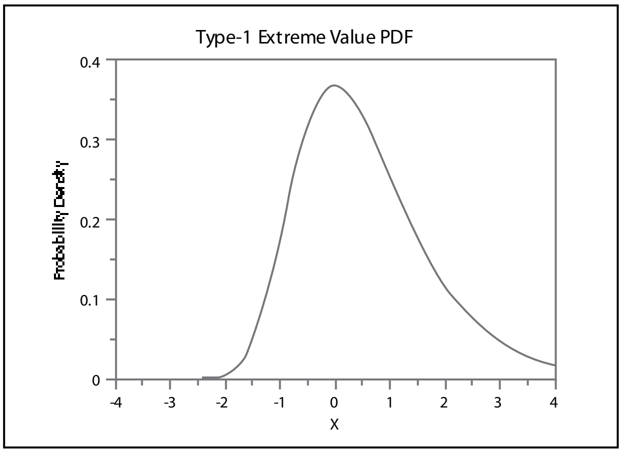


Fig. 1. Type-1 Extreme Value PDF

Source: Train 2007

The cumulative distribution is like: $F(\varepsilon_{ij}) = \exp(-\exp^{-\varepsilon ij})$

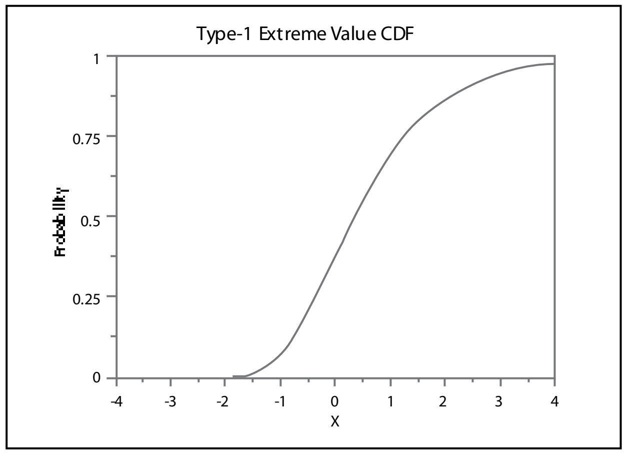


Fig.2. Type-1 Extreme value CDF

Source: Train 2007

There are 3 types of extreme value distributions:

i. Type-1, (Gaumbel-type distribution) where $Pr/X \leq x = exp[-e^{(x-\mu)/\sigma}]$ where μ, σ (>0) are parameters;

ii. Type-2 (Frechet-type distribution); and

iii. Type-3 (Weibull-type distribution)

The term “extreme value" is attached to these distributions because they can be obtained as limiting distributions of the greatest value among n independent random variables each having the same continuous distribution. By replacing X by −X, limiting distributions of least values are obtained (Kotz and Nadarajah 2000).

The variance of the distribution is $\pi_2/\sigma=1.64$. By assuming this, we have normalized the utility scale. The difference between two extreme value distributions is logistic. It is known that the coefficients in logit will now be larger than in a probit model by a factor of √1.64. The probit coefficients can be converted to the scale of the logit coefficients by multiplying them by √1.64

Section 4

Homestead Production Systems

Do homestead food production systems hold promise for household food security? Empirical evidence from the southwest coastal zone of Bangladesh

M. Karim, M.H. Ullah, K.A. Kabir and M. Phillips

WorldFish, Bangladesh and Malaysia, m.karim@cgiar.org, hadayet127@gmail.com, k.kabir@cgiar.org, m.phillips@cgiar.org

Abstract

Aquatic-agricultural systems, comprised of field crop systems (FCS) and homestead food production systems (HFS), are an important source of income, food and nutrition for millions of poor people living in southwest Bangladesh. The contribution of aquatic-agricultural systems to households is predicted to vary across agro-ecological zones. This study aims to determine the relative contribution of homestead and field food production systems among three household categories (functionally landless, marginal, small) and agro-ecological zones across a salinity gradient (polders 30, 3-H, 3-L, and 43) in southwest Bangladesh. The results indicate that HFS contributed to the food security status of functionally landless households while the contribution of FCS to these households was minimal. FCS contributed significantly, though, to the food security status of small and marginal households. Food security ratios associated with the HFS system did not vary largely (>0.05) across households; however the food security ratio associated with FCS in marginal and small households was significantly (<0.05) higher than functionally landless households. Among the polders, HFS had a significantly higher contribution to household food security status in Polder-3H and Polder-3L while FCS contributed most in Polder-3L. The variation is largely attributed to the size of land holding and access to cultivatable land among household categories and polders. Results also suggest that access to productive assets, such as land is the major factor influencing food security status among household categories. HFS are very suitable for poor farmers, especially those that are functionally landless and in some instance for marginal farmers. Results also suggest that HFS has greater resilience, in some cases, compared to FCS. The study also suggests that there is scope for further intensification of HFS. Therefore, ensuring access to quality inputs, and knowledge and technical skills for farmers should be considered a priority to maximize the benefits of HFS for landless and marginal farmers.

1. Introduction

Adequate production and supply of cereals and staple food commodities is still a major challenge to achieving food security in developing countries, though the provision of an adequate nutritional quality for life functions is getting increasing attention. Food security is a multi-faceted concept, defined in almost 200 different definitions (Smith et al. 1992). The most refined one was given by FAO (1996) as, "… a condition when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life". This definition overcomes the drawbacks of previous definitions, which mostly used a calorie-based approach. Households are major components of broader food systems and can themselves be considered as (sub-)systems. Households can therefore be seen as the most appropriate entry point for the analysis of food security (Alinovi et al. 2009). Food security at the household level could be defined as " the ability of the household to secure, either from its own production or through purchases, adequate food for meeting the dietary needs of all members of the household" (FAO 2014).

In developing countries such as Bangladesh, aquatic-agricultural systems (AAS) are an important source of income, food and nutrition for millions of people. Households dependent on these systems commonly have access to two distinct systems: homestead food production systems (HFS) and field crop systems (FCS). HFS is mainly a need-oriented, self-provisioning, integrated, multi-species, economically sustainable and environmentally safe farming system around the house where the soil is enriched by homemade biological formulations and integrated farming is undertaken (Bhattacharya et al. 2013). In constrast, FCS is predominantly a market-driven cropping system that often depends on external inputs and commonly uses high-yielding and selected crop species to respond to prevailing market demand. These two systems collectively produce a wide variety of foodstuffs, including cereals, fruits, vegetables, livestock and fish (Bhattacharya et al. 2013; John 2014). Agriculture production from field crops has long been highlighted as the major source of household income and livelihood (Hossain et al. 2007); the importance of homestead farming has often been ignored. The United Nations General Assembly declared the year 2014 as the International Year of Family Farming, recognizing the importance of this system. In addition to providing an income, HFS may contribute to improving food security and the nutritional status of homestead members, and conserving biodiversity. That's why in recent times interventions have been targeted at improving homestead food production, most of which have resulted in households increasing their consumption of a greater array of micronutrient rich ingredients (Talukder et al. 2000; Helen Keller International 2002; Galhena et al. 2013).

Southwest Bangladesh encompasses Khulna and Barisal division, with a total population of 24 million and an overall density of 660 people/km^2 (BBS 2011). The land elevation rarely exceeds 3 meters (UN 2010) and salinity plays a central role in crop agriculture production (Rabbani et al. 2013b). Cropping is generally limited to the monsoon season when rainwater can feed the crops. However, the areas with particularly close proximity to the ocean are often inundated for long periods as drainage congestion causes persistent waterlogging of land and can hinder field crop production (Roy 2004). This situation also opens up opportunities for culturing aquatic species such as the giant freshwater prawn, *Macrobrachium rosenbergii*, freshwater finfish species and black tiger shrimp, *Penaeus monodon*, the latter in more saline regions. Crop rotational (fish-paddy or fish-shrimp) systems in *ghers*[43] is normally practiced in this region (Roy et al. 2013). During the rainy season (June-December) the *gher* is full of water, and shrimp and fish are produced. From January to May, this low-lying land tends to dry out and crops such as MV *boro* rice are grown on the mainland while shrimp and fish shelter in the canals.

The coastal population is exposed to a number of climate-induced hazards such as variations in temperature, erratic rainfall patterns, drought, cyclones and storm surges, flooding, salinity intrusion and rising sea levels (Rabbani et al. 2013a). The landscape is strongly influenced by tributaries of the Ganges River flowing towards the Bay of Bengal. Due to the low-lying nature of land, proximity to the ocean and frequent natural disasters such as tropical cyclones and accompanying storm surges often bring various hazards to people living in the region. The increasing trend in sea level rise, water logging and salinity intrusion may be further intensified and exacerbated by climate change, which could significantly impact existing water resources and larger areas of agriculture land in the future (Shamsuddoha and Chowdhury 2007; Rabbani et al. 2013a). Agricultural activities as well as cropping intensities in the 31 upazillas of southwest Bangladesh have been reported to have already changed; where farmers can no longer grow multiple crops in a year the livelihood and food security of poor households has been negatively affected (Huq and Rabbani 2011; Rabbani et al. 2013a). Moreover, agricultural land (crop agriculture) showed an annual decline of about 0.27 percent from 1976-77 to 2010-11 (SRDI 2013). This trend will further diminish the access of poor people to this natural resource. Poor and marginalized households in particular need options for alternative, locally-driven, immediate and longer-term adaptation strategies that can support household food security. HFS can bring a diverse array of plant (vegetables) and animal sourced foods (such as goats, cattle and poultry) to poor and marginalized communities and support improved household food security status. In recent years several studies have been done on household food security and nutritional aspects (Faridi and Wadood 2010; Alam et al. 2011; Uddin 2012; Kashem et al. 2013). However, studies that specifically address the relative contribution of HFS and FCS to household food security status in the coastal area of Bangladesh have not been conducted. This research hypothesized that HFS can significantly contribute to improving the household food security status of coastal populations and could be considered a more eco-friendly and resilient system compared to FCS, in the context of dynamic geographical settings. It specifically aimed to assess the following questions: a) what is the relative contribution of HFS and FCS to household food security?; b) does HFS significantly improve household food security status?; and c) is HFS an environmentally sound and resilient system in the context of the coastal area?

[43] *Ghers* are modified paddy fields where elevated dikes surround the main land. A canal that usually takes up approximately 20% of the land is usually constructed around the periphery.

2. Materials and Methods

2.1 Study area

This study was conducted in three polders: Polder-30 in Batiaghata *Upazila*[44] (Khulna District), Polder-3 in Debhata *Upazila* and Kaliganj *Upazila* (Satkhira District) and Polder-43 in Amtali *Upazila* (Barguna District) (Fig. 1). These polders were selected based on their salinity levels, where Polder-3 was considered a medium to high saline zone (0-28 ppt), Polder-30 represents a low to medium saline area (0-20) and Polder-43 is considered a low saline area (0-6). The areas of Polder-30, Polder-3, Polder-43 were 7,874 hectares, 35,780 hectares, and 4,453 hectares, respectively. Polder-3 tends to be waterlogged during the month of July to September. Polder-3 is very large and further subdivided into Polder-3H (medium-highland; more than 10ft) and Polder-3L (low-lying land; elevation between 0 and 10ft).

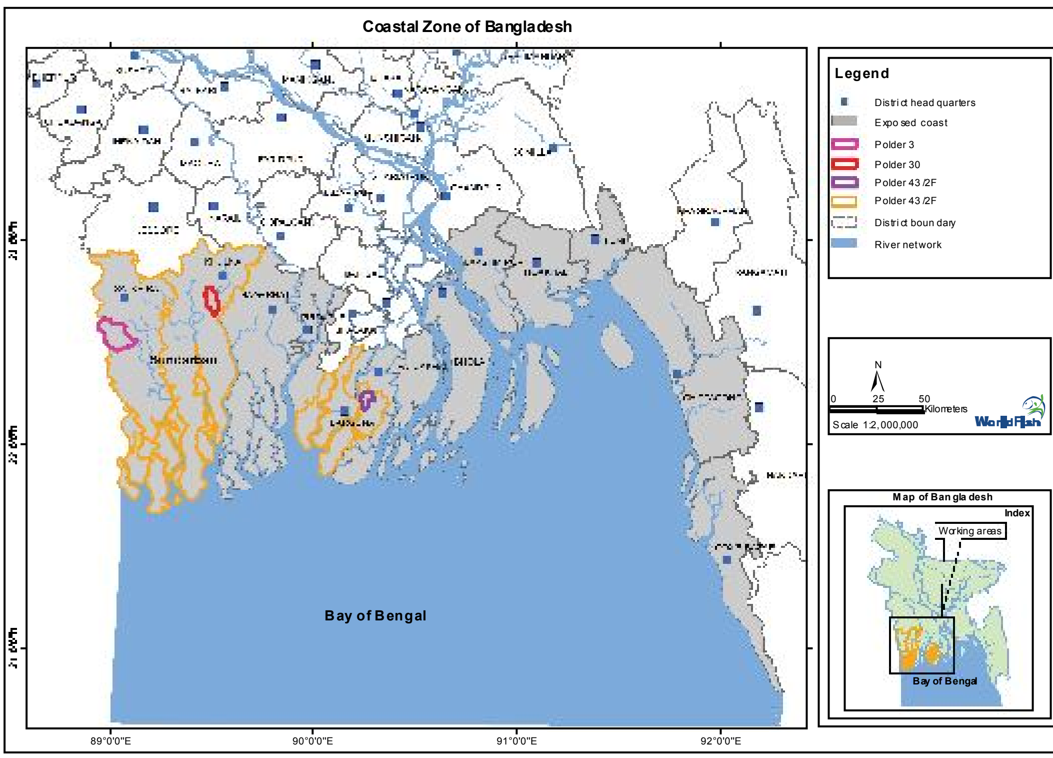


Fig. 1. Location of the study areas.

2.2 Data collection and analysis

The field research for this study was conducted over a two-month period between January and March 2012. A complete list of all the households in each polder was collected from the *Union Parishad*[45] and a total of 21,851 households were recorded in the study area. Each polder, including the subdivisions of Polder-3, was considered as separate strata to perform stratified random sampling. Statistical Package for Social Science, SPSS, version 16 software (SPSS, Chicago, IL, USA) was used to randomly select households from each strata. Sampling was conducted at a 5.86% level of interval. Initially, all surveyed households were categorized into five different land classes according to HIES (2010), however eventually this study considered only those households who owned land area less than 1 ha (Table 1). This is because this study focused mainly on small landholders and use of their homestead and field resources. Thus a total of 1,119 households from three types of land ownership categories, as defined by the Bangladesh Household and Income Expenditure (HIES) surveys, were sampled and surveyed from the study areas: a) functionally landless households (<0.19 ha); b) marginal households (0.2-0.6 ha); and c) small households (<0.61-1.0 ha).

---

[44] *Upazila* is a sub-district, a smaller administrative unit in Bangladesh formerly called thana.

[45] The smallest administrative unit of Bangladesh.

A semi-structured questionnaire was used to conduct the survey and collect information on land holding size, land lease or rent status, farming practice, income, species diversity, shocks and risk involved in different components and resource use patterns between HFS and FCS. The HFS of this study includes five components: aquaculture, vegetable gardening, fruit gardening, poultry and livestock. The questionnaire was translated, tested and modified prior to the survey. Ten male and one female temporary employees of WorldFish were assigned the task of visiting each household and interviewing the household head by asking the questions set out in the questionnaire.

Table 1. Distribution of households according to landholding size (% reported on household number)

Land categories	ha	Dec (~)	Polder-30	Polder-3-H	Polder-3-L	Polder-43	Total
Functionally landless	<0.19	< 47	212 (63)	148 (70)	160 (64)	145 (45)	**665 (59)**
Marginal	0.2-0.6	48-148	83 (25)	46(22)	74 (29)	112 (35)	**315 (28)**
Small	>0.6-1.0	149-247	43 (13)	16(8)	17 (7)	63 (20)	**139 (12)**
Total			**338 (30)**	**210 (19)**	**251 (22)**	**320 (29)**	**1,119 (100)**

Note: Values in parentheses are percentages

The data analysis was conducted using SPSS version 16.0. Descriptive analysis (frequency distribution, mean, standard deviation) was performed to present basic homestead and field crop resources, farming practices of household categories by location, the shocks and risk faced by the households, and integration and recycling patterns of resources between systems. Comparisons on income and food security ratio of different household categories and locations were made by ANOVA *F*-test and a two-tailed $P<0.05$ indicated statistically significant differences unless otherwise stated in the text.

The level of household food security was computed using quantitative methods developed by Bala and Hossain (2010). This method was developed based on the food security concept of USDA (2007). Using this concept, Bala and Hossain defined food security as follows:

Food security = [(food available from different sources and also equivalence food from different sources – food requirement)]/food requirement (1)

According to this concept, all food aid commodities were converted into grain equivalents based on calorie content. Yusuf and Islam (2005) however proposed that a dietary composition for balanced nutrition in Bangladesh should be 2,345 kcal/cap. The proposed 2,345 kcal is equivalent to 1.357 kg of rice based on price. Thus, Bala and Hossain converted all food aid commodities into grain equivalents based on economic returns (price) in order to compute food security, and these grain equivalents are termed equivalent foods (Majumder et al 2012).

Therefore, following Bala and Hossain and Majumder et al. (2012), food security for this study was computed as follows:

Household food security from homestead system = [(food available from aquaculture and equivalent food from income of aquaculture + food available from livestock and equivalent food from income of livestock + food available from poultry and equivalent food from income of poultry + food available from vegetable and equivalent food from income of vegetable + food available from fruit and equivalent food from income of fruit = total food requirement)]/total food requirement (2)

Household food security from FCS =[(food available from paddy and equivalent food from income of paddy + food available from fish and equivalent food from income of fish + food available from vegetable and equivalent food from income of vegetable = total food requirement)]/total food requirement (3)

The beta (*β*) diversity index, based on presence-absence (0/1) data, was measured to illustrate the comparative diversity of homestead and field farming systems. The eight measures of beta (*β*) diversity available and described in Koleff et al. (2003) were computed using PAST (PAleontological Statistics) software (Hammer et al. 2001). These two system varied in their structure and components. Hence, to measure *β* diversity index, this study only consider components or species that are horticultural crops/species. This allowed for a more realistic comparison between the two systems.

3. Results

3.1 Characterizing land categories and functional groups

About 60% of the surveyed households belong to the functionally landless category, followed by small (28.15%) and marginal (12.42%) households (Table 1). Polder-3H had a relatively high numbers (70%) of functionally landless households, while the lowest numbers of these households was recorded in Polder-43. In contrast, among the marginal households, Polder-43 had the relatively highest (35%) number. Likewise in the marginal household category, Polder-43 had relatively higher numbers of small households, while the lowest was recorded in Polder-3L. This suggests Polder-43 had relatively more resource-rich households.

On average, households owned two and a half times more non-homestead land (field) than homestead land. This difference is greater for the marginal household (almost three times) and small household (five times) categories. This difference was most pronounced in Polder-30 where households owned three times more non-homestead land than homestead land. The mean area of homestead land ranged from 0.03±0.03 (functionally landless; Polder-3-H) to 0.17±0.21 (small; Polder-43) (Table 2). The highest mean land area of non-homestead land was 0.67±0.16 (small; Polder-3L) while the lowest was 0.01±0.03 (functionally landless; Polder-3-H and Polder-3-L). Nevertheless, there was a great deal of variation in landholding size within household categories and polders.

Table 2. Mean homestead land and field crop land area (ha) by household category and location

Location	Functionally Landless		Marginal		Small		Overall mean	
	HL	FCL	HL	FCL	HL	FCL	HL	FCL
Polder-30	0.04 ±0.30	0.02 ±0.04	0.09 ±0.70	0.27 ±0.12	0.09 ±0.70	0.71 ±0.12	0.06 ±0.06	0.17 ±0.24
Polder-3-H	0.03 ±0.03	0.01 ±0.03	0.08 ±0.07	0.29 ±0.11	0.17 ±0.21	0.57 ±0.23	0.05 ±0.08	0.12 ±0.19
Polder-3-L	0.04 ±0.03	0.01 ±0.03	0.11 ±0.11	0.25 ±0.13	0.11 ±0.09	0.67 ±0.16	0.06 ±0.08	0.13 ±0.20
Polder-43	0.04 ±0.04	0.03 ±0.04	0.12 ±0.09	0.27 ±0.14	0.16 ±0.11	0.62 ±0.15	0.09 ±0.09	0.23 ±0.25
Overall mean	**0.04^{a} ±0.03**	**0.02^{a} ±0.04**	**0.10^{b} ±0.09**	**0.27^{b} ±0.13**	**0.13^{c} ±0.12**	**0.65^{c} ±0.16**	**0.07 ±0.08**	**0.17 ±0.23**

Note: HL= homestead land, FCL=field crop land. Mean values followed by different superscript letters indicate significant difference (P < 0.05) based on ANOVA (test was done for HL and FCL separately among the household categories).

On average, within homestead land aquaculture ponds occupied approximately 33% of the land, followed by fruit gardens (17%) and dwelling houses (15%) (Fig. 2a). Approximately 36% of the homestead land area of Polder-43 was covered by aquaculture pond followed by Polder-3L (32%). On average, on non-homestead land, crop land was the predominant land cover type (78%) followed by rice-fish plots (6%) (Fig. 2b). Approximately 90% of the non-homestead land area of Polder-43 was covered by crop land, followed by Polder-30 (83%).

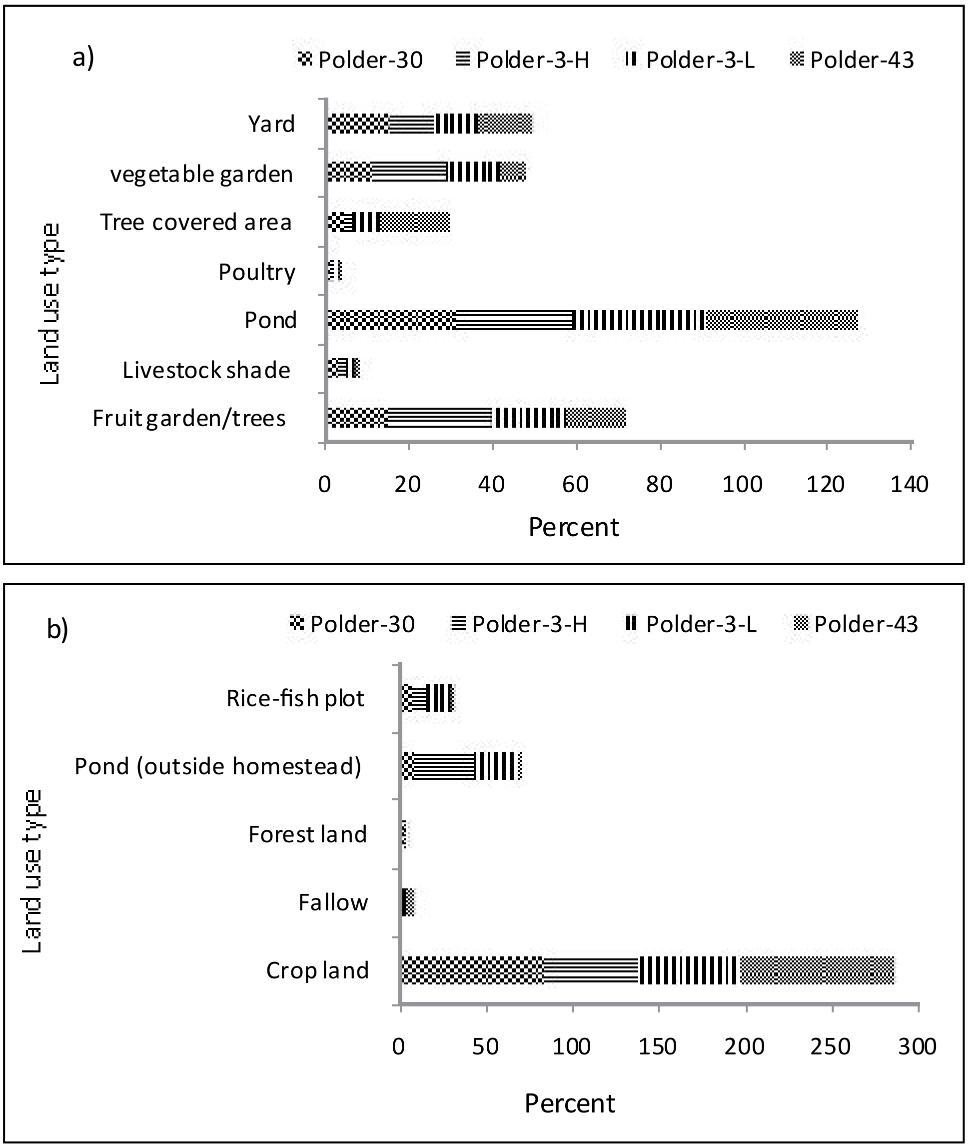


Fig. 2. Frequency distribution of land use by location for a) HFS and b) FCS.

3.2 Household income and food security

Most (69.72%) of the functionally landless households depended on HFS for food supply, while 30.28% depended on FCS (Table 3). In contrast, most small households relied on FCS (65.11%) for their food supply. The marginal households category was also more likely to depend on FCS (57.32%) for their food supply.

The small households category obtained the highest mean income from HFS while the households of the functionally landless category earnedthe lowest (Table 3). Income obtained from HFS did not vary significantly (>0.05) among the household categories. The income of small households from FCS was, however, significantly higher (<0.05) compared to the other categories. The income of marginal households from FCS was also significantly higher (<0.05) compared to the functionally landless category. The comparatively higher income of small households from both systems allowed them to purchase a greater amount of food staples equivalent of rice (ton). Like income from HFS, the higher food security ratio was also obtained for the small household category, though the ratio did not vary significantly (>0.05) among the categories. In contrast, the food security ratio of small households obtained from FCS was significantly (<0.05) higher than the other two categories. A very high and positive (598.83%) food security status, obtained from FCS, was also observed for the small households category while the lowest was recorded for the functionally landless category (123.2%).

The mean household income obtained from HFS was significantly (<0.05) higher in Polder-3L and Polder-3H compared to Polder-30 and Polder-43 (Table 4). In contrast, the mean household income obtained from FCS was found to be significantly (<0.05) higher in Polder-3L compared to other household categories. Like household income, the household food security ratio was found to be significantly higher in Polder-3L and Polder-3H compared to other categories. The household food security ratio obtained from FCS was found to be significantly (<0.05) higher in Polder-3L. The household food security status obtained from HFS was found to be positive and varied from 219.3% (Polder-30) to 334.22% (Polder-3L). The household food security status obtained from FCS was much higher (370.88%) in Polder-3L, while the lowest (193.69%) was recorded in Polder-43. HFS contributed greatly to the food supply of Polder-3L households while FCS was a greater contributor to the food supply of Polder-30 households.

Table 3. The relative contribution of HFS and FCS to food security status by household category

Variables	Functionally landless (N=665)		Marginal (N=315)		Small (N=139)	
	HFS	FCS	HFS	FCS	HFS	FCS
Income from Homestead Production (US$)	698.57[a]	412.65[a]	694.15[a]	888.33[b]	727.09[a]	1291.99[c]
Equivalent to rice (ton) [EC]	1.87[a]	1.11[a]	1.86[a]	2.38[b]	1.95[a]	3.46[c]
Required rice (ton/year)[RR]	0.5	0.5	0.5	0.5	0.5	0.5
Food security ratio [FSR= EC-RR/RR]	2.78[a]	1.23[a]	2.75[a]	3.8[b]	2.93[a]	5.99[c]
Food security status (%) [FSR*100]	277.85	123.2	275.46	380.49	293.27	598.83
*Contribution in HS food (%)	69.72	30.28	42.68	57.32	34.89	65.11
Contribution in food requi-rement (%) [EC/RR*100]	377.85	223.2	375.46	480.49	393.27	698.83

Note: *Food from homestead/total food*100

Table 4. The contribution of HFS and FCS to household food security status by location

Variables	Polder-30 (N=338)		Polder--3-H (N=210)		Polder-3-L (N=251)		Polder-43 (N=320)	
	HFS	FCS	HFS	FCS	HFS	FCS	HFS	FCS
Income from Homestead Production (US$)	592.23[a]	625.7[a]	798.13[b]	624.63[a]	805.37[b]	873.37[b]	677.72[a]	544.72[a]
Equivalent to rice (ton) [EC]	1.58[a]	1.67[a]	2.13[b]	1.67[a]	2.15[b]	2.33[b]	1.81[a]	1.46[a]
Required rice (ton/year)[RR]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Food security ratio [FSR= EC-RR/RR]	2.19[a]	2.37[a]	3.34[b]	2.37[a]	3.30[b]	3.71[b]	2.65[a]	1.94[a]
Food security status (%) [FSR*100]	219.3	237.35	330.31	236.77	334.22	370.88	265.4	193.69
*Contribution in HS food (%)	53.26	46.74	63.45	36.55	57.59	42.41	58.99	41.01
Contribution in food requi-rement (%) [EC/RR*100]	319.3	337.35	430.31	336.77	434.22	470.88	365.4	293.69

Note: *Food from fieldcrop/total food*100. Numbers in parentheses are standard error mean. Mean values followed by different superscript letters indicate significant difference (P < 0.05) based on ANOVA.

Approximately 11% and 52% of functionally landless households depended on HFS and FCS, respectively, and were food insecure when they solely considered HFS or FCS as their source of food supply (Table 5). This trend is, however, opposite for the small household category where approximately 38% and 9% of small households that depend on HFS and FCS, respectively, were food insecure. However, when households depended on both HFS and FCS for their food supply, they tended to be less food insecure (1%).

Table 5. Households with positive and negative food security status by household category (% reported on household number)

HH types	HFS		FCS		Overall	
	Negative FS	Positive FS	Negative FS	Positive FS	Negative FS	Positive FS
Functionally landless	11	89	52	48	2	98
Marginal	29	71	13	87	1	99
Small	38	62	9	91	0	100
Overall mean	20	80	36	64	1	99

Note: Negative FS= negative food security status, Positive FS= positive food security status

3.3 Defining two systems in the context of diversity and resilience

3.3.1 Diversity

The higher values of β diversity index in FCS indicates lower similarity among the varieties in different polders (Table 6). By contrast, lower values of β diversity index in HFS indicate higher similarity among the varieties in different polders. There were more than 70 and 40 horticultural crops/varieties in HFS and FCS, respectively.

Table 6. Global beta diversity index of homestead and FCS

Index	HFS	FCS
Whittaker	1.660	0.314
Harrison	0.550	0.100
Cody	25.000	24.000
Routledge	0.260	0.080
Wilson-Shmida	1.580	0.450
Mourelle	0.530	0.150
Harrison2	0.070	0.060
Williams	0.166	0.150

3.3.2 Shocks and risk ranking

Approximately 55% of households reported diseases as the major risk to HFS, followed by epidemic (27%) and poaching and accident (8.12%) (Table 7). Among the HFS components, poultry was reported to be highly affected by diseases (33.57%) and also epidemics (30%). Aquaculture, one of the major components of HFS, was mostly reported to be vulnerable to flooding. Overall, among the HFS components, vegetable production, fruit gardening and aquaculture seemed to be less risky while poultry was considered highly vulnerable.

Table 7. Shocks and risk for different components of HFS (% reported on household number; N=554)

Rank	Shocks and risks	Aquaculture	Fruit/ tree	Livestock	Poultry	Vegetable	Overall mean
1	Disease	0.54	0.00	20.76	33.57	0.00	54.87
2	Epidemic	0.00	0.00	1.99	25.99	0.00	27.98
3	Poaching and accident	0.00	0.00	2.71	5.42	0.00	8.12
4	Disaster	0.00	0.18	1.08	2.35	1.08	4.69
5	Flooding	3.25	0.00	0.00	0.00	0.00	3.25
6	Others (Poor water quality etc.)	1.08	0.00	0.00	0.00	0.00	1.08
	Overall mean	4.87	0.18	26.53	67.33	1.08	100.00

Approximately 47% of households reported diseases in rice, due to pest attack, as a major problem in FCS (Table 8). Flooding (28%) also caused serious problems in FCS. Diseases in fish (fish culture with paddy) were also reported to negatively affect FCS.

Table 8. Shocks and risk for FCS (% reported on household number; N=554)

Rank	Shocks and risk	Percent
1	Diseases outbreak in rice due to pest infestation	46.67
2	Flooding	28.10
3	Fish disease	20.00
4	Poisoning problem in rice field	1.43
5	Rice damaged due to saline water intrusion	1.43
6	Pest attack in vegetables	0.95
7	Fish died due to saline water intrusion	0.48
8	Irrigation problem	0.48
9	Vegetable field damaged by excess water	0.48

3.3.3 Environment, integration and recycling of resources

The different level of integration and recycling of resources in HFS and FCS can be described as inter- and intra-relationships of these systems, respectively (Fig. 3). The HFS system worked more as an inter-system where integration and resource flows were observed among five components. In HFS, 57.51 % of households used pond water for poultry production. Similarly, 50.08% of households used pond water for vegetable production. Approximately 21.8% of households used poultry and/or livestock manure to produce fruits and vegetables. In addition, approximately 11% and 8.39% of households fertilized aquaculture ponds for fish production through livestock manure and poultry litter, respectively. Homestead aquaculture ponds were found to be a major source of resource flows among HFS components.

In contrast, FCS acted more like an intra-system where rice was the major contributor to integration and resource flow (Fig. 3). Approximately 44% of households reported that they used straw as fertilizer to fertilize the same field for the next cropping cycle. Likewise, vegetables (mostly cabbage) were also used as fertilizer to fertilize fields. Eighteen percent of households used the same water to produce both rice and fish. Livestock are not a component of FCS, however, they had so much influence on FCS and were very closely linked with rice production and thus shown as an overlapping component within FCS.

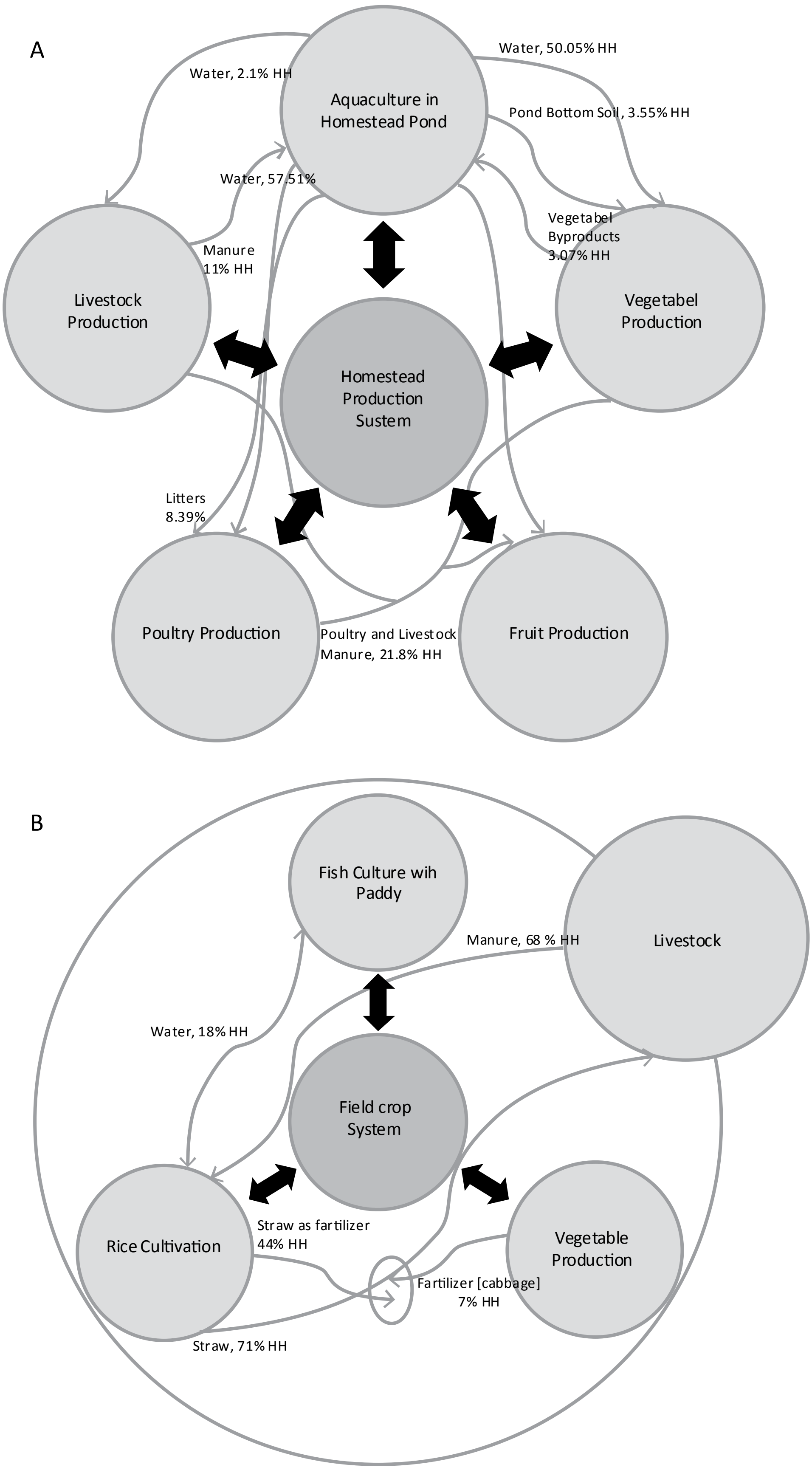


Fig. 3. Integration and recycling of resources among different components of HFS and FCS.

4. Discussion

4.1 HFS for household categories: who benefited most?

HFS showed strong potential to contribute to household food security, especially for functionally landless households in the southwest coast of Bangladesh. The food security ratio did not vary greatly among the household categories in HFS, whilst the food security ratio of small and marginal households was significantly higher than functionally landless households in FCS. This implies that functionally landless households, in general, are likely to explore and utilize more of their homestead resources. Households with smaller land holdings, such as functionally landless households, tend to be less reliant on FCS which is probably due more to the fact that they don't have sufficient access to field cropland, than to their willingness and ability. Land is a critical asset, especially for the rural poor as a means of livelihood through the consumption and sale of crops and other products (Meinzen-Dick et al. 2007). Functionally landless households with limited access to land may seek employment opportunities from other farmers or non-farm sources; however the growth and stability of such employment is also dependent on the production and profitability of homestead farming (Meinzen-Dick et al. 2007). Thus, resource-poor farmers often tend to depend more on homestead production for their food staples and secondary staples than those endowed with a fair amount of assets and resources such as land and capital (Wiersum 2006; Galhena et al. 2013). This is strongly supported by the findings of this study since almost 70% of the food staples of functionally landless groups came from HFS. In recent years, a rapid increase in participation of women, particularly from resource-poor households, in homestead farming was observed (BBS 2013; Khatun et al. 2014). This was most probably also one of the major reasons of higher dependency of poorer households on HFS. Marginal and small households were however more dependent and focused on FCS even though they owned sufficient homestead land. This is also evident from the relatively higher (more than 65%) contribution of FCS to the total household food supply of small households. Marginal households also received a comparatively larger share of total household food supply from FCS. This indicates that marginal and small households are not much interested in bringing more homestead land under cultivation. They seem to invest more in cropland. Rice is the largest and most profitable crop practiced within FCS and requires additional inputs such as high yielding varieties of seeds, chemical fertilizers, irrigated water, pesticides and labor (Quddus 2009). Households with comparatively larger land holdings and higher income, mostly mariginal and small, were thus more likely to focus on FCS. In contrast, HFS requires minimal inputs and labor, most of which are managed by household members and thus mainly contributes to meeting farmers' basic needs (John 2014). This in fact indicates that HFS is more suitable for resource-poor or functionally landless households in helping to meet household food security and producing a marketable surplus for the purchase of non-producible items. If resource-rich marginal and small households are involved in more HFS, they can increase their food security status as well as contribute to a steady supply of products for the local market (Meinzen-Dick et al 2007). Thus, HFS can positively contribute to food security from the household to the national level.

4.2 Does location influence the relative contribution of HFS and FCS to household food security?

The households of Polder-3H and Polder-3L earned significantly higher than Polder-30 and Polder-43 from HFS and thus became more food secure. This is most probably attributed to the suitable agroecologial settings that offer better farming practice opportunities among the studied areas. Households in Polder-3H and Polder-3L were also likely ready to explore optimum opportunities from both the systems. Livestock, vegetable and fruit gardening were reported to be most preferable and profitable homestead farming components, mainly for the subsistence farmers of Bangladesh (Sarma and Ahmed. 2011; Khatun et al, 2014). The higher land elevation of Polder-3H might be helpful in producing vegetables and fruits even during periods of waterlogging (July to September) in this area. In contrast, households may also use water logging areas for seasonal fish culture (Das et al 2009) and thus can contribute to improving their household food security. The largest share of household food supply in Polder-3H (≈63%) and Polder-3L (≈58%) also came from HFS. This also indicated that resource poor households (≈59% in this study), mostly functionally landless and partly marginal households irrespective of locations, in the coastal area of Bangladesh predominantly depend on

HFS for meeting a greater portion of their basic food staples. Salinity has been reported to exert a negative effect on the farming households and agro-diversity in the coastal zone of Bangladesh (Rahman et al 2011; Rabbani et al 2013b). The higher household food security ratios obtained from HFS however was reported from Polder-3H and Polder-3L which had the highest salinity levels among the study areas. Thus, in fact the results of this study did not demonstrate any negative effects of salinity on HFS, which implies a certain resilience to salinity changes in the studied areas.

The household food security ratio from FCS did not vary significantly among the polders except Polder-3L. The higher food security ratio in the households of Polder-3L was perhaps due to the higher yield from aman and boro crop. Aman is a rain-fed rice crop (Basak, 2011; WFP, 2014) and covers about 70% of the total rice cropped area in the coastal zone of Bangladesh (Mia and Islam 2005). Polder-3L, as a low lying area, has the highest capacity to store rainwater and thus significantly supports aman crop (Basak, 2011). In addition, Boro rice crop is completely dependent on irrigation (WFP, 2014). Polder-3L is expected to have higher ground water recharge capacity, consequently higher ground water level, and also situated adjacent to the Ichamati River thus providing easy access to irrigation. Thus the significantly higher food security ratio in the households of Polder-3L implies that availability and access to freshwater resources, minimizing the negative impact of salinity intrusion, may be a crucial factor for FCS. Therefore this study argues that salinity, availability of freshwater and land elevation may influence the relative contribution of food security both in HFS and FCS.

4.3 Are HFS resilient and environmental sound systems in the context of coastal areas?

The agro-ecology of coastal Bangladesh is highly dynamic and significantly influenced by different factors such as changing land use patterns (Mia and Islam 2005), salinity (Roy 2004; Rahman et al. 2011; Roy et al. 2013), and climate induced hazards including variations in temperature, erratic rainfall patterns, drought, cyclones and storm surges, flooding, and rising sea levels (Shamsuddoha and Chowdhury 2007; Rabbani et al. 2013a ; Rabbani et al. 2013b; SRDI 2013). The resilience of a system may depend on its capacity to maintain functioning, structure, and feedback in the face of disturbance (Folke et al. 2004). The lower similarity, with lower number of varities, among the horticulture varieties of FCS indicates that these species are not equally capable of adapting to the dynamic ecological settings of the different polders. In contrast, the higher similarity among the horticulture species (more than 70) of HFS indicates that most of the species were present in all four polders and have comparatively higher resilience capability to adapt to different, adverse and dynamic environmental conditions. This is also supported by previous findings that species in HFS are less susceptible to environmental factors such as salinity. Additionally, aquaculture, livestock and poultry components of HFS comprise approximately 25 fish species, four and three animal species, respectively. A recent study done by Bhattacharya et al. (2013) also reported more than 40 local varieties of horticultural crops and 25 fish species in HFS in West Bengal, India. The higher number of species in HFS also reveals this system's capacity to consistently support diversified horticultural crops and may be very helpful against confronting climate change.

A system's ecological resilience and stability may also focus on a system's response to shocks and long-term change (Folke et al. 2004; Leslie and Kinzig 2009). This study identified six different types of shocks and risks in HFS. The problems in FCS are categorized under nine different key points. Both systems were considerably threatened by diseases. However, among the components in HFS, poultry is severely affected by diseases. The most common diseases are IBD, Aflatoxicosis, Chicken Anemia virus, Egg Drop Syndrome and Avian influenza (bird flu). Despite facing diseases, poultry farming has recently experienced tremendous development in Bangladesh due to its role in poverty alleviation and economic development (Uddin et al 2010). In contrast, flooding stands as a noteworthy factor that can cause huge damage mostly to FCS. Flooding is a large-scale natural disaster and can unpredictably damage huge amounts of crops as it is very rarely possible to protect cropland (Khan et al. 2012). Within HFS, livestock, vegetables and fruit gardening are found to make a larger contribution to household income. Bhattacharya et al. (2013) reported that household income in HFS was comprised of aquaculture (54%) followed by animal husbandry (37%) and horticulture (9%). Since poultry is a risky agribusiness, households have the option to choose and invest in other HFS components. This will still allow them to earn sufficient money to improve their household food security status. Thus, HFS allows year round cultivation of different agricultural products (horticulture, aquaculture, etc.) that can provide either a source of additional income to the households or function as an alternative livelihood (Bhattacharya et al. 2013).

Intelligent management of available resources of a farming system through integration and recycling is important for optimum utilization of land, improving food security, better income generation, as well as nutritional security of small and marginal farmers (Jayanthi et al. 2009; Dadabhau and Kisan 2013). The higher level of integration and recycling of resources in HFS shows that this system has better potential to integrate and recycle most of its resources. The components of this system worked more in an inter-relationship where pond water is considered to be the most important driver of the system. All of the five components of HFS, including aquaculture, somehow depend on pond water during their production cycles. This occurs through several ways, such as for washing, making foods, drinking purposes, and irrigating plants and vegtables, in the form of nutrient supply and finally to produce fish from the pond. The diversity of resource flow is also much higher in HFS than FCS in the form of water, manure, vegetable byproducts and pond bottom soil. The most notable advantage of utilizing these byproducts within the system is that this increases the biological capacity of the system and increases system productivity. Jayanthi et al. (2009) articulated that integration and utilization of low-cost/no-cost material at the farm level of recycling reduces production costs and consequently improves productivity and income considerably. However, the lower level of integration in FCS compared to HFS implies that households might explore the potential of further intensification of HFS for increasing production and income.

This study nevertheless confirms that there are some limitations, although it has yielded some interesting and preliminary findings on household food security. The food security model that was used does not consider nutritional aspects of the households. However, this study assumes that if households produce sufficient food and have money to buy food staples they are likely to maintain the dietary composition for balanced nutrition proposed by Yusuf and Islam (2005). Additionally, HFS and FCS are two distinct systems. Therefore the system characteristics of these two systems should differ from each other and, in some cases, may not be comparable. The comparative overview was not specifically done to draw any conclusions about the better system, but rather to depict some advantages and disadvantages that might be useful for particular groups.

5. Conclusion

HFS has several advantages such as available family labor, multi-crop and diversified species cultivation, use of household refuses, resource flow among the components, low cost or available input and, most importantly, owning a small pice of homestead land. HFS proved to be very suitable for poor farmers, especially those that are functionally landless and in some instances for marginal farmers. In Bangladesh, functionally landless households own <0.19 ha of land and have long been known to depend on a combination of various forms of agricultural tenancy, laboring and non-agricultural livelihoods (Hossain et al. 2003). HFS could allow most of these household farmers to minimize risk, and increase production and profits whilst improving the utilization of organic wastes, residues and byproducts. HFS has the potential to improve the household food security of the poor irrespective of their land holding size. The potential and benefits of HFS could be much higher if other household categories, such as small households, also become interested in HFS. This will provide sufficient quantities of food staples at local markets at affordable prices, and will consequently help poorer household meet their household food requirements. However, intensification of HFS might be hampered due to an inadequate supply of inputs and adoption of improper management practices. Therefore, available supply of quality inputs must be ensured and farmers' knowledge and technical skills should also be improved through capacity building programs in the form of awareness programs, trainings and workshops.

References

Alam M.A., M.A. Rahman, M.S. Flora, M.R. Karim, M.P.I. Sharif and A. Ahmad. 2011. Household Food Security and Nutritional Status of Rural Elderly. *Bangladesh Medical Journal*. 40(3): 8-11.

Alinovi, L., E. Mane and D. Romano. 2009. *Measuring household resilience to food insecurity: Application to Palestinian households.* Food and Agriculture Organization, Rome.

Bala, B. K. and M.A. Hossain. 2010. Food security and ecological footprint of the coastal zone of Bangladesh. *Environment, Development and Sustainability*. 12(4): 531-545.

Basak, J.K. 2011. Changing Rainfall Pattern Effects on Water Requirement of T.Aman Cultivation in Bangladesh. *Public Journal of Environmental Science*. 11(1).

Bhattacharya, A., A.D. Deo, J.K. Sundaray and A.G. Ponniah. 2013. *Impact of homestead farming system on rural economy: A study in South 24 Pargana district of West Bengal*. Presented at International Ecosystem Conservation, Climate Change and Sustainable Development Conference, held in Kerala, India on 3-5 October 2013. Abstract, 1 p.

Dadabhau, A.S. and W.S. Kisan. 2013. Sustainable Rural Livelihood Security Through Integrated Farming Systems – A Review. *Agri. Reviews*. 34(3): 207-215.

Das N.G., M.S. Hossainand M.S. Islam. 2009. Waterlogged Area as New Horizon for Aquaculture Development: A Golden Dream to the Rural Communities of Begumgonj, Noakhali. *Bangladesh Journal of Marine Sciences and Fisheries*. 1(1): 47-62.

FAO. 2014. Household food security and community nutrition. FAO Agriculture and Consumer Protection Department. http://www.fao.org/ag/agn/nutrition/household_en.stm

Faridi, R. and S.N. Wadood. 2010. An Econometric Assessment of Household Food Security in Bangladesh. *The Bangladesh Development Studies*. 33(3): 97-111.

Galhena, D., R. Freed and K. Maredia. 2013. Home Gardens: A Promising Approach to Enhance Household Food Security and Wellbeing. *Agriculture & Food Security*. 2(1): 2-8.

Giraldo, D. P., M. J. Betancur and S. Arango. 2008. *Food security in developing countries: A systemic perspective*. Paper presented at the International Conference of the System Dynamics Society held in Athens, Greece on 20-24 July 2008.

Hammer, Ø., D.A.T. Harper and P. D. Ryan. 2001. PAST: Paleontological Statistics Software Packagefor Education and Data Analysis. *Palaeontologia Electronica*. 4(1): 9pp.

Hossain, M., D. Lewis and S. Begum. 2007. Rice Research, Technological Progress and Poverty: The Bangladesh Case. Pp. 56-102. In *Agricultural Research, Livelihoods and Poverty*. Eds M. Adato and R. Meinzen-Dick. Baltimore, MD: Johns Hopkins University Press.

Huq, S. and G. Rabbani. 2011. Climate Change and Bangladesh: Policy and Institutional Development to reduce vulnerability. *JBS*. 13: 1–10.

Jayanthi, C., C. Vennila, K. Nalini and B. Chandrasekaran. 2009. Sustainable integrated management of crop with allied enterprises: Ensuring livelihood security of small and marginal farmers. *The Asia Pacific Tech Monitor*. 26(1): 21-27.

John, J. 2014. Homestead Farming in Kerala: A Multi-Faceted Land-Use System. *Review of Agrarian Studies*. 4(1): 80-94.

Kashem M.A., M.G. Farouque and P.C. Roy. 2013. Impact of Crop Varieties on Household Food Security in Haor Areas of Bangladesh. *Int. J. Agril. Res. Innov. & Tech*. 3(2): 7-11.

Khan M.N.H., M.Y. Mia and M.R. Hossain. 2012. Impacts of Flood on Crop Production in Haor Areas of Two Upazillas in Kishoregonj. *J. Environ. Sci. & Natural Resources*. 5(1): 193-198.

Khatun M.F., M.K. Hossain, K.A. Hossain and M.M. Rahman. 2014. Participation Potential of Rural Women in Different Homestead Farm Activities. *The Agriculturists*. 12(1): 57-67.

Majumder S., B.K. Bala and M.A. Hossain. 2012. Food Security of the Hill Tracts of Chittagong in Bangladesh. *Journal of Natural Resources Policy Research*. 4(1): 43-60.

Meinzen-Dick, R., P. Kameri-Mbote and H. Markelova. 2007. Property Rights for Poverty Reduction. *2020 Focus Brief on the World's Poor and Hungry People.* Brief. International Food Policy Research Institute, Washington DC.

Quddus, M.A. 2009. Crop production growth in different agro-ecological zones of Bangladesh. *Journal of Agicultural University*. 7(2): 351-360.

Rabbani, G., S.H. Rahman and L. Faulkner. 2013a. Impacts of Climatic Hazards on the Small

Wetland Ecosystems (ponds): Evidence from Some Selected Areas of Coastal Bangladesh. *Sustainability 2013*. 5(4): 1510–1521.

Rabbani, G., A. Rahman and K. Mainuddin. 2013b. Salinity-induced loss and damage to farming households in coastal Bangladesh. *Int. J. Global Warming*. 5(4): 400–415.

Rahman M.H., T. Lund and I. Bryceson. 2011. Salinity impacts on agro biodiversity in three coastal, rural villages of Bangladesh. *Ocean and Coastal Management*. 54(6): 455–468.

Sarma P.K. and J.U. Ahmed. 2011. An economic study of small scale cattle fattening enterprise of Rajbari district. *J. Bangladesh Agri. Univ.* 9(1): 141–146.

Shamsuddoha, M. and R.K. Chowdhury. 2007. *Climate Change Impact and Disaster Vulnerabilitiesin the Coastal Areas of Bangladesh.* COAST Trust, Dhaka.

Soemarwoto, O. 1987. Homegardens: a traditional agroforestry system with a promising future. In *Agroforestry: A Decade of Development*. Eds. H. Steppler and P.K.R. Nair. Nairobi, Kenya: International Council for Research in Agroforestry.

SRDI. 2013. *Trends in the availability of agricultural land in Bangladesh*. Technical Report. Soil Resource Development Institute, Ministry of Agriculture, Bangladesh.

Uddin, M.B., S.S.U. Ahmed, M.M. Hassan, S.A. Khan and M.A. Mamun. 2010. Prevalence of poultry diseases at Narsingdi, Bangladesh. *Int. J. BioRes.* 1(6): 9-13.

Uddin, M.E. 2012. Household Food Security Status of Marginal Farmers in Selected Storm Surge Prone Coastal Area of Bangladesh. *The Agriculturists*. 10(1): 98-103.

WFP (World Food Program). 2014. Agricultural Production & National Food Balance. Accessed on 7th December 2014. Available at http://www.foodsecurityatlas.org/bgd/country/availability/agricultural-production#section-12.

Wiersum, K.F. 2006. Diversity and change in homegarden cultivation in Indonesia. In *Tropical Homegardens: A Time-Tested Example of Sustainable Agroforestry*. Vol 3. Ed. Nair BMKPKR. Dordrecht, The Netherlands: Springer Science.

Homestead farming: A biodiverse system to enhance resilience to climate vulnerability

J.K. Sundaray[1*], A. Bhattacharya[2], A.G. Ponniah[3], T.K. Ghoshal[2], A.D. Deo[4], J.P. Sharma[2] and M. Phillips[5]

[1*]Central Institute of Freshwater Aquaculture, India, jsundaray@gmail.com
[2]Kakdwip Research Centre, CIBA, India
[3]Central Institute of Brackishwater Aquaculture, India
[4]Central Institute of Fisheries Education, India
[5] WorldFish, Malaysia

Abstract

Climate change will have a profound impact on agriculture and aquaculture in India due to the inundation of land with saline water and the widespread freshwater shortages that will impact vulnerable rural communities. Against this backdrop, homestead farming, a resource-rich farming system adjacent to the homestead, is examined as a mechanism to support rural livelihoods and provide resilience against the expected increase in environmental and economic turbulences due to climate change. A study was conducted on 480 households, selected from Kakdwip, Namkhana and Sagar blocks in West Bengal, India to assess the biodiversity in homestead farming systems (HFS) and the potential for mitigating the impact of climate change on rural livelihoods using HFS. A total of 42 crop varieties, 38 aquaculture species and five animal species were recorded in these small (average size of 0.1 ha), complex farming systems including coconut, mango, potato, fish, cattle and poultry. Seventy-six percent of the crops grown were food items (vegetable and fruits), followed by spices (12%), medicinal plants (12%), timber (10%) and fodder (5%). Ninety-two percent of the aquaculture produce was fish and the remaining 8% was shrimp/prawns. By incorporating a biodiverse assemblage, a synergy is promoted that enhances farm processes such as the activation of soil fertility through utilization of organic wastes. This can also result in a 39% increase in income above the national poverty line average. Through continuous production and utilization throughout the year, this farming system helps to mitigate the risks of dependency on a single crop that in some years is lost due to extreme climatic events like heavy rain, cyclones and disease. It also supports the dietary diversity of households and contributes 6%, 24% and 26% of total required energy, protein and fat, respectively, resulting in a reasonable degree of nutritional wellbeing of the household members. The present study has shown that investing in this system can help to mitigate the impact of climate variability.

Keywords: homestead farming, biodiversity, polyculture, climate change, resilience

1. Introduction

Climate change is a change in the state of the climate that can be identified by changes in the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC 2007). Vulnerability to climate change is the degree to which geophysical, biological and socio-economic systems are susceptible to and unable to cope with the adverse impacts of climate change (Fussel and Klein 2006). Climate change is projected to intensify the challenges already faced by smallholder farmers globally. Changes in rainfall, rising temperatures and variations in soil carbon utilization by crops are expected to negatively influence the growing conditions and the potential yields of many crops (Amikuzuno and Hathie 2013). Although the effect of changes in climate on crop yields varies greatly from region to region (Cline 2007) the decline in production worsens food insecurity and poverty both globally and locally (Altieri and Koohafkan 2008). In many countries including India, agriculture is largely rain-fed and farmers commonly cultivate local crop varieties and local livestock and fish breeds with little resilience to the immediate effects of climate variability such as drought, flood and large temperature fluctuation. Conversely, some local varieties are well adapted to local conditions and cultivating a range of local and improved strains of produce can enhance resilience. The severe cyclonic storm, *Aila,* which hit the Sundarban region in India and Bangladesh in 2009, resulted in extreme devastation to the agricultural sector (CSE 2012). It is estimated that climate variability will decrease cereal productivity by 10 to 40% by 2100 and a 1^0C increase in temperature will reduce wheat production by 4 to 5 million tons (Biswal 2008).

Climate change adaptation strategies are now a matter of urgency (FAO 2009). Farming households need to utilize innovative practices, experiential knowledge and locally available resources in order to be self-reliant. In many areas, particularly in the developing world, farmers practice some kind of farming system adapted to the local conditions that enables them to generate sustainable yields to meet their subsistence needs, despite marginal land endowments, climatic variability and low use of external inputs (Wilken 1987; Denevan 1995). Part of this success is linked to the high levels of biodiversity exhibited by traditional farming systems, which in turn positively influence agro-ecosystem function (Vandermeer 2002). Diversification is an important farm strategy for managing production risk in small farming systems. In traditional farming systems the prevalence of complex and diversified cropping systems is of key importance to the stability of peasant farming systems, allowing crops to reach acceptable productivity levels even under trying environmental conditions. One of the most suitable coping mechanisms and strategies used by small and marginal holders to enhance resiliency against climatic anomalies is Homestead Farming Systems (HFS). HFS is a dynamic system, containing multiple species in an ecologically sustainable environment and is a good example of diversified production of horticulture, aquaculture and animal husbandry (Bhattacharya et al 2013b). Raised beds that do not get water- or saline-logged and the cultivation of local or improved varieties that are well adapted to the microclimate around the homestead provides resilience to HFS.

2. Materials and methods

2.1 Study area

To assess the utilization of HFS resources and the potential for mitigating the impact of climate change on rural livelihoods, a household survey was conducted in three coastal blocks in the Sundarban region of South 24 Pargana District of West Bengal, India during 2011 and 2012. The selected blocks were Kakdwip (21°52′06″N, 88°11′12″E), Namkhana (21°46′00″N, 88°14′00″E) and Sagar (21°38′09″N, 88°07′26″E), all located in the southern extremity of the district. Scattered through this area are the distributaries of the Ganges River, which are fed by sea tides. The average temperature of the district varies from a maximum of around 38°C to a minimum of around 14°C. The annual average rainfall is 1800 cm, more than 75% of which falls during the monsoon season. This area is regularly hit by the bay cyclones (District Disaster Management Plan 2012).

2.2 Sampling procedure and data collection

A random sampling method was adopted to draw representative samples of 480 households (HH) from 18 villages in each block. Twenty households were considered from each village (in Sagar, 40 households from each village). Three complementary approaches were adopted for the study: (a) formal interviews with the village-level government body to collect secondary data; (b) direct observation by project associates/authors of this paper; and (c) a pre-structured questionnaire conducted with the head or members of the selected households to collect primary information. In addition, some existing literature regarding the challenges faced by the households was also reviewed.

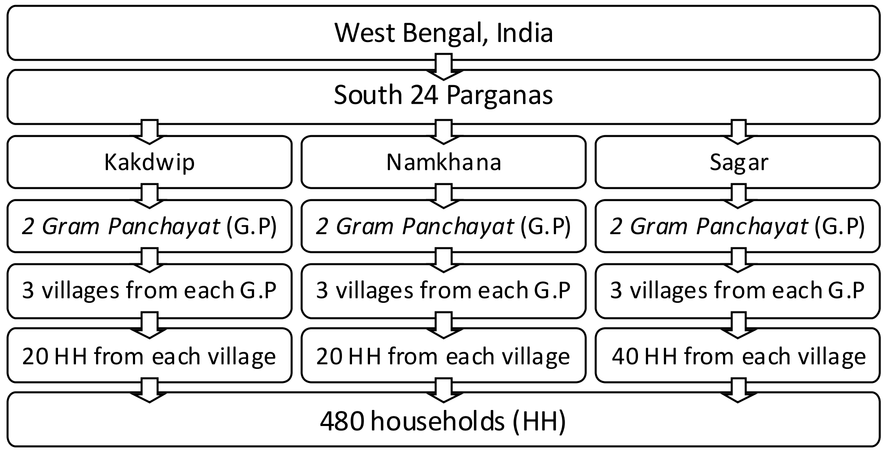


Fig. 1. Sampling frame.

2.3 Data processing and analysis

The data from the completed questionnaires were statistically analyzed with Statistical Packages and MS-Excel statistical program for both quantitative and descriptive explanations.

3. Results and discussion

3.1 Impact of salinization in the agricultural sector

Among the studied households almost 10% were facing extreme salinity intrusion that resulted in some human health impacts, reduction in crop quality and widespread freshwater shortages. The low average productivity of 2.3 ton per ha in homestead production systems in this area is likely due to salinity intrusion (District Statistical Handbook 2009). In some areas, salinity has increased beyond the safe threshold for agriculture (CSE 2012), especially for paddy production, which is an integral crop for food security and income. The limit for paddy production is 4-6 PPT, but in some of the study sites salinity reached 10 PPT. Salinity intrusion is particularly prominent in the Sagar block where salinity ranged from 5-25 PPT. Salinity penetrated to a depth of ~1.5 m in the study area, severely affecting paddy cultivation (Anon 2011). As a result farmers were switching from the traditional practice of paddy cultivation to growing produce in HFS as a climate change adaptation strategy.

3.2 Impact of climate change on the livelihoods of people in the study area

In the study site only 43% of households were engaged in natural resource-based activities (such as paddy cultivation, horticulture, wage labor in agricultural fields, wood and honey collection, fish and shrimp seed collection) as their major source of income (Table 1). Reports in 2009 demonstrated that agriculture was the primary livelihood for approximately 60% of the population (Anon 2009). This drop in the number of people relying on agriculture for their primary livelihood may have been attributed to a drop in the productivity of the land due to climate variability or the shortage of land access that resulted in 32% of the rural population shifting to non-farm casual labor (e.g. construction) as their primary occupation. Since the employment opportunities in agriculture are decreasing, seasonal migration of the earning member of the family has become the standard practice of this population. For rural households, moving away from agricultural activities can further exacerbate food insecurity by reducing access to fresh and nutritious produce. This leaves households particularly vulnerable, especially when facing the risks from climate variability (CSE 2012).

Ninety-nine households in the study region were small and marginal farmers. Farmers in this category are the most disadvantaged and are particularly vulnerable to climate anomalies (Altieri and Koohafkan 2008). Severe soil erosion and the pressure of a growing population have reduced agricultural land by 21% from 2001 to 2009 (Hazra et al. 2010). The share of households falling below poverty line (BPL) is close to 35%, 48% and 44% in Kakdwip, Namkhana and Sagar blocks, respectively (CSE 2012), due to a reduction in livelihood opportunities for households in the study region. This is a direct indicator of vulnerability of people and highlights the inability of the area to sustain and support the livelihoods of people in the area (Anon 2009). Substantial investment of resources is necessary to widen the livelihood opportunities for people in the study area with homestead farming systems being one area with potential for investment.

Table 1. Occupational distribution of the households

Source of income	% share of households
Agriculture and all natural resource based activities	43
Non-farm casual labour	32
Business	10
Van/Rickshaw pulling	5
Salaried employee in govt. sector	5
Others	5

3.3 Characteristics of the homestead farm in the study area

The homestead farm is a unit where fresh water (rainwater) is conserved in the homestead pond to provide access to fresh water for a range of household activities throughout the year. The homestead farm size ranged from 0.03 ha to 0.5 ha with a mean of 0.1 ha in this region and aquaculture comprised the largest area (Table 2). The HFS is a biodiverse micro-environment that is an integral source of food, fodder, fuel, medicines, spices, construction materials and income in many countries around the world. HFS is a dynamic, resource-rich system where the composition and diversity of species are influenced by changes in the socioeconomic circumstances and cultural values of the households that maintain these farms (Eyzaguirre and Watson 2002). The primary objective of homestead farming is subsistence production and income generation (Trinh et al. 2003). The surveyed households cultivate a combination of species with different maturity periods to ensure an uninterrupted supply of produce for their own consumption (Garí 2003) and also for the sale of surplus products to enhance income (High and Shackleton 2000; Murphy 2008; Shackleton et al. 2008).

Table 2. Land sharing among various HFS components

Components	Share of total homestead land
Aquaculture	50
Horticulture/agro-forestry	37
Animal husbandry	13

3.4 Potential contribution of homestead ponds to mitigating climatic loss

Homestead pond water is not only the key resource in HFS, but it is also an important source of fresh water in the event of inundation of surrounding land with saline water due to climate variation. Each component of HFS is directly or indirectly linked with homestead pond water, with 94% of households using it to support horticulture and agroforestry and 77% of households using it for animal rearing (Table 3).

Table 3. Utilization of homestead pond water

Particulars	% of households involved
Horticulture/agroforestry	94
Domestic activities	93
Animal rearing	77

The effective utilization of homestead pond water by a huge proportion of households helps to mitigate the damage done by saline water intrusion and therefore the pond plays a key role in influencing the economics of HFS which can return up to US$ 3,169 per ha (gross) (Table 4).

Table 4. Contribution of different components in gross return from HFS

Components	Gross return (US$ per ha land)
Aquaculture	1,711
Horticulture	275
Animal husbandry	1,183
Total	3,169

3.5 Adaptation strategies to climate change: Species composition in HFS

Systems with higher crop diversity and mixed farming (fish-crop-livestock) are thought to be more resilient to the risks of climatic change (FAO 2011). The households in this study displayed a diversified species mix with 31 key species of vegetables, crops, aquaculture and livestock. The diversified species in homestead farms demonstrates that the vegetable crops, medicinal and fodder or firewood plants cultivated in the homestead farms were convenient (Table 5) and enhanced access to food, provided treatments for common ailments, fed domestic animals, and were used as fuel and cash income, respectively (Akrofi 2012). Along with this, the aquaculture species are the primary source of animal protein. Although not yet common, the introduction of *Piaractus brachypomus*, pacu, as an aquaculture species is thought to improve the resilience of the system.

Table 5. Frequency of key species in HFS

Components	Scientific name	Common name	Frequency	Economic usage
Crops (Horticulture/ Agro-forestry)	*Abelmoschus esculentus*	Ladies finger	40	F
	Luffa acutangula	Ribbed gourd	45	F
	Capsicum annum	Chili	33	F, S
	Solanum lycopersicum	Tomato	45	F
	Solanum tuberosum	Potato	116	F
	Allium cepa	Onion	41	F
	Cucurbita maxima	Pumpkin	57	F
	Colocasia esculenta	Arum	70	F
	Solanum melongena	Brinjal	110	F
	Mangifera indica	Mango	134	F, FW, FO, T
	Musa paradisiaca	Banana	100	F
	Cocos nucifera	Coconut	342	F, FW, T
	Curcuma longa	Turmeric	17	S
	Azadirachta indica	Neem	15	M, T
	Piper betle	Betel vine	105	C
	Bambusa tulda	Bamboo	81	T
Aquaculture	*Labeo rohita*	Rohu	421	F
	Catla catla	Catla	420	F
	Cirrhinus mrigala	Mrigal	328	F
	Puntinus japonicus	Japani Punti	292	F
	Labeo bata	Bata	118	F
	Oreochromis niloticus	Tilapia	78	F
	Hypophthalmichthys molitrix	Silver Carp	148	F
	Mystus gulio	Tangra	13	F
	Pangasius hypophthalmus	Pangus	19	F
	Amblypharyngodon mola *Piaractus brachypomus*	Mola Pacu	9 13	F F
	Penaeus monodon	Tiger shrimp	9	F
	Macrobrachium rosenbergii	Scampi	14	F
Animal husbandry	*Gallus gallus domesticus*	Hen	32	F
	Bos indicus/Capra aegagrus	Cattle(Cow/Goat)	92	F

Note: F- Food item, S- Spices, FW- Firewood, FO- Fodder, T- Timber, C- Cash crop

Table 6. Types of varieties with their percentage of occurrence

Components	Economic products	% of total species of each component
Crops (Horticulture/ agro-forestry)	Food items (vegetable and fruit)	76
	Spices	12
	Timber	10
	Medicinal	12
	Fodder/Firewood	5
	Others (Ornamental, cash crops etc.)	5
Aquaculture	Fish	92
	Shrimp/Prawn	8
Animal husbandry	Poultry products	40
	Livestock products (meat)	60

A total of 42 crop species belonging to different botanical families were recorded across the surveyed homestead farms. Of the horticultural crops, 37 species (88%) were used as food-related crops (food items such as vegetable, fruit and spices) and 13 (32%) were non-food crop species (medicinal, timber, firewood or fodder). Among the species 76% were used as food items (vegetable and fruits) followed by spices (12%), medicinal plants (12%), timber (10%), fodder or firewood (5%) and others (5%) such as ornamental and perishable crops (Table 6). Apart from these crops, 38 aquaculture species and five animal species were also encountered in these small (0.1 ha), dynamic systems. Among the aquaculture species, finfish species dominated with 92% of homestead culturing fish in ponds while shrimp/prawns comprised only 8% (Table 5). The average biodiversity index in HFS is high 0.74 (where 1 is the maximum) (Table 7).

Table 7. Biodiversity index in an 1 ha area of HFS

Average no. of species/variety (a)	Average no. of individuals (b)	Biodiversity index (b*a)
20	27	0.74

3.6 Impact of assembly of biodiversity in rural economies

Biodiversity in all components (e.g. aquaculture, horticulture/agro-forestry, animal husbandry) increases the resilience in changing climatic conditions and under both biotic and abiotic stress. Biologically or genetically-diverse populations and species-rich ecosystems have greater potential to adapt to climate change (FAO 2007) and systems with many short duration crops that provide benefits within a few months help to mitigate the risk of a crop being damaged by a natural disaster. The practice of cultivating or culturing indigenous and locally-adapted plants and animals in HFS that are highly resistant to adverse conditions is also important. Further, the integration of resources between terrestrial and aquatic subsystems creates a synergy that promotes and enhances beneficial processes such as the activation of soil fertility to improve the productivity of the system. It was found that the households that integrated more components in their HFS realized 27% higher income than the other households that did not draw on synergies between different components (Bhattacharya et al 2013b). This can result in a 39% increase in income above the national poverty line average (Table 8).

Table 8. Enhancement of household economy by HFS

Per Capita Income of BPL households (rural) (Rs/month) (a)	Average household size (rural) (b)	Total Income of BPL households (Rs/annum) (a*b)	Income after practicing HFS (Rs/annum)	Income increase
13.6[1]	4.7[2] ≈ 5	816	1133	39%

[1]Planning Commission 2013 (Converted into US$)
[2]NSSO 2010

3.7 Seasonality in HFS and the impact on food and nutritional security

Food security in most subsistence communities in some regions of the world is influenced by seasonality (Savy et al. 2005). In areas where agricultural production is mainly rainfed and highly labor-dependent the effect of seasonality on food security is particularly pronounced (Masanjala 2006; Savy et al. 2005). Rural households engaging in agricultural activities often face food insecurity in the dry season when reserve food starts to decline (Hesselberg and Yaro 2006). The failure of a single crop due to the extreme climatic events like heavy rain, cyclones, large temperature fluctuation or disease can increase the vulnerability of poor households at certain times of the year. However, HFS can prevent acute food insecurity including over the dry season. The continuous production and utilization (73% consumption and 27% marketing as surplus product) throughout the year makes this system valuable for mitigating the risks of dependency on a single food source. Figure 2 demonstrates the important contribution of HFS to dietary energy, protein and fat requirements. Further, the high species diversity (Table 5) also ensures high dietary diversity and a range of micronutrients.

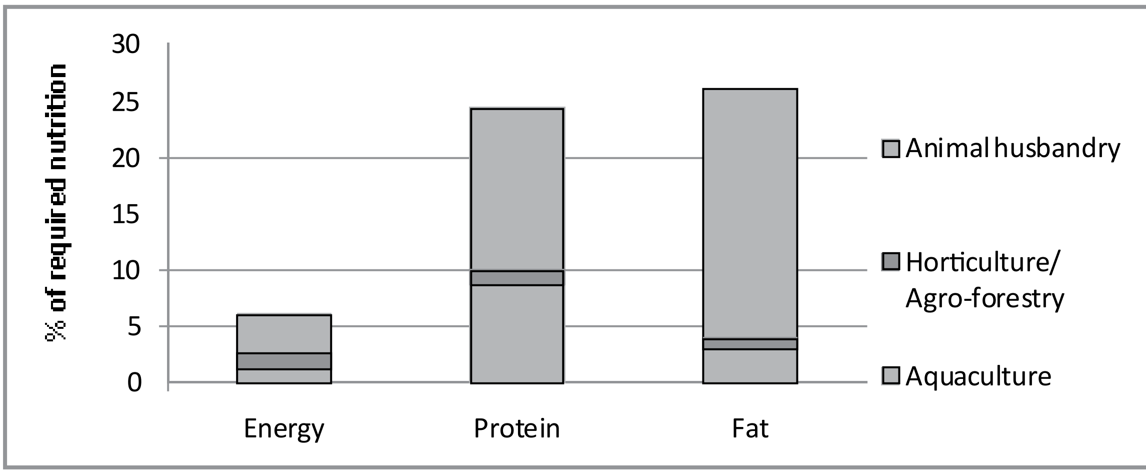


Fig. 2. Contribution of HFS to nutritional wellbeing.

4. Way forward for climate variability and mitigation measures

4.1 *Diversification of crops*

The study highlighted that HFS are highly diverse, which can enhance resilience to climate change. The introduction of more climate- and salt-resilient species including *Piaractus brachypomus* (pacu), *Musa paradisiaca* (banana) and *Cocos nucifera* (coconut) is likely a good option for adapting to climate change (Bagamba et al. 2012).

4.2 *Culture of brackishwater species in homestead ponds*

Homestead ponds are regularly subjected to salinization making it advisable to culture brackish water species including *Scatophagus argus* (spotted scat), *Etroplus suratensis* (pearl spot), Mystus gulio (*Tangra*).

4.3 *Enhance the practice of betel vine*

Betel vine is a cash crop that acts as a buffer against economic loss because it has a short cropping cycle and can generate US$ 2,500 per ha per year.

4.4 *Technical support for improved management practices*

Long-term training and technical support is required to enhance farmers' knowledge of climate variability and different techniques for adapting to climate variability.

5. Conclusion and recommendations

HFS, the traditional farming practice involving local knowledge and techniques adopted by local people, remains the dominant climate change adaptation strategy for poor rural households (Altieri and Koohafkan 2008). HFS enhance resilience and help to meet farmers' subsistence needs by delivering diverse and nutritious food and additional income. This predominantly man-made ecosystem offers an integrated approach to long-term and sustainable development outcomes. Further studies should use indicators to quantify the impact of effectively managed homestead farming systems on nutritional status and wellbeing of household members.

Despite being an important element of rural landscapes and playing a pivotal role in the predominantly bioresource-based rural economy, HFS has not received attention in any policies or programs by the government. Therefore, it is recommended that HFS be included in government policies to enhance the livelihoods of the rural poor by mitigating climatic impact.

Acknowledgements

The authors gratefully acknowledge the CGIAR Challenge Program on Water and Food (CPWF), World Fish and ICAR, New Delhi for providing financial support.

References

Altieri, M. A. and Koohafkan, P. 2008. Extent of traditional and family farming systems. Enduring Farms: Climate Change, Smallholders and Traditional Farming Communities. Penang, Malaysia: Third World Network (TWN). 17-19.

Amikuzuno, J. and Hathie, I. 2013. Climate Change Implications for Smallholder Agriculture and Adaptation in the White Volta Basin of the Upper East Region of Ghana. Paper presented at Impact World 2013, International Conference on Climate Change Effects, May, 27-30, in Potsdam.

Anon. 2009. District Human Development Report, South 24 Parganas. Development and Planning Department, Government of West Bengal.

Anon. 2011. Post-Aila salinity defeats Sunderbans farmers. The Hindu. June 8, http://www.thehindu.com/sci-tech/agriculture/article2087079.ece.

Akrofi, S. 2012. Home Garden: a potential strategy for food and nutrition security in HIV households: A case study in rural Ghana, PhD thesis. Wageningen, the Netherlands., Wageningen University.

Bagamba, F., Bashaasha, B., Claessens, L. and Antle, J. (2012). African Crop Science Journal, Vol. 20. pp. 303 - 316

Bhattacharya, A., Sundaray, J. K., Deo. A. D., Ponniah, A. G. 2013b. Resource recycling in homestead farming: An innovation towards the inclusive development in Sunderban of West Bengal. Paper presented at the National Seminar on Innovations in Science and Technology for inclusive development. Indian Science Congress Association (Bhubaneswar Chapter). 23-24 Nov, 2013. Bhubaneswar.

Biswal, B. (2008). Climate Change: Impacts on Indian Agriculture. http://www.slideshare.net/soumyashree85/global-climate-change-its-impact-on-indian-agriculture-presentation

Cline, W. R. 2007. Global Warming and Agriculture: Impact Estimates by Country. Washington, DC: Center for Global Development.

CSE 2012. Living with changing climate. Impact, vulnerability and adaptation challenges in Indian Sundarbans. Centre for Science and Environment. New Delhi. 1-108.

Denevan, W.M. 1995. Prehistoric agricultural methods as models for sustainability. Adv. Plant Pathology 11. 21-43.

District disaster management plan. 2012 South 24 Parganas: http://s24pgs.gov.in/pdf/...up/Final_Disaster%20Management_Plan_2012.pdf.

District Statistical handbook. 2009: http://www.s24pgs.gov.in/s24p/DSHB_S24PGS_2009.pdf.

Eyzaguirre, P. B and Watson, J.W. 2002. Home gardens and agrobiodiversity: an overview across regions. Paper presented at the Second International Home Gardens Workshop: Contribution of home gardens to in situ conservation of plant genetic resources in farming systems, 17–19 July 2001, Witzenhausen. Federal Republic of Germany. International Plant Genetic Resources Institute, Rome.

FAO. 2007. Adaptation to climate change in agriculture, forestry and fisheries: Perspective, framework and priorities. Inter-departmental working group on climate change. Rome, Italy: FAO.

FAO. 2009. Coping with a changing climate: considerations for adaptation and mitigation in agriculture. Environment and Natural Resources Management Series. No. 15. Rome: FAO.

Fussel, H. M. and Klein, R.J.T. 2006. Climate change vulnerability assessments: an evolution of conceptual thinking. Climatic Change, 75, 301-329.

Garí, J. A. 2003. Agrobiodiversity strategies to combat food insecurity and HIV/AIDS impact in rural Africa. Advancing grassroots responses for nutrition, health and sustainable livelihoods. Population and Development Service, FAO, Rome, Italy (preliminary edition).

Government of India Ministry of Foreign Affairs. 2011. Census of India 2011. http://censusindia.gov.in

Hazra S, Samanta K, Mukhopadhya A and Akhand A. 2010. Temporal Change Detection (2001-2008) Study of Sundarban. School of Oceanographic Studies, Jadavpur University. Kolkata

Hesselberg, J. E. & J. A. Yaro. 2006. An assessment of the extent and causes of food insecurity in northern Ghana using a livelihood vulnerability Framework. Geo Journal 67. 41–55.

High, C. & C. M. Shackleton. 2000. The comparative value of wild and domestic plants in home gardens of a South African rural village. Agroforestry Systems, 48: 141-156.

IPCC. 2007. Summary for Policymakers. In Climate Change (2007) Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 7-22.

Masanjala, W. H. 2006. HIV/AIDS, Household income and consumption dynamics in Malawi. In S. Gillespie (ed.), AIDS Poverty and Hunger: Challenges and Responses Highlights of the International Conference on HIV/AIDS and Food and Nutrition security, Durban South Africa. April-14-16 2005 pp. 56-73. International Food Policy Research Institute, Washington D.C.

Murphy, L. L. 2008. AIDS and kitchen gardens: insights from a village in Western Kenya. Population Environment, 29: 133–161.

Savy, M., Y. Martin-Prevel, P.S. Sawadogo, Y. Kameli & F. Delpeuch. 2005. Use of variety/diversity scores for diet quality measurement: relation with nutritional status of women in a rural area in Burkina Faso. European Journal of Clinical Nutrition, 59. 703-716.

Shackleton, C. M, F. Paumgarten & M. L. Cocks. 2008. Household attributes promote diversity of tree holdings in rural areas, South Africa. Agroforestry Systems, 72: 221–230.

Sundarban Development Board. 2010-11

Trinh, L. N., J. W. Watson, N. N. Hue, N. N. De, N. V. Minh, P. Chu, B. R. Sthapit & Eyzaguirre, P. B. 2003. Agrobiodiversity conservation and development in Vietnamese home gardens. Agriculture, Ecosystems and Environment, 97. 317–344.

Vandermeer, J. (ed.) 2002. Tropical Agroecosystems. Boca Raton: CRC Press.

Wilken, G.C. 1987. Good Farmers: Traditional Agricultural Resource Management in Mexico and Guatemala. Berkeley : University of California Press.

Homestead production systems in Sundarbans region of West Bengal, India – Current status and opportunities

S. Mandal, D. Burman, S. K. Sarangi, B. K. Bandyopadhyay and B. Maji

[1]Central Soil Salinity Research Institute, Regional Research Station, Canning Town, India,
subhasis2006@gmail.com, burman.d@gmail.com, sksarangicanning@gmail.com, bimalbkb@gmail.com,
b.maji57@gmail.com

Abstract

Homestead production systems (HPS) are an integral part of the daily household activities and produce food (fruits, vegetables, fish and livestock) for household consumption in coastal areas of West Bengal. They contribute significantly towards meeting daily food and nutrition requirements, generate income when surplus produce is grown and can therefore help to mitigate price or output shocks due to unforeseen events and can help to reduce poverty. A survey was conducted in the Sundarbans region of West Bengal, India to understand the current status of HPS and opportunities to improve HPS and livelihoods of rural communities. Aquaculture in homestead ponds (average area 445 m^2) and homestead gardens (vegetables and fruits; average area 120-240 m^2) were the two key components of the system. The ponds were mostly perennial but some held a limited amount of water during non-monsoon months. On average, 70 to 75% of the total vegetables produced (average total of 340 kg/household) in the HPS were consumed by the households (HH) and this accounted for 30 to 40% of the total household requirement. Part of the harvest (25 to 30%) was marketed every one to two days. Similarly, around 30 to 35% of the fish produced (143 kg/household) in the HPS was consumed by the farm family. Around 50 to 60% of the total fish produced in the HPS were sold. In the case of livestock production was minimal, resulting in 80 to 85% of production being consumed by the households. Nevertheless this provided almost 50% of the households' needs, with a small amount left over to sell at the local markets (CSSRI 2014). Productivity of HPS could be improved and these systems could provide greater contribution to the goal of regional food security. To achieve this, farmers need assured supply of quality inputs and training on production and management of the main components: fish, vegetables and livestock. Since HPS are attended to by all members of the household, training programs should focus on the whole family, including men, women and children (12 to 18 years of age). In addition to technical training farmers need financial advice, and improved support groups and technical resources. Enhancing the production level would increase the quantity of marketable surplus and thereby increase the contribution of HPS to regional food and nutrition security.

Key Message: Homstead production systems make substantial contributions towards meeting daily food and nutrition needs, income, employment, mitigating price/output shocks due to unforeseen events and fighting poverty.

Keywords: homestead, food security, potential, resource constraints

1. Introduction

Homestead gardening has the potential to improve the nutritional status of household members, but traditional gardening practices need to be developed so that households produce a wide variety of vegetables and fruits throughout the year (Torlesse et al. 2004). The homestead area in India was defined as the dwelling house together with the courtyard, compound, garden, outhouse, place of worship, family graveyard, guesthouse, shop, workshop, offices for running household enterprises, tanks, wells, latrines, drains and boundary walls annexed to the dwelling house. Sometimes gardens, orchards or plantations, though adjacent to the homestead and lying within the boundary walls, may be located on a clearly distinct piece of land. In such cases, gardens, orchards or plantations were not considered as homestead land (Govt. of India 2006).

Although there has been no systematic study on homestead production systems (HPS) the majority of the households (HH) in the study area (coastal salt affected areas of Sundarban) have some kind of HPS adjacent to their dwelling house, irrespective of the land holding size. In coastal areas of West Bengal the operational farm holding size is very small (<0.5 ha per HH) and these plots may be further fragmented as families expand. The poor farming communities are poverty stricken, having very low investment capacities, and land productivity is very low (primarily mono-cropped, rice-based farming systems with 2.0 t/ha in wet season) due to acute shortage of irrigation water in non-monsoon months. Therefore, the HPS systems are important for improving livelihoods and attaining household level food security in this region. Access to good quality water is extremely limited in the coastal areas (particularly during non-monsoon period) and farmers depend primarily on rainwater harvested in monsoon months from their pond(s). Therefore, the homestead pond is an integral component of HPS in the coastal area and each component of the HPS is linked with the availability of water in these ponds. With training interventions these resources could be used more efficiently and the productivity of the whole HPS can be enhanced significantly. Families were able to grow 12 different species and improved the homesteads' food intake by 4 kg of vegetables per week. Homestead plots can provide a ready source of food where it is needed most: in the households of the rural poor (Nielsen et al. 2006). Homestead production contributed to reduced prevalence of anemia (63.9 percent) among children in program households in Bangladesh (Talukdar et al. 2010).

It is believed that HPS can be utilized more intensively and can potentially contribute more significantly to rural community livelihoods, although very little work has been done previously on HPS in West Bengal to prove this. In the study site almost every household possesses a single or multiple ponds with most being 35 to 40 years old and with very little management (e.g. de-silting, treating soil or water). All the economic (at subsistence scale) activities of HPS depend on and revolve around the utilization of the water resources from the pond. Rearing fish in these ponds is very common but mostly to fulfill the households' requirement, without depending on any external inputs such as feed or fertilizer. There has not been any significant change in input use or management practices, particularly for homestead aquaculture, despite the knowledge being widely available amongst the scientific community and extension workers. Besides fisheries, the homestead pond is used for growing vegetable crops, fruit trees, poultry and sometimes irrigation of paddy fields. Although the volume of production is low, information on marketable surplus of these quantities may explore new opportunities and better linkage with markets. The system is complex and variable with a range of components and resource recycling pathways connecting them. There is very little planning around the methods for HPS so quantifying the inputs and outputs is very difficult. The current study used primary surveys to provide detailed information on production status, potential and constraints to enhancing production capacities. Key issues dealt with in this study were:

- What is the current status of HPS, including socio-economic patterns of the farmers, resources under the system and production patterns?
- Quantifying the benefits and identifying ways to improve the production capacities of the system
- Exploring possible market linkages with the homestead products and other opportunities

The present study on HPS provides detailed information on production status, potential and constraints to enhancing production capacities. Based on this, policy makers can be made better aware of the grassroot level happenings and challenges, and produce appropriate future strategies for the region.

2. Methods

2.1 Sources of data and sampling design

The primary survey was conducted in 2012 and 2013. Detailed socio-economic information was collected through a pre-structured and tested survey specifically designed for the homestead production system. In addition, some secondary information was collected and used in this report, for example, from the District Statistical Handbook 2007, Govt. of West Bengal.

The Sundarbans region of coastal West Bengal is comprised of 19 blocks under two districts; South 24 Parganas (13 blocks) and North 24 Pargans (6 blocks). The Sundarbans region is a coastal, salt-affected landscape. The current study focused on North 24 Pargans. ICAR-Central Soil Salinity Research Institute, Regional Research Station Canning Town carried out the survey. In North 24 Parganas there are six blocks, Haroa, Hasnabad, Hingalganj, Minakhan, Sandeshkhali I and Sandeshkhali II. Out of these, the village level HPS survey was carried out in two blocks: Sandeshkhali I and Sandeshkhali II. These two blocks were selected based on available secondary information (Bandyopadhyay et al. 2003), extent of salinity of this region and after discussion with the scientists, Assistant Director of Agriculture (ADA), Govt. of West Bengal, working in the fields of agriculture and fisheries, and with local farmers. The multistage stratified random sampling design was followed to select the, *Gram Panchayats* (elected local government at village level) and villages within the *Gram Panchayats* for the survey. Farm households with at least one farm pond, conducting some form of homestead production were purposely selected for the survey. The survey was carried out in four *Gram Panchyat*s: Hatgachi in Sandeshkhali I and Bermajur-I, Bermajur-II and Durgamandap in Sandeshkhali II block. The survey covered six villages, Dakhin Kanmari, Semulhati, Bermajur, Jupkhali, Daudpur and Durgamandap and was conducted in a total of 240 households in the North 24 Pargana District.

2.2 Analytical technique

Descriptive statistics were primarily used for analyzing the data collected through primary surveys. Farm budgeting technique was used for analyzing annual costs and returns of the enterprises or the system. Financial analysis through discounted method such as Internal Rate of Return (IRR), Benefit Cost Ratio (BCR) and Net Present Value (NPV) were employed to examine the long-term feasibility of the current HPS. These financial criteria account for the time value of money invested on the system and provide better information on making decisions for long-term investments in HPS. The financial analysis was based on some assumptions such as: economic life of the pond was 15 years (although these are used for a longer period, at the 15th year the costs of reparing the ponds become very high, and also for better accounting of the costs and returns); discount rate of 12% (the prevailing maximum rate of interest charged by the bank and sufficient to cover the time value of money); full benefit (first year is the planning period) of the system will be from the second year onwards; major excavation/repair after 10 to 12 years; and key components of the systems are fish and vegetables. Under this analysis, the contribution of family labor was included as a cost item. The criteria of the financial analysis (IRR, BCR and NPV) indicated that the system was not generating sufficient income for long-term investment if the contribution of family labor is included as a cost, which normally farmers' do not consider as a cost item.

According to the standard size-classification (set by the Indian Planning Commission), more than 95% of the farmers in the study area are classified as marginal farmers (<1 ha of operational holdings). We attempted to further classify our farmers based on land holding size within the marginal group as it has been found that productivity is related to land holding size (Chand 2011). The new classification was as follows: landless (0 - 0.2 ha), marginal 1 (0.2 – 0.4 ha), marginal 2 (0.4 – 1 ha), small (1-2 ha) and others (>2 ha). However, while analyzing the data it was observed that the income generating activities of HPS were closely linked with the size of ponds (availability of water) rather than size of total operational holdings. In addition, the activities and production under HPS were linked with the family size, alternative livelihood options and size of ponds within the HPS but not to the total size of operational holdings. Under these circumstances, the data analysis was carried out without making any size-classification (homogeneous as almost all farmers are marginal), focusing on HPS irrespective of the total operational holdings of the farmers to avoid any unforeseen confusion over data interpretation. This will provide useful information targeted at marginal farmers and facilitate the future planning of HPS activities in the region. This indicates that future HPS programs should be focused on farmers irrespective of their land holding patterns.

3. Results and discussion

3.1 Socio-economic features of homestead farmers

The average age of the respondents was skewed to the age group 40 to 60 years, followed by age group 20 to 40 years (31%), 60 to 80 years (12%), over 80 years (2%) and below 20 years (2%), demonstrating that these HPS activities are mainly carried out by the middle aged population. The young population either engaged in other non-agricultural activities or migrated in search of alternative income sources in distant places. Rural economies are poorly diversified; the vast majority of rural poor are engaged as day laborers in agriculture (72%), a seasonal occupation that can leave households without income for several months of the year (Van et al. 2009 and Martin et al. 2008). Average family size of the farm families was 5.23 including children. All family members including the children (below 14 years of age) participate in activities of homestead production systems on a daily basis, for few minutes to a few hours. Similar participation has been observed under aquaculture operation also. Mostly the activities under HPS are carried out throughout the year (in both the *kharif* and *rabi* seasons).

Occupational patterns of the farm households was analyzed on the basis of percentage of respondents devoting maximum time on a particular avocation, as well as percentage of respondents earning maximum income from a particular avocation. In terms of time spent, cultivation of crops was the most dominant occupation (34%) followed by pisciculture plus cultivation (27%), wage labor (21%) and other (18%). In terms of major sources of income, pisciculture plus cultivation provided the largest percentage of income to farm families (39%) followed by cultivation (38%), wage labor (19%) and other (4%). Farm households are engaged in cultivation activities for longer periods of time, but pisciculture plus cultivation provided the major source of income.

Major income sources for farmers in the study area were pisciculture, growing vegetables, wage earnings, brackishwater aquaculture, service and others. Both male and female members of the family contributed to all of these activities. Cultivation was primarily dependent on rainfall; lands are mostly mono-cropped with rice in the *kharif* season. Farmers are engaged in crop cultivation for around 3 to 3.5 months only and earn meager amounts (Rs. 17188/HH/year). Pisciculture (freshwater) provides relatively better income (Rs. 23334/HH/year) compared to crop cultivation. The pisciculture activities are dependent on the availability of water in ponds and are feasible for eight to nine months per year. Vegetables are grown mostly by using water from ponds and restricted to a very limited area. On average, production of vegetables fetches earnings of Rs 5100/HH/year but this component contributes significantly to household nutrition if nutrient-rich vegetables are grown. A study at Mymensingh, Bangladesh revealed that farmers produced on an average of 244.17 kg of vegetables year round. They consumed most of the vegetables (149.5 kg), distributed a small portion (25.67 kg) and sold a larger portion (69 kg) to meet their daily necessities (Dey et al. 2012). Wage labor (such as work under the national scheme MGNREGA, other public works or in others' fields) and migration to other places (nearby towns or distant places) provides good income to the households (Rs 37152 and Rs 38173 per HH per year from wage earnings and migration, respectively). But this income stream is not always ensured and very often fails to provide a decent livelihood option for the farm households. Brackishwater aquaculture is also prevalent in the region and generates significant income (Rs. 53450/HH/year) but requires high investment and intensive care. Therefore, this system (brackishwater aquaculture) is operated at large scales by wealthy people from outside the region.

3.2 Resources in Homestead Production Systems

Homestead production systems are comprised of several key resources including water, fish, horticultural crops, livestocks. The pond and the water in the pond is a keystone resource of the HPS as all of the components of HPS are dependent on this water. Out of all enterprises, fisheries and growing vegetables on the dyke area are the most important components as they provide nutrition as well as income to the family. The expansion of area and intensification of crops under homestead activities primarily dependent on the homestead ponds (size, depth, distance and availability of water throughout the year) rather the total operational holdings size of the farmers. Although rigours studies are not available in the study area, the authors of this paper have observed that farmers' with lower operational holdings are more likely to use the HPS more intensively to maximize the production and more dependent on this system as compared to the large farmers because large farmers tend to focus their efforts on field crops.

On average, each farm household in the study had more than one pond within or outside the HPS. Some of the households had as many as five ponds. Average age of the ponds was observed to be 58 years, some of which were very old (more than 100 years) and some which were excavated recently (within five to six years). The age of around 56% of the total ponds in the sample was over 60 years, followed by < 20 years (18%), between 40 and 60 years (15%) and 20 to 40 years (11%). Average maintenance cost of ponds (renovation, de-silting, etc.) for every 10 to 12 years has been calculated to be Rs. 5025/-[46]. Sedimentation occurs in older ponds, which reduce the capacity to hold water, in turn affecting productivity. Good management is required but very often farmers were not so keen for renovations due to financial constraints.

Average size of the ponds was estimated to be 0.04 ha. Maximum pond size was observed to be 0.09 ha. Although the majority of the ponds in the study area were perennial by definition, water availability in the ponds during dry months was very limited and not sufficient for aquaculture operation throughout the year. Adequate water was only available in the ponds for aquaculture for eight to ten months, following which time ponds are dried and fish are harvested. This dry period may provide an opportunity remove some of the sediment from the bottom of the pond, provided households have the time and human resources to do so. Maximum water depth in the ponds was eight to nine ft and in some ponds the depth was as low as 3 ft, primarily due to lack of renovation work (de-silting). Shallow water depth has implications for fish health and survival because the temperature and therefore dissolved oxygen fluctuations are more extreme in shallow water. Most of the ponds are located within the backyard of dwelling houses or very close to the homestead area (within 15 to 20 meters). This is because most ponds were excavated for making the uplands to construct the houses. Daily management of the land is easier when it is closer to the homestead area. Rainfall is the primary source of water in the ponds and is stored during the rainy season. In most of the HPS pond, fish are grown in a very traditional way without any care or scientific management (stocking density, fish composition or feeding). Only one cycle of fish are grown during the eight to nine month period for which the pond is operational each year. Periodic harvesting is done to meet household consumption needs in small quantities and a one-time harvest is done after complete drying of the ponds.

Besides aquaculture in the homestead pond, growing vegetables, fruit and timber trees on the dyke or in homestead gardens was the major activity under HPS. A number of vegetables were grown in the homestead gardens including brinjal, okhra (*bhindi*), potato, cabbage, cauliflower, pumpkin, yam, spinach, colocasia, amaranthus, cucumber, bitter gourd, beet and carrot. The area of vegetables cultivation under the HPS was 200 to 250 m^2. Inputs like seeds, pesticides and human labor (mainly family labor) were key cost components in the production system. Input cost (excluding imputed value of human labor) and average production of vegetables was calculated to be Rs. 450kg/HH and 340 kg/HH, respectively. The value of vegetables produced in the system was estimated to be Rs. 5100/HH. On average one to two human laborers (mostly family members) were engaged in this operation for around two to three hours daily. Vegetables in the HPS are quite a profitable enterprise and many farmers undertake their cultivation intensively and with good care. Other non-aquaculture activities under HPS are rearing of cattle and backyard poultry (3 to 4 no per HH), ducks (3 to 4 no per HH) and a few households were rearing sheep (*garol* breed suitable for the coastal region). Rearing of large ruminants like cattle or buffaloes was not so prevalent in this region.

3.3 Fisheries in homestead production systems

A number of fish are grown in the homestead ponds as composite fish culture. These are *rohu, catla, mrigal, japani punti, silver carp, tangra, vetki, tilapia, mourala, prawn, pangas, golden carp, sol, koi* and *magur*. Fish are grown in the ponds without following any scientific management practices like stocking density, composition of fish, periodic liming of ponds or providing fish feed. Few farmers have undergone training for scientific fish

[46] 1 US$ = Rs. 62 (approximately)

rearing management and mostly follow traditional cultivation practices. However some farmers have been observed growing fish with intensive care and for earning profit. These farmers could provide a platform around which to build community learning groups and workshops. Since water is available normally for eight to nine months a year, mostly one cycle of fish are grown in the pond. Average size of fish seeds varied from 1.5”to 5” depending on the fish species. Many farmers preferred to use bigger fish seeds (fingerlings) to avoid risk of mortality.

Average production of fish from the pond was estimated to be 75kg/pond/year and 143 kg/HH/year[47]. The average value of fish produced was Rs. 8250/pond/year and Rs. 15730/HH/year. Average weight of fish during harvesting varies across fish species from 75 gm (e.g., prawn) to 400 to 800 gm (e.g., carps). Out of total production (143 kg/HH/year) from the homestead ponds, average quantity of fish sold was estimated to be 107 kg/HH/year and the rest (36 kg) was consumed by the family members. Average consumption of fish per household per year has been estimated to be 84 kg, out of which 43% (i.e., 36 kg) was obtained from homestead production. With an avergage family size of 5.23 person in the study area, the per capita fish cosumption (16 kg per annum) was much higher than the Indian average (9.8 kg per annuam, Govt. of India 2011) because fish is extensively grown and consumed by the population in this part of India. Value of fish from homestead ponds sold in the market has been estimated to be Rs. 11770 per HH per year.

3.4 Contribution of HPS to household food security

Farm households obtain several food items from their HPS almost daily but the variety depends on seasonal availability. Primarily these are vegetables, fish, fruit and livestock and livestock products (egg, meat, milk, etc.). It was estimated that on an average 70 to 75% of vegetables produced in the HPS were consumed by the family members, which accounted for nearly 30-40% of their total requirement (Table 1). Some part of the harvest (25 to 30%) was being marketed daily or on alternate days. Similarly, around 30 to 35% of fish produced in the HPS were consumed by the farm family, accounting for 50 to 60% of their total household fish requirement. Almost 50 to 60% of the total fish produced in the HPS went to market. In the case of livestock, since the production quantity was limited, 80 to 85% were consumed by the HH (accounting for almost 50% of their needs). The rest (10 to 15%) were sold to the local markets. Availability of fish, vegetables and livestock products from the HPS were quite small in quantity, but contributed greatly to daily household requirements, thus reducing external dependence and making the farm family more self-reliant. A study conducted by Lokesh and Hanstad (2004) in Karnataka indicated that 90 to 100% of the vegetables and fruits, and 100% of the milk products consumed by the households in their study were produced on the households’ homestead plots.

Table 1. Contribution of HPS to households food security

Items	Contribution (%)			
	Home consumption of total produce	Fulfilling the total requirement	Marketed of total produce	Average production (kg/HH)
Vegetables	70-75	30-40	25-30	340
Fish	30-35	50-60	60-65	143
Fruits	85-90	-	5-10	-
Livestock	80-85	50	10-15	-

Source: Annual Report (2013-14)

[47] Note: First average is per pond and second average is per household. Most farm households have multiple ponds with an average of 1.90 ponds/HH.

As well as contributing to daily household nutrition requirements, HPS also played a critical role in mitigating the risk of food insecurity associated with natural disasters. There was a devastating cyclone (*Aila*) in the Sundarbans in May 2009 that caused almost all farmland to be inundated with saline water. This hindered crop production for more than two years. The HPS was the only area suitable for cultivation due to its high elevation and the relatively limited intrusion of saline water. Saline water recedes quickly from the HPS and salinity was washed away after a few good showers and the plots under HPS became suitable for growing crops.

3.5 Economics of the homestead production system

The homestead production system is complex and diverse and it is difficult to obtain reliable input-output data from the respondent farmers. Fisheries in the homestead ponds are grown in a traditional way without much care and scientific management. But the crops (mainly vegetables) in the homestead garden are grown quite intensively and farmers try to maximize their output from the small area under operation. Economic analysis of fisheries in ponds, based on operational annual costs and return (without the initial investment and other fixed investment like pump, cast nets, etc.), indicated that the system was profitable. The annual operational expenditure components were expenditures on fish seed, fish feed, repairing of cast nets, human labor for feeding and harvesting of fish, human labor for daily supervision/intercultural operation of vegetable production and harvesting, purchasing of vegetables seeds, plant protection chemicals, medicines and miscellaneous. Annual operational costs and return has been calculated to be Rs 7620 and Rs. 14280 for average pond and vegetables production area, respectively, in the study area.

To analyze the financial feasibility of long-term investments in the system (including the initial investment in pond excavation), discounted cash flow measures like Internal Rate of Return (IRR), Net Present Value (NPV) and Benefit-cost Ratio (BCR) were computed (Table 2). The estimated IRR was 11%, i.e., less than the discount rate of 12%. NPV was negative (Rs. -2816) and BCR was less than one (0.98). Under current practices the long-term investment in HPS was not a financially attractive proposition. However, it has multiple functions, utility and value for HH in the coastal areas under study. Normally the initial investment needed for pond excavation is financed by various government-sponsored schemes. With technological interventions and financial support the system can be made more efficient and can contribute significantly to the economy of the region.

Table 2. Economics of existing HPS

Sl no	Item	Quantity	Rate	Value	Remarks
A.	Fixed cost				
a.	Pond excavation	1	550 labour @Rs.150/day	82500	
b.	Cast net	1	1250	1250	
c.	Pump	1	15000	15000	
B.	Variable cost				
a.	Repairing of embankment		65 labour @Rs.150/day	6000	Every 10-12 years
b.	Repairing of net	1		70	Every year
c.	Fish seed	2000		3000	
d.	Fish feed			100	
e.	Supervision/intercultural (human labor)	20	Rs. 150/ - day	3000	Own supervision
f.	Release of fish seeds, feeding and harvesting (human labour)	5	Rs. 150/- day	750	Own/hired/mutual sharing
g.	Miscellaneous			100	
h.	Medicine/lime			150	
i.	Vegetables (seeds etc)			450	
C.	Return				
	Sale of fish			17000	Rs21900 from 3rd year onwards
	Sale of vegetables			3000	
	Sale of water				

Financial analysis: IRR = 11% (<12 % the discounting rate), NPV = Rs. (-)2816, BCR = 0.98.

Note: in Rs per *bigha* or 33 decimal of pond, 2012; Engagement of human labor in pond management is low apart from the pond excavation. Releasing the fish seeds, feeding and harvesting are the activities done by human labor and thus the quantity of human labor was low.

4. Harnessing the opportunities of homestead production systems

The primary objective of HPS in the study area is to supplement the daily food requirement without any commercial motive. Food-based strategies, including homestead food production through homestead vegetable production programs, not only increase food security but also have an impact on reducing micronutrient deficiencies and women's empowerment as well as their economic security (HKI/IPHN, 2006). The area of operation under HPS was very small and the quantity of marketable surplus was limited. Any produce sold was sold at the local market called *haat* (within a 2 to 3 km radius) on a daily basis. Since the areas under individual crops were very limited, the quantity and type of produce available to sell was not linked with the changing market prices. Homestead production systems in the study area were not market responsive because the capital investment and area under cultivation were limited, so level of production and type of commodities grown could not be easily altered in line with market supply.

The aquaculture component appeared to be managed very differently to the vegetable component of HPS. Aquaculture production management was very traditional, less capital intensive and devoid of any rigorous management, (i.e., stocking densities, fish composition, feeding management, phased harvesting, de-silting of ponds or fertilization in ponds to increase the food availability for fish). Farmers were not so driven to maximize the output from their ponds, rather it was their way of life. Conversely, vegetable production units were quite intensive. Farmers tried to maximize their output with all-out efforts from this small production unit. It was observed that some of the farmers were changing the crop mix and purchasing quality seeds from their markets to grow in their vegetable gardens depending on market demand. Farmers were keen to gain knowledge particularly on crop protection and nutrient management. Efforts should be made to enhance farmers' ability to adopt intensive aquaculture practices as well.

The HPS were comprised of several crops like vegetables, fruits, medicinal and aromatic plants or multipurpose tress. In a very small area, a number of vegetables were raised. There was no specialization of crops and individual outputs were quite small. But it was also observed that a few farmers were growing only a few number of vegetables (like brinjal, cabbage, cauliflower, chilly or tomato) and these farmers were earning a better income from their plots as compared to their fellow farmers. Their production systems were also somewhat driven by market demand and they were more conscious about the crop choice/mix to maximize return. However, a larger variety of crops (mix) provided better food and nutrition to the family, which is actually the primary objective of the HPS. Thus a valid question arises: should less variety be produced to meet market demand and raise income or should vegetable production be diverse to obtain household food and nutrition security, sacrificing the expected higher return from specialized crops? Research is needed to analyze the trade-off between these two situations. Based on the farmers' own choice, priorities and socio-economic conditions, interventions may be suggested.

Extent of production from HPS was not directly dependent on the total size of operational holdings. Rather, decisions to operate HPS were dependent on the availability of water in the homestead ponds, family labor, family size, family food requirement and finally the ability to earn cash income by selling available marketable surplus.

5. Conclusion and recommendations

The survey on HPS elaborated their role, importance and contribution to the farm households in the coastal region. HPS contributed significantly towards meeting daily food and nutrition needs, engaged entire families and provided cash income, in turn mitigating price or output shocks within the market systems. However, resource use under HPS can be made more productive and contribute to attaining regional food security. There is a need to enhance the production capacity of the system as a whole. Farmers need ensured supply of quality inputs and training on production management of all enterprises—fish, vegetables and livestock. Training should include nutrition education and behavior change components (Lannotti et al. 2009). Since all members of the family participate in HPS, training and upscaling programs should target the whole family, including men, women and children (12 to 18 years of age), either through community groups or school-based projects. Farmers also need financial support to enhance their investment capacity and ensure productive resources use. Enhanced production levels would increase the quantity of marketable surplus and thereby contribute more to regional production. The government may consider implementing schemes for the promotion and improvement of existing homestead production systems for a large number of farmers in the coastal areas.

Acknowledgements

The authors acknowledge the financial and technical support to this research work by the Indian Council of Agricultural Research (ICAR) and the CGIAR Challenge Program on Water and Food. This paper presents findings from 'G2 Productive, profitable and resilient agriculture and aquaculture systems', a project of the CGIAR Challenge Program on Water and Food. We would like to profusely thank the reviewers of the paper for their valuable contributions.

References

Annual Report 2013-14. Central soil Salinity Research Institute, Karnal - 132001, India, pp. 127-128.

Bandyppadhyay, B. K., B. Maji, H. S. Sen, and N. K. Tyagi. 2003. Coastal Soils of West Bengal – their nature, distribution and characteristics, *Technical Bulletin* no 1/2003, Central Soil Salinity Research Institute, Regional Research Station, Canning Town, West Bengal, India, pp. 62.

Chand, Ramesh., P. A. Lakshmiprasann, and Aruna Singh. 2011. Farm Size and Productivity: Understanding the Strengths of Small Holders and Improving their Livelihoods. *Economic and Political Weekly*. Supplement. Vl. XLVI. Nos. 26 & 27. pp. 5.

Dey, S., U. K. Sarker, and M.A. Awal. 2012. Year round homestead vegetables production: reduction of nutritional deficiency and income generation for small households, Bangladesh J. Prog. Sci. & Tech. 10(2): 187-190.

HKI/IPHN. 2006. Homestead Food Production: The potential and opportunity to improve the food security and rural livelihood in Barishal Division. Homestead Food Production Programme Bulletin No. 3 (April, 2006) 1-4 pp.

Govt. of India. 2006. Livestock Ownership Across Operational Land Holding Classes in India, 2002-03, NSS 59th Round, National Sample Survey Organisation, Ministry of Statistics & Programme Implementation, p. 7.

Govt. of India. 2011. Manual on Fishery Statistics. Ministry of Statistics and Programme Implementaion. Central Statistics Office. New Delhi.pp. 1. www.mospi.gov.in.

Lannotti, Lora., Kenda, Cunningham, and Ruel. (2009). Improving Diet Quality and Micronutrient Nutrition Homestead Food Production in Bangladesh, IFPRI Discussion paper 00928, pp. 7.

Lokesh, S. B., and T. Hanstad. 2004. *Reaping the Rewards of Homestead Gardens: Nutritional and Income Benefits from Homestead Plots in Karnataka*. Bangalore, India: Rural Development Institute.

Matin, Imran., Munshi. Sulaiman, and Mehnaz. Rabbani. 2008. *Crafting a Graduation Pathway for the Ultra-Poor: Lessons and Evidence from a BRAC Programme.* Dhaka : BRAC Research and Evaluation Division.

Nielsen, R., T. Hanstad, and L. Rolfes. 2006. Implementing homestead plot programmes - experiences from India, FAO-LSP Working paper 23.

Torlesse, H., H. Moestue, A. Hall, S. de Pee, L. Kiess, and M.W. Bloem. 2004. Dietary diversity in Bangladesh: evidence from the nutritional surveillance project, In Alleviating malnutrition through agriculture in Bangladesh: biofortification and diversification as sustainable solutions : [Dhaka and Gazipur, Bangladesh, April 22–24, 2002] / editors Nanna Roos, Howarth E. Bouis, Nazmul Hassan, and Khandaker Aminul Kabir. pp. 44-49.

Talukder, A. N. J. Haselow, A. K. Osei, E. Villate, D. Reario, H. Kroeun, L. SokHoing, A. Uddin, S. Dhungel, and V. Quinn, 2010. Homestead food production model contributes to improved household food security and nutrition status of young children and women in poor populations - lessons learned from scaling-up programs in Asia (Bangladesh, Cambodia, Nepal and Philippines). Field Action Science Report, www.factsreports.org.

Van. Haeften, Roberta, and Phil Moses. 2009. *Bangladesh Food Security Country Framework FY 2010-2014.* Washington, DC : Food and Nutrition Technical Assistance Project (FANTA II), Academy for Educational Development (AED).

Homestead farming system: comparative characterization and role in resource poor farmers' livelihood in Bangladesh and West Bengal

K.A. Kabir[1], J.K. Sundaray[2], S. Mandal[3], D.A. Deo[2], D. Burman[3], S.K. Sarangi[3], A. Bhattacharya[2], M. Karim[1], M.B. Shahrier[1], S. Castine[1] and M. Phillips[1]

[1]WorldFish, Bangladesh and Malaysia, k.kabir@cgiar.org, m.shahrier@cgiar.org, m.karim@cgiar.org, sarahcastine11@gmail.com, m.phillips@cgiar.org
[2]Central Institute of Brackishwater Aquaculture, India, jsundaray@gmail.com, ashutoshddeo@gmail.com, aninditabhattacharya.87@gmail.com
[3]Central Soil Salinity Research Institute, India, subhasis2006@gmail.com, burman.d@gmail.com, sksarangicanning@gmail.com

Abstract

Homestead farming is widely practiced across the land size spectrum in rural areas of the Ganges delta, in Bangladesh and West Bengal, India, by utilizing family labor to produce a diversified range of crops. A survey was carried out from 2012 to 2013 to increase understanding of this small, complex and dynamic farming unit across the Ganges delta. The survey covered 1280 homesteads in Bangladesh and 720 from West Bengal, in high, medium and low salinity areas, with particular attention to poorer households with access to less than 1 ha of land. Homestead farming system (HFS) income in Bangladesh ($246) is slightly higher than West Bengal ($224) though household farming land area is higher in the latter. Five major and often interlinked farming units—pond aquaculture, vegetable, fruit, poultry and livestock production—were common in both countries with the exceptions of betel vine which was more prevalent as a cash crop in West Bengal, and a lower diversity of homestead ponds in Bangladesh. Larger differences between the two countries are observed in vegetable and fruit production. In Bangladesh, homestead farming is dominated by vegetable yield with a median of 12,350 kg/ha (range=10,292-14,820) whereas fruit is more significant in West Bengal with a median yield of 12,593 kg/ha (range=0-98,800). Products from all the farming units in both countries have a positive correlation between production and consumption except for dairy milk in Bangladesh and vegetable and poultry meat in West Bengal. The value of inputs (fertilizer, seed, feed) used in HFS is much higher in Bangladesh than in West Bengal with per household expenditure of $71 in Bangladesh compared to just $15 in West Bengal. The contribution of HFS to household income is higher in Bangladesh (23%) than it is in West Bengal (16%). There are significant differences in HFS productivity between low and high salinity areas. The major constraint of farming system intensification in Bangladesh for aquaculture is a lack of investment and for other crops is disease management, while households in West Bengal prioritize lack of skills for aquaculture and non-aquaculture crops.

Key message: Presence of more farming units in HFS provides higher opportunity for food production, improving food and nutritional security and income.

Keywords: farming components, food production, aquaculture, non-aquaculture

1. Introduction

The coastal delta of the Ganges River system, encompassing large parts of Bangladesh and the Indian State of West Bengal, is one of the most highly populated regions of the world (Amhed 2006). Bangladesh has a population density of 1,203 per sq. km of land area (World Bank 2014) and in West Bengal the density is 1,029 people per sq. km (Census of India 2011). Human development indicators for the rural areas indicate that 35% and 26% of the rural population fell below the national rural poverty line in 2010 in Bangladesh and India, respectively (World Bank 2014).

The Ganges coastal delta comprises diversified aquatic-agricultural farming systems across a complex landscape subjected to wide seasonal fluctuations in salinity and freshwater availability, and vulnerability to sea level rise, flooding and extreme weather events such as cyclones (Huq and Ayers 2007; Sayeed 2007). The Ganges delta is considered to be an irrigated cropping system with a yield gap (Václavík et al. 2013).

An increase in food production is required in the Ganges delta and sustainable intensification is widely considered necessary for future food requirements (Garnett et al. 2013). Recent research in Bangladesh on productivity improvement in rice suggests significant opportunities do exist within the region to increase productivity of field crops (CPWF 2013), though access of poorer households to sufficient land area remains a concern. Small land holdings are common across the Ganges coastal delta, with 80% of farming households in Bangladesh having access to less than 0.5 ha of productive land (Bangladesh Bureau of Statistics 2011); in West Bengal 59% of the population has land holdings of less than 0.5 ha (Agriculture Census 2010-11). Homestead farming systems (HFS) have been developed based on micro-sites and under the existing land constraints, it is an important food production unit for the poor in Bangladesh (Miah and Hussain 2010) as well as in West Bengal (Nelson et al. 2006). Much research has focused on field crops but less on overall integrated homestead farming systems.

Homestead farming is widely practiced across the land size spectrum in rural areas of Bangladesh and India (Dey et al. 2012 and Bhattacharya et al. 2013). HFS comprise operational farm units that occupy a portion of the homestead land, utilize family labor, particularly women, and involve the production of various combinations of aquaculture, vegetables, poultry, livestock and fruit crops (Dash and Misra 2001). HFS have been promoted for family income and home consumption across Bangladesh (Lannotti et al. 2009) and West Bengal (Robin et al. 2006) though less attention has been given to HFS in more challenged coastal deltaic regions of both countries.

Understanding of the influence of salinity and water management on field crops is increasing (Huq and Ayers 2007; Sayeed 2007) but less knowledge is available on homestead farming systems within salinity challenged areas. Further, there have been no studies of a comparative or commonality nature on homestead systems across the two countries despite their shared deltaic agro-ecologies.

This paper presents information from consultations with households in both Bangladesh and West Bengal, and an extensive survey of HFS during 2012 and 2013 in order to compare homestead farming systems in Bangladesh and West Bengal for identifying opportunities for cross-country sharing of knowledge and experience across the region.

2. Methods

2.1 Study sites

The study was conducted in three regions in southern Bangladesh and five regions in West Bengal. These eight regions varied in water salinity, ranging from approximately 0 to 25 ppt (Table 1). In Bangladesh large (1000s of ha), circular embankments, called polders, which are prevalent throughout the coastal zone of Bangladesh, define the three regions. The individual polders investigated in the present study are Polder 43, Polder 30 and Polder 3 (Figure 1). In West Bengal, the study was conducted in three coastal blocks called Kakdwip, Namkhana and Sagar under South 24 Parganas, and two blocks in north 24 Parganas called Sandeshkhali I and Sandeshkhali II (Figure 1).

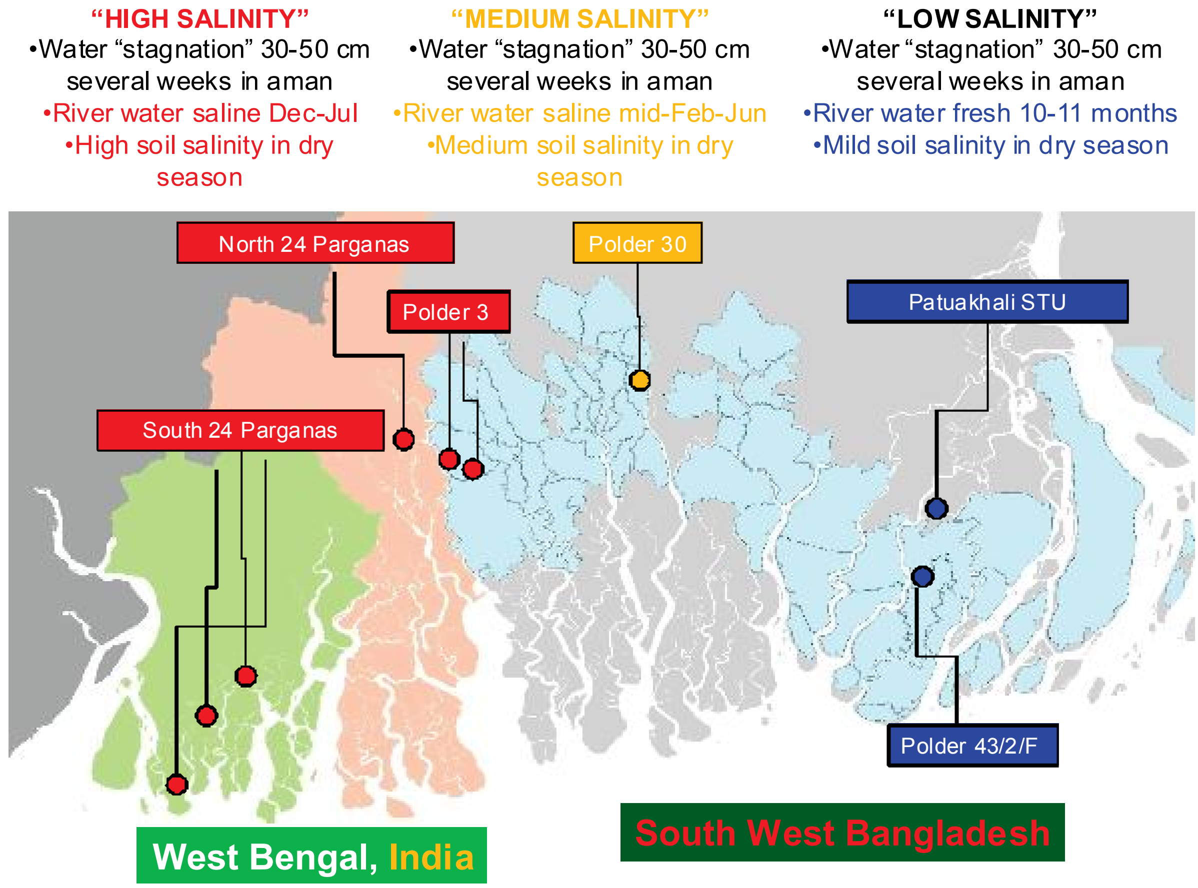


Fig. 1. Study areas of the lower Ganges basin in Bangladesh and West Bengal, India.

The blocks and polders were selected as representative of the socio-economic, agricultural practice and environmental conditions in each country. Each location was categorized into three zones of low salinity, moderate salinity or high salinity based on the range of water salinity (Table 1). However, salinity levels are variable, driven by seasonal changes, and are naturally heterogeneous even among different plots within a single farmer's field (Rahman et al. 1993; Fleming 2004; SRDI 2001; Gain et al. 2007; Shamsuddin et al. 2006).

Table 1. Survey areas in southwest Bangladesh and West Bengal, India, categorized by water salinity level and total number of households sampled

Country	Region	Water Salinity (ppt)	Number of households (HH) sampled
Bangladesh	Polder 43	Low (0-05)	320
	Polder 30	Moderate (0-10)	338
	Polder 3	High (05-25	461
	Total		1,119
India	Block Kakdwip	Low (0-05)	120
	Block Namkhana	Moderate (0-10)	120
	BlockSandeshkhali I	Moderate (0-10)	120
	Block Sandeshkhali II	Moderate (0-10)	120
	Block Sagar	High (05-25)	240
	Total		720

2.2 Survey households

In India, 720 households were surveyed from each block apart from Sagar where 240 households were sampled (Table 1). Sagar is an island with a dynamic brackishwater ecosystem and is vulnerable to soil erosion, tidal movement and salinization. The relatively higher number of households selected in Sagar was intended to capture this dynamic and vulnerable environment. Between 320 and 461 households were surveyed in each of the three polders in Bangladesh (Table 1).

Complete lists of all the households residing in each of the polders and blocks were collected from the Union Parishad and Panchayat office in Bangladesh and West Bengal, respectively. Each of the polders and blocks were considered as a separate region to allow for stratified random sampling. SPSS software was used to randomly select households from each region at 5.86% confidence interval.

2.3 Data collection

A household survey was conducted between January and March 2012 in Bangladesh and August 2012 and January 2013 in West Bengal, India. Both open ended and closed questions were asked to ensure participants could elaborate when suitable. The survey collected information on socio-economics, homestead farming system components, yield and its contribution to household income.

2.4 Data analysis

Households having > 1 ha total land were excluded from the analysis as this study was focused on asset-poor households. The sample number from Bangladesh was 1106 and 652 from West Bengal. Data were analyzed by using R – statistical package and SPSS. For conversion from local currency to US Dollars we used the conversion rate at the time of the survey, that is 43 Indian Rupees and 75 Bangladeshi Taka to 1 US$. The results were presented at median value due to the lack of normal variation among households in each country and salinity level.

3. Results

3.1 Farming land, HFS units and yield

There are five major components in HFS and ponds constitute a major portion of homestead area in both countries (Table 2). However, homestead land area in Bangladesh is nearly half that of West Bengal (Figure 2) and thus in terms of area very small farming units are available for the poor.

Table 2. Distribution of HFS units in Bangladesh and West Bengal in relation to homestead land area

	Bangladesh (%)	West Bengal (%)
Pond	45	50
vegetable garden	15	29
Livestock shade	3	8
Poultry shade	1	6
Fruit trees	36	7

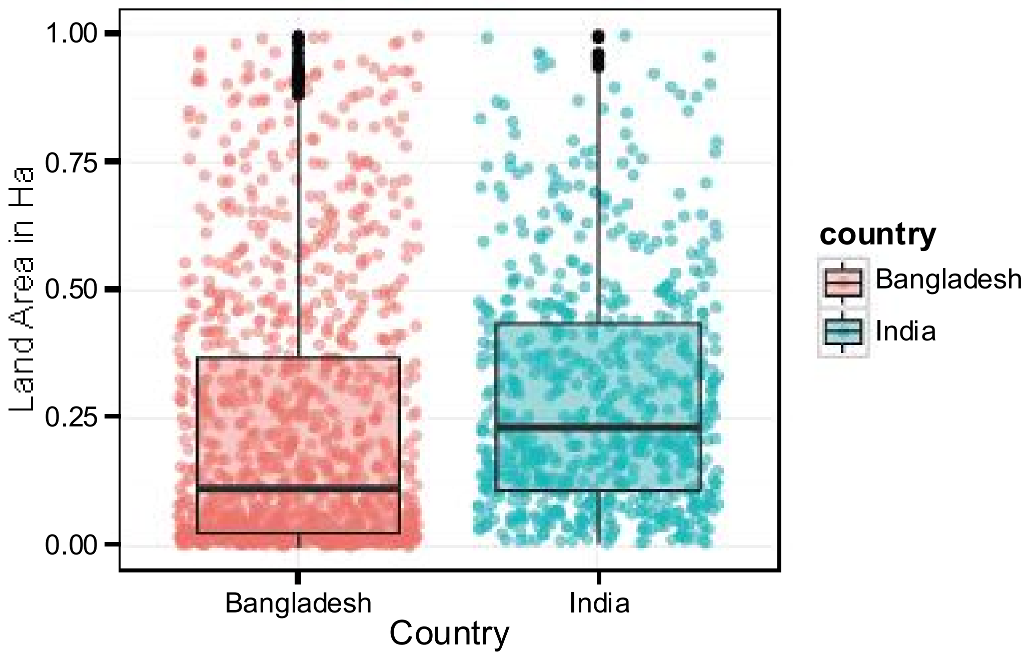


Fig. 2. Homestead land area (ha) in Bangladesh and West Bengal (India) based on land owned.

There is a significant difference in homestead land size between regions (Kruskal-Wallis chi-squared test = 397.3, df = 7, P = 0.000). Landholdings at Kakdwip, a low salinity area, were the largest with median 0.14 ha, and also had the highest income. Landholding is smallest in Polder 3, a high salinity area, with a median of just 0.03 ha per household.

Though five major farming components were identified they are not seen in all farming households (Table 3) and betel vine is seen only in West Bengal.

Table 3. Presence of farming components in Bangladesh and West Bengal

	Bangladesh		West Bengal	
	Number of HH	% of sampled HH	Number of HH	% of sampled HH
Pond	463	42	475	73
Vegetable garden	310	28	284	44
Livestock shade	410	37	79	12
Poultry shade	536	48	20	3
Fruit trees	655	59	25	4
Betel Vine	0	0	98	15

Presence of more farming components is significantly related to increased production from HFS. In Bangladesh, homestead farming is dominated by vegetables with a median of 12,350 kg/ha (range=10,292-14,820) whereas fruit drives production in West Bengal with a median yield of 12,593 kg/ha (range=NA-98,800). Regarding the production of animal source food, fish and prawn production are similar in both countries, while HFS in West Bengal produce more chicken products and HFS in Bangladesh produce more livestock products (Figure 3).

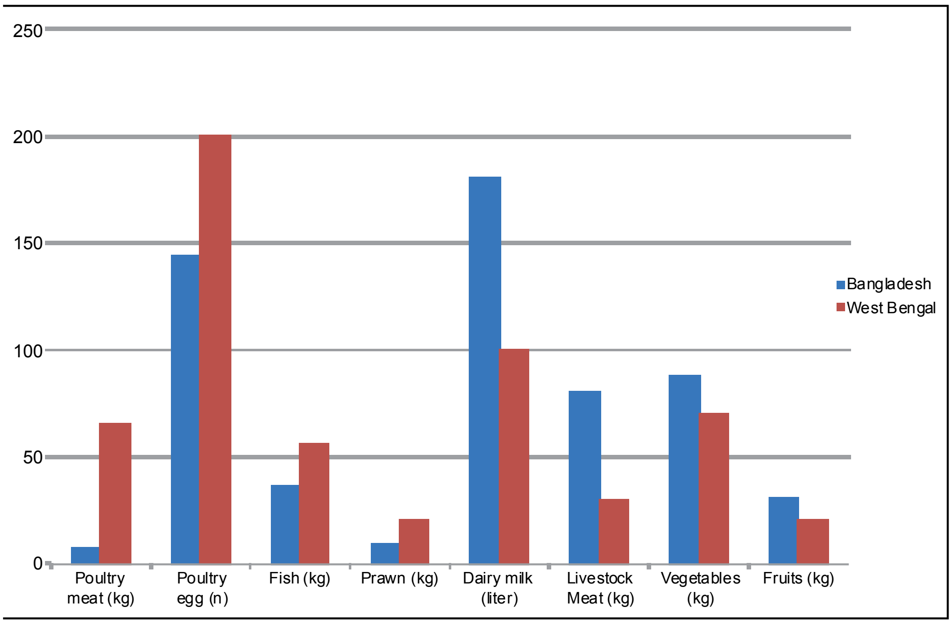


Fig. 3. The annual yield of homestead products per household in Bangladesh and West Bengal.

Overall, the low salinity soil type has significantly higher productivity in terms of the yearly homestead products produced in both Bangladesh and West Bengal (Figure 4). For example, HFS yield value from low salinity areas in West Bengal was much higher (US$324) than from high salinity areas (US$164) of West Bengal. This was also the case in Bangladesh.

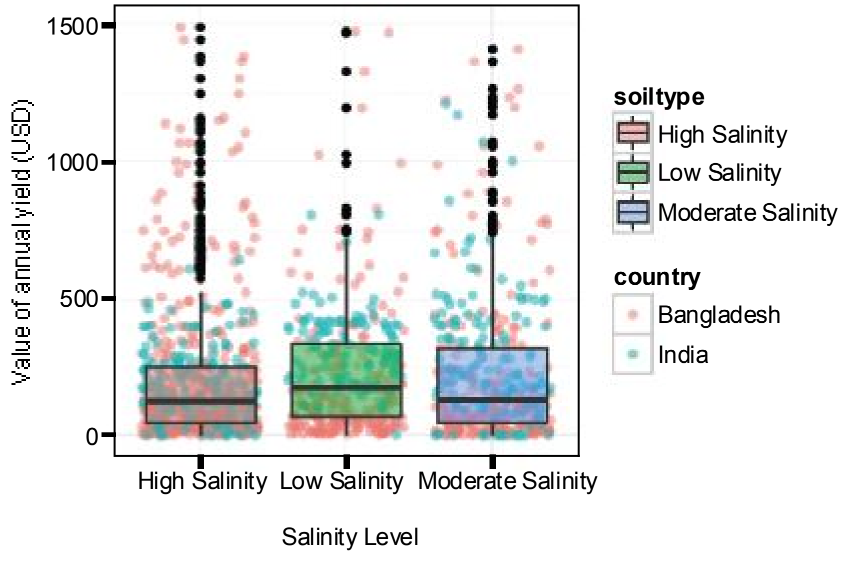


Fig. 4. Value of annual yield (in USD) by salinity level.

3.2 Consumption of HFS products

Homestead food consumption in Bangladesh is positively correlated with productivity of most of the HFS components ($P<0.05$). This relationship is strongest for aquaculture ($r = +0.79$), poultry meat ($r = +0.85$), poultry egg ($r = +0.89$) and fruit ($r = +0.76$), while it is relatively weak for vegetable ($r = +0.50$) and negative for livestock milk ($r = -0.09$). On the other hand, in West Bengal productivity has strong positive correlation ($P<0.05$) with fruits ($r=+0.96$), poultry egg ($r=+0.88$) and livestock milk ($r=+0.76$) and is weakly related with poultry meat ($r=+0.22$), vegetable ($r=+0.38$) and aquaculture ($r=+0.48$).

3.3 Contribution of HFS to household income

Homestead farming plays a key role for poor households, contributing between 10-25% of total household income in 2011 (Figure 6). Total contribution of HFS to household income is higher in Bangladesh (23%) than it is in West Bengal (16%). Non-aquaculture activities contributed more in Bangladesh (median $176) than in West Bengal (median $44) while aquaculture activities contributed more in West Bengal than in Bangladesh, with a median of $180 and $70 per household per year, respectively (Table 4).

Table 4. Household income from different sources and contribution of HFS to household income

Country	Total ($)	Off Farm ($)	Field ($)	HFS Aquaculture ($)	HFS Non-Aquaculture ($)	HFS Total ($)	HFS contribution to Total hh income (%)
Bangladesh	1079	667	381	70	176	246	23
West Bengal	1622	1103	333	180	44	224	14

3.4 Constraints and challenges for increasing productivity from HFS

Major constraints as reported by households for improving HFS aquaculture in Bangladesh are the lack of investment capital, while in West Bengal it is the lack of skill. For non-aquaculture HFS in Bangladesh, disease was the major problem and in West Bengal it was again lack of skill (Figure 5a and b).

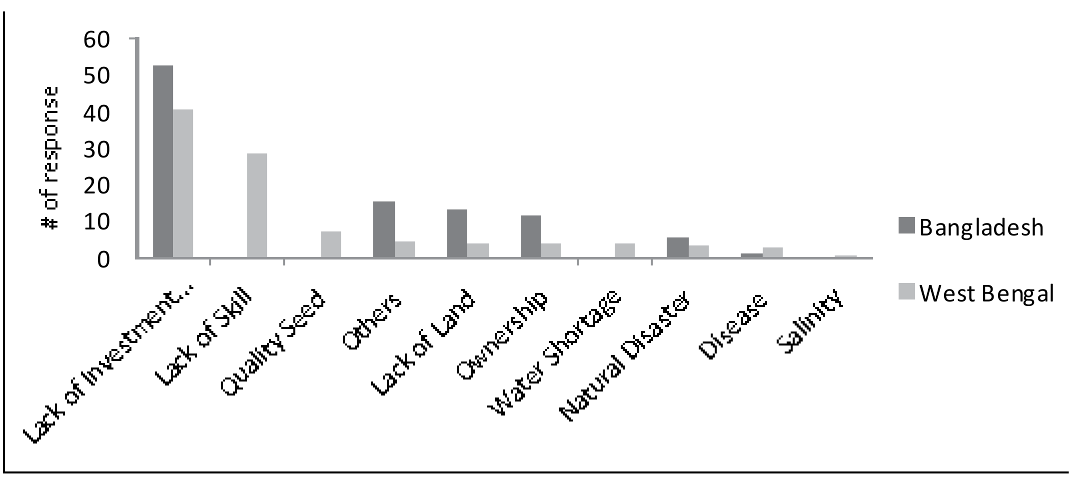


Fig. 5a. Major constraints and challenges for improvement of HFS aquaculture.

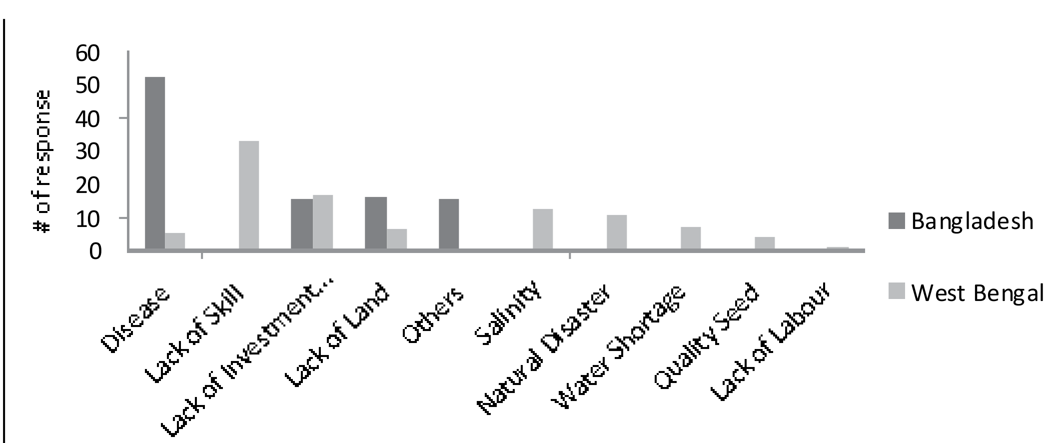


Fig. 5b. Major constraints and challenges for improvement of HFS non-aquaculture.

3.5 Integration between HFS units: pond plays a key role

There is a high prevalence of ponds in Bangladesh and West Bengal, which likely plays an important role as a water source for other farming components and as a key component for integration of farming components and recycling of resources. In both Bangladesh and West Bengal households with ponds have higher interaction among farming components than in households without ponds. In Bangladesh 50%, 58% and 2% of households use pond water for vegetable production, poultry and livestock, respectively, and 4% use pond bottom soil for vegetable production. Twenty-one percent of households use poultry and livestock manure and 3% vegetable by product as feed for fish production in ponds. Also 22% of households use poultry and livestock manure in vegetable and fruit production. While in West Bengal pond water use is more common, there was variation between two study areas. In South 24 Parganas, 100%, 83% and 82% of households use pond water for vegetable production, poultry and livestock, respectively. While in North 24 Parganas, 21% and 19% of households use pond water for vegetable production and poultry, respectively. Integration among other components appears to be not very strong. Only 6% and 4% of households in South 24 Parganas use poultry and livestock manure for fish culture and vegetable and fruit production. In North 24 Parganas no other integration was reported during the survey.

In contrast, households without ponds in Bangladesh had limited integration, with only 10% of households using poultry and livestock manure in vegetable and fruit production. No other integration was observed. The situation in West Bengal was even more limited; homesteads without ponds reported no integration or resource reuse between farming components. This finding suggests a strongly influence of ponds in intensifying and integrating HFS in Bangladesh and South 24 Parganas of West Bengal, and relatively weak influence on N24 Parganas.

4. Discussion

The findings from southern Bangladesh and West Bengal reveal a diversity of production systems and essentially confirm the importance of HFS for income, food and nutrition on homesteads with limited land. The results also suggest opportunities to increase productivity of the homestead farming components, increasing their contribution to income and improved nutrition of poor households.

4.1 Farming land, HFS units and yield

HFS in Bangladesh and West Bengal are comparable in terms of their production components i.e., fruit, vegetables, fish and small livestock, but differ in terms of their input investment, yield and consumption. Findings suggest potential for the poor to increase household food security and nutrition if systems are well managed, with access to necessary inputs and skills. Other authors have found that diversified HFS results in improved yields, leading to increased food consumption and improved nutrition in homesteads (Taher et al. 2004). Homestead production systems also offer opportunities for increasing seasonal availability of foods (Bushamuka et al. 2005). High salinity areas appear to be less productive. Intrusion of saline water changes soil salinity and restricts agriculture in coastal areas (Faisal and Parveen, 2004; Chowdhury et al., 2006). Further analysis of the datasets is ongoing to further understand the impacts of salinity on household farming systems, and further research is required on saline-adaptive technology development for homestead food production.

4.2 Consumption of HFS products

Homestead products are marketed and consumed at the household level. Present research finds strong correlation between HFS production and household consumption. Weinberger (2013) similarly mentioned that HFS is small-scale, non-commercial and mostly for household consumption. HFS has been considered a viable development approach, targeting nutrition for several decades, as evidenced by the large set of literature available on the topic (Marek et al. 1990; Schipani et al. 2002; Bloem et al. 1996; Marsh 1997; Cameron et al. 2012; Cabalda et al. 2011; Heim et al. 2009, 2011).

Benefits of HFS have been reported to include providing enhanced food supply and increased diversity of food, especially for the poor (Bushamuka et al. 2005; Talukder et al. 2010; Olney et al. 2009; Trinh et al. 2003; Cabalda et al. 2011). The current study essentially confirms these findings in coastal areas in the Ganges delta, and its importance for poor people.

Another advantage in HFS is production of food close to consumption areas and the reduced need for transportation and preservation (Novo and Murphy 2006). Weinberger (2013) also mentioned that improved access to and consumption of nutritious foods, improved social protection and a healthier environment can be derive from HFS.

4.3 Contribution of HFS to household income

The current study found HFS contributes 10-25% of household income. From a global perspective such contributions range from 0% (Méndez et al. 2001) to 50% (Trinh et al. 2003). One important lesson from the experiences of Helen Keller International (HKI) is that the objectives of households have changed and a focus on agricultural production of nutritious foods must consider both market-oriented income opportunities as well as household consumption (McDermott et. al., 2013). McDermott (2013) also mentioned creating food-related skills (poultry shed construction, vaccination) and technologies to help resource-poor landless and land-constrained people to earn more money indirectly through HFS or food production. This paper did not explore this aspect, but for the pro-poor this opportunity must be better understood and further studies should be carried out on this topic.

4.4 Challenges and opportunities

HFS interventions often aim to improve nutritious food consumption, income, intra-household equity and child care (McDermott et. al., 2013). This research identified lack of skills, particularly on disease management and technology extension support, as well as lack of investment as key constraints in Bangladesh and West Bengal. The other factors hampering HFS sustainability include, but are not limited to, heavy use of agrochemicals, dependency on hired labor, risk of market fluctuation for commercial products, scarcity of land, high population density and impact of urbanization (Soemorowoto and Conway 1992; Karyano 1990; Michon and Mary 1994; Kehlenbeck and Maass 2004; Arifin et al. 1998). According to Alam (2011) the most important characteristics that will ensure future sustainability are the capacity of the farming system to rapidly cope with changing circumstances. Even in the face of social and demographic changes in and around rural landscapes, HFS itself remain relatively stable (Alam 2011)

Lannotti et al. (2009) evaluated the Helen Keller International (HKI)-supported homestead food production (HFP) program that was conducted in Bangladesh for two decades in partnership with 80 local NGOs. They found that the initiative increased household food production, availability and access to food, and improved micro nutrient deficiency, especially when agricultural interventions came with behavioral change communication (BCC) that empowered women through increased access to resources. It also improved child care and nutrition. Similar outcomes have been observed in West Bengal (DRCSC, undated).

4.5 Integration between HFS units: pond plays a key role

Ponds play a key role as a water source for other HFS units and influence more integrated production, allowing several options for resource reuse and recycling. For centuries, a pond has been used as source of domestic water supply and small-scale irrigation (Little et al., 2007). Prein (2002) reported “on-farm ponds” as emerging foci for agricultural diversification. Ponds provide opportunities for integration with horticulture on dikes and are practiced widely in Asia (Ruddle and Zhong, 1988). The pattern of integration and resource reuse between pond aquaculture and livestock rearing is also common in this region (Little and Edwards, 2003). Whilst Micheilsons (2002) noted that individual component yield and input use efficiency can be lower than very intensive fish farming, in total, integration of aquaculture and agriculture can provide multiple benefits (Barman 2000; AIT/DOF 2001; Karim 2006) and increase overall HFS production (Karim 2011; Karim 2006). This research also indicates that the presence of a pond in a homestead provides positive outcomes, supporting more farming units within the HFS and making higher contributions to household income and nutrition.

5. Conclusions and recommendations

This study was the first attempt to compare the whole HFS of two countries of the lower Ganges delta. The study identifies HFS as a valuable component for the poor for food production and household consumption in both countries, with several key messages:

- Ponds are common in homestead areas, a feature more common in West Bengal than Bangladesh
- Presence of a pond plays a key role in improving HFS
- HFS productivity is higher in low salinity areas compared to high saline areas
- Presence of more HFS components results in increased productivity of household food production

Further research is required on:

- Factors that influence yield and consumption
- HFS in saline areas
- Resource flow within the components for designing an integrated production unit on a very small piece of land for the poor
- Potential role of credit in HFS improvements
- Mitigation of diseases
- Technology transfer for rural areas of West Bengal

Acknowledgements

We would like to acknowledge the CGIAR Challenge Program on Water and Food and CGIAR Research Program on Aquatic Agricultural Systems for supporting this study. We also thank WorldFish/USAID AIN project for providing additional funding for Bangladesh data collection, entry and analysis. We are grateful to Dr. Khandaker Murshed-E-Jahan, Dr. Manoranjan Mondal and Dr. T P. Tuong for their contribution in developing the survey questionnaire and Dr. Rayhan Hayat Sarwer for developing the survey method. We would like to thanks C. W. Chang for his kind support in analyzing this large data set.

References

Agricultural Census Database. 2010-11. Number and area of holding by size group. http://agcensus.dacnet.nic.in

AIT/DOF, 2001. Fish seed quality in Northwest Bangladesh. State of the System report. Aquaculture Outreach Programme, AIT, Thailand, 37 pp.

Alam, M. 2011. Tropical Homegardens in Bangladesh: Characteristics and Sustainability. E. Lichtfouse (ed.), Alternative Farming Systems, Biotechnology, Drought Stress and Ecological Fertilisation, Sustainable Agriculture Reviews 6, DOI 10.1007/978-94-007-0186-1_8, © Springer Science+Business Media B.V. 2011

Ali, M. N., Ghosh, B., Gantait, S., Chakraborty, S. 2014. Selection of Rice Genotypes for Salinity Tolerance Through Morpho-Biochemical Assessment. *Rice Science* 21(5): 288–298.

Amhed, A.U. 2006. Who is doing what in Bangladesh? Report on the First Meeting. Comprehensive Disaster Management Programme, Government of Bangladesh, Dhaka.

Arifin HS, Sakamoto K, Chiba K (1998) Effects of urbanisation on the vegetation structure of home gardens in West Java, Indonesia. Jpn J Trop Agri 42:94–102

Bangladesh Bureau of Statistics. 2011. Population and housing census: preliminary results. Census of India, 2011. Final Population Totals: West Bengal Profile.

Barman, B.K., 2000. Assessment of Nile tilapia (Oreochromis niloticus) Seed Production and Grow-out Systems for Small-scale Farmers in Northwest Bangladesh. PhD Dissertation. Asian Institute of Technology, Thailand, 246 pp.

Barua, S., S. Tripathi, A. Chakraborty, S. Ghosh, and K. Chakrabarti. 2012. Characterization and crop production efficiency of diazotrophic bacterial isolates from coastal saline soils. *Microbiological Research* 167(2): 95-102 (January 20).

Bhattacharya, A., A.D. Deo, J. K. Sundaray, and A.G. Ponniah. 2013. Impact of homestead farming system on rural economy -A study in South 24 Pargana district of West Bengal. Abstract, International Ecosystem Conservation, Climate Change and Sustainable Development Conference, October 3-5, Kerala, India.

Bloem, M.W., Huq, N., Gorstein, J., Burger, S., Kahn, T., Islam, N., et al. (1996). Production of fruits and vegetables at the homestead is an important source of vitamin A among women in rural Bangladesh. European Journal of Clinical Nutrition, 50 Suppl 3, S62–S67.

Bushamuka, V.N., S. de Pee, A. Talukder, L. Kiess, D. Panagides, A. Taher, and M. Bloem. 2005. Impact of a homestead gardening program on household food security and empowerment of women in Bangladesh. *Food and Nutrition Bulletin* 26 (1): 17-25.

Cabalda, A. B., Rayco-Solon, P., Solon, J. A. A., & Solon, F. S. (2011). Home gardening is associated with Filipino preschool children's dietary diversity. Journal of the American Dietetic Association, 111(5), 711.

Cameron, R. W. F., Blanuaa, T., Taylor, J. E., Salisbury, A., Halstead, A. J., Henricot, B., et al. (2012). The domestic garden–its contribution to urban green infrastructure. Urban Forestry & Urban Greening, 11(2), 129–137.

CPWF. 2013. Cracking the productivity code: demonstrating the benefits of community water

management and improved crop technologies in the coastal zone of Bangladesh isn't simple. http://waterandfood.org/2013/08/15/cracking-the-productivity-code

Chowdhury, M.A., Shivakoti, G.P., Salequzzaman, M., 2006. A conceptual framework for the sustainability assessment procedures of the shrimp aquaculture industry in coastal Bangladesh. Int. J. Agric. Resour. Govern. Ecol. 5, 162–184.

Dash, S.S., and M.K. Misra. 2001. Studies of hill agro-ecosystems of three tribal villages on the Eastern Ghats of Orissa, India. *Agriculture, Ecosystem and Environment* 86: 287–302.

Dey, S, U.K. Sarker, and M.A. Awal. 2012. Bangladesh Year round homestead vegetable production: Reduction of nutrient deficiency and income generation for small households. *J. Prog. Sci. & Tech* 10(2): 187-190.

DRCSC, undated. http://www.drcsc.org

Faisal, I. M., & Parveen, S. (2004). Food security in the face of climate change, population growth, and resource constraints: implications for Bangladesh. Environmental Management, 34(4), 487–498. doi:10.1007/s00267-003-3066-7.

Fleming, C. 2004. Challenges Facing the Shrimp Industry in Bangladesh. American International School, Dhaka.

Gain, A.K., K.P. Aryal, P. Sana, M.N. Uddin. 2007. Effect of river salinity on crop diversity: a case study of south west coastal region of Bangladesh. *Nepal Agriculture Research Journal* 8.

Garnett, T., M.C. Appleby, A. Balmford, I.J. Bateman, T.G. Benton, P. Bloomer, B. Burlingame, M. Dawkins, L. Dolan, D. Fraser, M. Herrero, I. Hoffmann, P. Smith, P.K. Thornton, C. Toulmin, S.J. Vermeulen, and H.C.J. Godfray. 2013. Sustainable intensification in agriculture: premises and policies.*Science* 341: 33–34.

Heim, S., Stang, J.,& Ireland,M. (2009). A garden pilot project enhances fruit and vegetable consumption among children. Journal of the American Dietetic Association, 109(7), 1220.

Heim, S., Bauer, K. W., Stang, J., & Ireland, M. (2011). Can a community-based intervention improve the home food environment? Parental perspectives of the influence of the delicious and nutritious garden. Journal of Nutrition Education and Behavior, 43(2), 130.

Huq, S. and J.M. Ayers, (2007) *Critical list: the 100 nations most vulnerable to climate change*, in *IIED Sustainable Development Opinion*. London: International Institute of Environment and Development. http://www.drcsc.org

Karim, M., Little, D.C., Kabir, M.S., Verdegem, M. J.C., Telfer, T., Wahab, M. A., 2011. Enhancing benefits from polycultures including tilapia (*Oreochromis niloticus*) within integrated pond-dike systems: a participatory trial with households of varying socio-economic level in rural and peri-urban areas of Bangladesh. Aquaculture. 314 (1-4): 225–235.

Karim, M., 2006 The livelihood impacts of fishponds integrated within farming systems in Mymensingh District, Bangladesh PhD Dissertation, University of Stirling, 351 pp.

Karyano (1990) Homegardens in Java. Their structure and function. In: Landauer K, Brazil M (eds) Tropical homegardens. The United Nations University, Tokyo, Japan, pp 138–146

Kehlenbeck K, Maass BL (2004) Crop diversity and classification of of homegardens in Central Sulawesi, Indonesia. Agroforestry Syst 63:53–62

Lannotti, L., K. Cunningham and M. Ruel. 2009. Improving Diet Quality and Micronutrient Nutrition: Homestead Food Production in Bangladesh. IFPRI Discussion Paper 00928. www.ifpri.org/millionsfed

Little, D.C., Karim, M., Turongruang, D., Morales, E.J., Murray, F.J., Barman, B.K., Haque, M.M., Kundu, N., Belton, B., Faruque, G., Azim, E.M., Ul Islam, F., Pollock, L.J., Verdegem, M.J., Young, J.A., Leschen, W., Wahab, M.A., 2007. Livelihood impacts of ponds in Asia-opportunities and constraints. In: Zijpp, A.J., van der, J.A.J., Verreth, Le Quang Tri, M.E.F., van Mensvoort, R.H., Bosma, M.C.M. (Eds.), Fishponds in Farming Systems .2006. : Beveridge; Proceedings of a Symposium Held in Can Tho City, 28– 30 April 2006, Organised by Can Tho University, Vietnam and Wageningen University. Wageningen Publishers, Netherlands.

Little, D.C. and P. Edwards, 2003. Integrated Livestock-Fish Farming Systems: The Asian experience and its relevance for other Regions. Inland Water Resources and Aquaculture Service and Animal Production Service. Food and Agriculture Organization, Italy. 177 pp.

Marek, T., Brun, T., & Reynaud, J. (1990). Do home garden projects improve income and nutritional status? A case study in Senegal. Food and Nutrition Bulletin, 12(1), 20–25.

Marsh, R. (1997). Household food security through home gardening– evidence fromBangladesh. In F. Heidhues&A. Fadani (Eds.), Food security and innovations: Successes and lessons learned. Frankfurt: Peter Lang Press.

McDermott, J., Aït-Aïssa, M., Morel, J., Rapando, N., 2013. Agriculture and household nutrition security– development practice and research needs. Food Sec. (2013) 5:667–678

Méndez VE, Lok R, Somarriba E (2001) Interdisciplinary analysis of homegardens in Nicaragua: Micro-zonation, plant use and socioeconomic importance. Agroforestry Sys 51:85–96

Miah, G.M. and J.M. Hussain. 2010. Homestead Agroforestry: a Potential Resource in Bangladesh. In SUSTAINABLE AGRICULTURE REVIEWS 3: Sociology, Organic Farming, Climate Change and Soil Science, ed. Eric Lichtfouse and Springer, Chapter 16.

Michon G, Mary F (1994) Conversion of traditional village gardens and new economic strategies of rural households in the area of Bogor, Indonesia. Agroforestry Syst 25:31–58

Micheilsons, C.G.J., K. Lorenzen, M.J. Philips and R. Gauthier, 2002. Asian carp farming systems: towards a typology and increased resource use efficiency. Aquaculture Research 33, 403-413.

Mondal, M.K., S.I. Bhuiyan, and D.T. Franco. 2001. Soil salinity reduction and prediction of salt dynamics in the coastal ricelands of Bangladesh. *Agricultural Water Management* 47(1): 9-23.

Nielsen, R., T. Hanstad, and L. Rolfes. 2006. Implementing homestead plot programmes: Experience from India. LSP Working Paper 23, FAO.

Novo, M. G., & Murphy, C. (2006). Urban agriculture in the city of Havana: A popular response to a crisis. In R. V. Veenhuizen (Ed.), Cities farming for the future, urban agriculture for sustainable cities (pp. 329–349). Philippines: RUAF Foundation, IDRC and IIRR.

Olney, D. K., Talukder, A., Iannotti, L. L., Ruel, M. T., & Quinn, V. (2009). Assessing impact and impact pathways of a homestead food production program on household and child nutrition in Cambodia. Food and Nutrition Bulletin, 30(4), 355–369.

Prein, M., 2002. Integration of aquaculture into crop-animal systems in Asia. Agricultural Systems 71, 127-146.

Rahman, S.A., M.S. Hussain, Z. Parveen, and A.S.M. Mohiuddin. 1993. Identifying characteristics of potential and actual acids sulphate soils. *Bangladesh Journal of Soil Science* 24:41-49.

Rahman, S.M., M.I. Khalil, and M.F. Ahmed. 1995. Yield-water relations and nitrogen utilization by wheat in salt-affected soils of Bangladesh. *Agricultural Water Management* 28(1): 49–56.

Ruane, A.C., C.M. David, H. Yu Winston, A. Mozaharul, Sk.G. Hussain, A.S. Khan, A. Hassan, Md. Bhuiya, T.A. Hossain, R. Goldberg, R.M. Horton, and C. Rosenzweig. 2013. Multi-factor impact analysis of agricultural production in Bangladesh with climate change. *Global Environmental Change*. 23(1):338–350

Ruddle, K. and G.F. Zhong, 1988. Integrated agriculture - aquaculture in south China: The dike-pond system of the Zhujiang Delta. Cambridge University Press. USA, 173 pp.

Sayeed, S.K. 2007. Climate change and Bangladesh: A perspective on where we are. In *The Daily Star*, Dhaka.

Schipani, S., van der Haar, F., Sinawat, S., & Maleevong, K. (2002). Dietary intake and nutritional status of young children in families practicing mixed home gardening in northeast Thailand. Food and Nutrition Bulletin, 23(2), 175–180.

Shamsuddin, S., C. Xiaoyong, M.K. Hazarika. 2006. Evaluation of groundwater quality for irrigation in Bangladesh using geographic information system. *J. Hydrol. Hydromech* 54: 3-14.

Soemorowoto O, Conway GR (1992) The Javanese homegardens. J Farm Syst Res-Ext 2:95–118

SRDI. 2001. Soil Salinity in Bangladesh. Soil Research Development Institute, Ministry of Agriculture, Bangladesh, Dhaka.

Taher, A., A. Talukder, N.R. Sarkar, V.N. Bushamuka, A. Hall, S. de Pee, R. Moench-Pfanner, L. Kiess, and M.W. Bloem. 2004. Homestead gardening for combating vitamin A deficiency: The Helen Keller International, Bangladesh, experience. In *Alleviating malnutrition through agriculture in Bangladesh: Biofortification and diversification as sustainable solutions*, ed. N. Roos, H.E. Bouis, N. Hassan, and K.A. Kabir, Washington, D.C.: International Food Policy Research Institute.

Talukder, A.,Haselow,N. J., Osei,A.K.,Villate, E., Reario,D., Kroeun, H., et al. (2010). Homestead food production model contributes to improved household food security and nutrition status of young children and women in poor populations. Field Actions Science Reports.

Trinh LN, Watson JW, Hue NN, De NN, Minh NV, Chu P, Sthapit BR, Eyzaguirre PB (2003) Agrobiodiversity conservation and development in vietnamese home gardens. Agri, Ecosys Env 97:317–344

Václavík, T., S. Lautenbach, T. Kuemmerle, and R. Seppelt. 2013. Mapping global land system archetypes. *Global Environmental Change* 23(6): 1637-1647.

Weinberger, K. 2013. Home and community gardens in Southeast Asia: potential and opportunities for contributing to nutrition-sensitive food systems. Food Sec. (2013) 5:847–856

World Bank. 2014. World devel. indicator data. http://data.worldbank.org/country?display=graph

Producing fish in small shaded homestead ponds: finding solutions with rural women

K. A. Kabir, G. Faruque, R. Sarwar, B. Barman, A. Choudhury, M. Hossain, E. Hossain, N. A. Aleem, M. Karim, K. Kamp and M. Phillips

[1]WorldFish, Bangladesh and Malaysia, k.kabir@cgiar.org, f.golam@cgiar.org, r.sarwer@cgiar.org, b.barman@cgiar.org, a.choudhury@cgiar.org, md.hossain@cgiar.org, md.e.hossain@cgiar.org, n.aleem@cgiar.org, m.karim@cgiar.org, k.kamp@cgiar.org, m.phillips@cgiar.org

Abstract

Small household ponds in rural Bangladesh were not constructed for aquaculture and commonly face various challenges for fish production, including physical shading caused by planting of trees for wood and fruit. Such ponds are considered underutilized with considerable potential for improvement. WorldFish initiated a farmer–researcher collaborative participatory action research (PAR) project in 2013 to increase fish production and consumption from shaded household ponds and to improve women's decision-making capacity in the use of these resources. The research was carried out in eight villages of southwest Bangladesh covering freshwater and brackishwater areas. There were six polyculture treatments (T) of which three (T1-T3) were in brackishwater and three (T4-T6) in freshwater areas. There were three treatments with four replications of each treatment in each village. All treatments were designed in consultation with women farmers and implemented by the women with assistance from a project team. The results showed no significant variation in fish production across the areas, though average yield was higher in fresh water. Comparison across all treatments showed significantly higher yield in T4, a polyculture treatment combining GIFT Tilapia, *Heteropneustes fossilis*, *Anabas testudineus* and *Cyprinus carpio*. Overall annual fish productivity increased more than 600% from the baseline; 76% of fish produced were consumed at household level and annual household fish consumption increased nearly 500%. The PAR approach to aquaculture improvement did not create problems for women in daily household activities; rather 25% mentioned that lime improved water quality for their household work and 50% indicated that while taking care of fish at the pond they also had the opportunity to water vegetables and fruit trees regularly, contributing to increased yield of these crops. Women's decision-making capacity on daily pond management increased (99%) while not very much on access to markets (8%). New learning as reported by women farmers was associated with technology, research and leadership. A critical challenge for women farmers was access to quality inputs and markets. The positive outcomes from the PAR approach, including developing farmers' capacity to analyze research outputs, suggests scope for wider application of the approach.

Key message: Engaging rural women through a participatory action research (PAR) approach helped address the challenges associated with shaded homestead pond aquaculture. Outcomes include increased fish production, household consumption and some capacity development among women's decision making regarding use of the pond resource for aquaculture.

Keywords: participatory action research (PAR), women, aquaculture, fish consumption, learning, decision making

1. Introduction

1.1 Characteristics of small homestead ponds and challenges of increasing productivity

Many households in rural areas possess a small pond close to their homestead (Huda et al. 2010; Kranzlin 2000; Little et al. 2007) and altogether approximately 4.27 million household ponds are found in Bangladesh (Belton and Azad 2012). This accounts for 20% of rural households (Jahan et al. 2010) with variation among different land-classes (Belton et al. 2011). Usually homestead ponds are small in size, ranging between 0.08-0.1 ha. However, there is further variation in prevalence of ponds and their size in different parts of the country. Studies in the southern Bangladesh polder zone indicate that 59% of households have a pond in their homestead, a proportion that gradually decreases with lower land holding groups (Bloomer 2012). The average size of ponds in this area is 0.039 ha (CAARP-WorldFish 2009).

Ponds were excavated to raise the base of their dwelling houses to avoid flooding and fish culture was often not their primary function (Belton and Azad 2012). Rather these ponds are used for multiple purposes, including bathing, washing, watering livestock and irrigation for dike or homestead vegetable production (ADB 2004).

Aquaculture is growing in Bangladesh and the trend of producing fish from homestead ponds is also increasing (DOF 2013). However, the average annual yield is still below 1.75 ton/ha (Jahan et al. 2010) and it drops to less than 1.0 ton/ha for either smaller or poorly managed ponds (ADB 2004). Belton and Azad (2012) made a critical analysis of fish production from those ponds and concluded that poorer households are less likely to own a pond than their better-off counterparts, that any pond they do own is likely to be smaller than the average and that they are more likely to be managed at a lower intensity, and hence be relatively unproductive, both in terms of total and per unit area output.

Homestead ponds are often surrounded by home gardens (Jahan 2011), which usually include timber and fruit trees and seasonal vegetables (Keatinge et. al. 2012). These trees often shade a major surface area of the small ponds and constrain primary productivity by restricting sunlight (Brunea et al. 2003; Giovannini and Piedrahita 1994). Indian major carps are commonly grown in these ponds due to cultural preference (Belton and Azad 2012), a choice that contributes to the low productivity. In some ponds farmers do not stock any fish and harvest is obtained only through rearing of naturally recruited fish that come into those ponds from rice fields or nearby open waters during the monsoon by rainwater flow or flooding. Raising productivity by cutting and trimming trees is not preferred by the farmers as the trees provide major energy requirements, usually in the form of firewood (GoB 2000), and many other benefits as well, particularly for poor households. No specific research has been carried out in this region to explore options for management of shaded ponds, particularly which fish species might grow better under this shaded condition and what type of pond management can allow them to grow more fish as well as to use pond water for other uses.

1.2 Finding solutions with people

In Bangladesh, solving local level aquaculture problems by the traditional extension service approach is highly constrained by very limited staff capacity of the Department of Fisheries and a production-oriented top-down approach (Lewis 1997; Alam and Thomson 2001). NGOs have tended to work with a target group of landless and marginal farmers, and have tried to prioritize poor women in particular but their interventions are very much project-bound and often go with an imposed agenda, not focused on the socioeconomic context, and with limited inter-project learning sharing (Lewis 1997). However, there is a growing awareness that many of the constraints to increased production, consumption and incomes for the poor are primarily social; for example, unequal access to both technical and material inputs and other resources (Worby 1994). Also research in this domain is mostly done by the National Agricultural Research Stations (NARS) with very limited collaboration with farmers and a tendency to ignore small farmers' problems while focusing more on commercially important issues. There is also a gap between researchers and extension services, both government and NGOs. The room for innovation and exchange of ideas is thus not functioning well (Lewis 1997). Participatory action research (PAR) involves collaborative research, education and action oriented towards innovation and social change (Kindon et al. 2007). However, in many research programs in Bangladesh people's participation is still limited and examples of farmers directly conducting their own research is largely absent.

1.3 Can women make a difference?

In Bangladesh, women's ability to generate income in the agricultural sector is severely constrained by their limited use, ownership, and control of productive physical and human capital (Quisumbing and Maluccio 2003) and limited adult education (Ahmed et. al. 2007). However, participation of rural women in agriculture has greatly increased in the past two decades, particularly as labor in post-harvest activities (Rahman 2000) and they are also widely engaged in agricultural work within the homestead area (Begum 1985; Abdullah 1985). There is evidence to show that directly raising women's incomes can be instrumental in strengthening their status in society (Lewis 1997). However, very little is known about the impact of engaging them in PAR where the primary goal is not income. Also, the outcomes of women farmer's research capacity building through PAR for solving local-level farming problems are poorly documented in Bangladesh, especially in aquaculture.

Based on these various challenges, the CGIAR Research Program on Aquatic Agricultural Systems, led by WorldFish, designed a program to increase productivity from those small shaded ponds by conducting research with women. The approach is based on a method where farmers and scientist work together to not only solve a problem but also to develop the capacity and confidence of the farmers. This process is thought to empower the overall community and allow sharing of knowledge in a more convincing way to a diverse audience within the community. The primary aim of this research was to develop low input-based management practices to increase fish production in shaded ponds without interfering with the use of pond water for other household purposes. The overall aim was to improve household nutrition by increasing fish consumption, especially by identifying suitable fish species composition, and to increase women's decision-making capacity for homestead farming. This paper presents preliminary results on the effectiveness of this research-in-development approach to farmers' learning and developing farmers' capacity to analyze research results and share them with the community for greater impact.

2. Methods

2.1 Study area

The study was conducted in eight villages under eight *upazilas* of seven administrative districts in the southwestern part of Bangladesh (Table 1). Four villages were in freshwater and four in brackish water areas (Figure 1). Freshwater and brackish water areas were differentiated based on annual river water salinity of that area. River salinity remains at 0 ppt yearround in freshwater areas, whilst in brackish water areas the river water salinity varies considerably during the year, and in different regions. Generally, salinity starts to increase in late February and continues to increase until June reaching up to 25 ppt in the highly saline regions (i.e. Satkhira) and 5-10 ppt in low and medium saline parts (i.e. Barguna, Khulna). Salinity starts to drop down with the monsoon rainfall, eventually reaching 0 ppt in low and medium saline regions (i.e. Barguna, Khulna) and 5-7 ppt in highly saline regions.

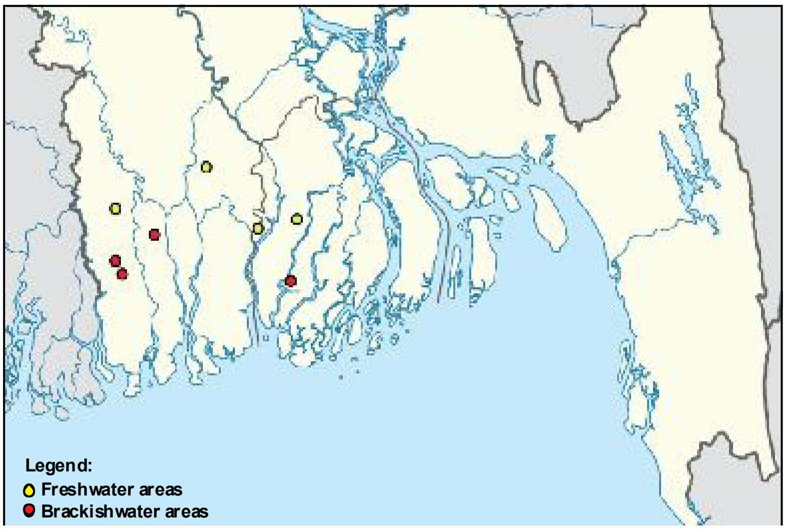


Fig. 1. Study areas.

2.2 Developing a PAR model for this research

This study was conducted jointly by two CGIAR Research Programs and three bilateral projects in order to allow for cross-project learning sharing and integration of an aquatic agricultural system approach for solving common problems with people. PAR can only be successfully achieved through mechanisms that encourage meetings, joint reflections and the collective development of findings and conclusions (Funtowicz and Ravetz 1993; Ottmann 2005). This research therefore involved three interconnected layers (Figure 2)—scientists, facilitators and farmer researchers—to ensure effective participation of all stakeholders and thus attempt to bridge the chasm between science and people.

The scientist team comprised a pool of WorldFish experts from disciplines of aquaculture, fisheries, biology, economics and gender to provide overall technical guidance, advisory support and coordination of the research. The scientists' team interacted directly with the farmer researchers in designing the experiments and farmers' research capacity building activities. The facilitators were technical staff from the respective projects who were involved in daily communication with the farmer researchers. The farmer researchers, all women, were the real actors of this research. They contributed to the process of research design, implementation, data collection, preliminary analysis and sharing the learning within the groups and beyond.

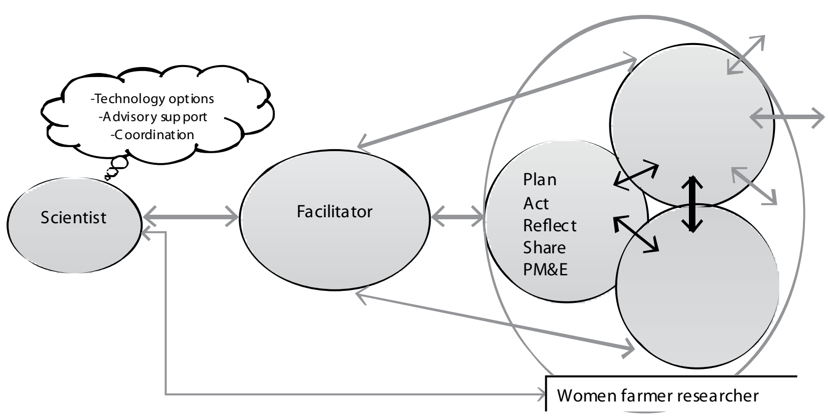


Fig. 2. PAR model for shaded pond research.

The scientist team consulted with each community to identify together potential interventions for improving productivity of ponds, with facilitators responsible to assist the fortnightly sharing meeting organized by farmer researchers. Various events for sharing of learning were planned among and within areas to evaluate farmer research results, develop their capacity to analyze research findings by using PRA tools, to improve their confidence by sharing research findings with broader audiences and also to establish linkages within and with other communities.

2.3 Pond and farmer selection

Ponds with a surface area of around five decimal and a minimum 60% shading at the sunniest time of the day were selected for this research. Farmer researchers, all women, were selected based on their interest in research, experience in pond management, access to a homestead pond and literacy level. A total of 96 women farmer researchers participated in the research (Table 1).

Table 1. Number of farmer researchers of the study by area

Hub/Upazila	District	Region	No. of farmers
Nagorkanda	Faridpur	Fresh water (0 ppt salinity)	12
Babugonj	Barisal		12
Monirampur	Jessore		12
Rajapur	Jhalokhathi		12
Amtoli	Barguna	Brackish water	12
Batiaghata	Khulna		12
Kaligonj	Satkhira		12
Shyamnagar	Satkhira		12

2.4 Farmer consultation and experimental design

At each community, consultations with farmers were conducted using different PRA tools. The focus of the early consultations was to make homestead resource profiles. Topics included: identifying major homestead farming components; understanding the role of ponds in the homestead system and its integration with other farming practices; SWOT analysis of pond aquaculture; identifying farmers' species preferences; identifying preference for fish feeding; finding options for addressing multiple use of homestead ponds; annual water calendar and water use from homestead ponds; women's preferred activities in pond management; current role of women in household decision-making including homestead agriculture; women's perspective about nutrition; women's level of participation in agriculture input purchase and product marketing; and possible role of women in participatory technology development and knowledge sharing.

Consultation outputs from four hubs of each region were merged together and a summary was prepared by the scientist team. Species selection and pond management protocols were developed based on the consultation summary and further shared with farmers before implementation. Three polyculture treatments were designed for each hub with low stocking density (Table 2). Each treatment had four replications. In each treatment, species were selected under the categories of regular uptake, high value, fast growing and cultural preference. Twenty-five gm tilapia were strategically stocked to allow for quick recruitment and 100 gm carp species were stocked to allow them to grow to marketable size within an eight-month timeframe.

Table 2. Selected fish in different treatments

Category	Brackishwater area			Freshwater area Brackishwater area		
	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5	Treatment 6
Regular uptake	GIFT Tilapia (25)	GIFT Tilapia (25)	GIFT Tilapia	GIFT Tilapia	GIFT Tilapia	GIFT Tilapia
High value	*Mystus gulio (50); Macrobrachi um rosenbergii (5)*	*Macrobrachi um rosenbergii (5); Heteropneus tes fossilis (25)*	*Clarias batrachus (15)*	*Heteropneus tes fossilis (2)*	*Clarias batrachus (15)*	
Fast growing		*Anabas testudineus (50)*		*Anabas testudineus (50)*	*Anabas testudineus (50)*	
Cultural prefer-ence	*Labeo rohita (2)*		*Cyprinus carpio (1) Catla catla (2); Cirrhinus cirrhosus (4)*	*Cyprinus carpio (1)*	*Hypophthal michthys molitrix (2)*	

Note: Figures in parentheses indicate the stocking density per decimal.

A feeding strategy was developed based on the consultation summary and was the same across all treatments and regions. Total feed requirement was calculated based on total biomass stocked in each pond. Feed composition was 25% kitchen waste, 50% homemade feed prepared from locally available raw ingredients according to the guideline provided by the scientists to keep consistency at all areas and 25% commercial extruded feed.

2.5 Pond management

Before fish stocking, ponds were treated as follows. Unwanted fish were removed by using rotenone at 50 gm/dec; liming was conducted using dolomite and zeolite at 750 gm/dec and 25 gm/dec respectively; and ponds were fertilized by urea, Triple Super Phosphate (TSP) and Muriate of Potash (MoP) at 150 gm, 75 gm and 75 gm per decimal, respectively. Ponds were fenced by blue nets to avoid entry of predators and to prevent escape of fish during rain or floods.

Ponds were stocked with GIFT Tilapia, *Mystus gulio*, *Macrobrachium rosenbergii, Labeo rohita, Heteropneustes fossilis, Anabas testudineus, Clarias batrachus, Cyprinus carpio, Catla catla, Cirrhinus cirrhosis, Hypophthalmichthys molitrix* and *Barbonymus gonionotus* at 25 gm, 1 gm, 5 gm, 100 gm, 5 gm, 2 gm, 5 gm, 100 gm, 100 gm, 100 gm, 100 gm, and 2 gm, respectively. Fish seed of each species was supplied from a single source and all were collected from hatcheries.

Feed was mixed type (i.e. 50% homemade, 25% commercial feed and 25% kitchen waste) with restricted feeding ration based on weight gain. Feeding frequency was twice a day across all hubs.

2.6 Monitoring, record keeping and data collection

Farmer researchers and scientists together set the monitoring protocol including daily feed application, observation of feed utilization, pond water color, water depth, fish breeding, abnormalities of fish health and behavior, fish disease, harvesting, consumption, sales and monthly body weight sampling. Besides, farmer researchers also listed interested visitors and any other challenges and inspirations they encountered while conducting research. Information was documented in homestead pond record books and later these data were entered in a MS Access database by the WorldFish scientist team.

Fortnightly meetings were organized at each hub among all farmers to share progress and challenges. The facilitator monitored the record keeping and guided sessions on technical aspects of aquaculture research, gender and nutrition. This also allowed the farmer researchers to compare between the treatments and developed their skills for sharing their observations. All discussions were documented in the meeting registrar.

Qualitative and quantitative data on pond productivity, learning and social change were collected through surveys towards the end of each farming season.

2.7 Data analysis

Participatory data analysis was conducted by the farmers during the regional learning sharing workshop. In addition, data was entered into MS Access software from which data were exported to MS Excel sheets for preparation of different tables. Both descriptive and statistical analysis was done. SPSS software was used for statistical analysis. To make a comparison among treatments as well as regions, mean and standard error have been calculated. In order to see the significance differences among the treatments and regions, an ANOVA test (Duncan test) was conducted.

2.8 Analyzing social changes

Social change data was mainly collected through two sessions conducted between May and June (first session) and September and October (second session) of 2014. A simple descriptive representation of learning and decision-making has been fitted into tables based on the response of women farmer researchers on those topics.

2.9 Participatory analysis of research findings by farmers

At the end of the first year's culture season two regional (one in each region) learning sharing and analyzing workshops were conducted where different PRA tools were applied to understand farmer researchers' capacity to analyze research findings, setting priorities for research outcomes and exercises to build their confidence on sharing their learning to a broader audience. In this paper some comparisons are made between farmer findings and scientist analysis in order to evaluate farmers' capacity to analyze research findings and also to test the effectiveness of the participatory process developed for this purpose.

3. Results

3.1 Production

Fish production from shaded ponds in the 2013-14 season increased significantly ($p<0.05$) from the baseline of 2012-13 (Figure 3). Fish production was better in freshwater regions than brackish water regions in terms of the amount of fish produced per ha though the difference was not statistically significant. While comparing among treatments across both regions, fish production was significantly ($p<0.05$) higher in treatment 4. This can be considered the best species composition. Tilapia constituted 44.9% of total fish production, ranging from 32% to 77% in different treatments. Tilapia breeding also occurred within ponds, producing 0-4 cohort with variation between ponds within the treatment and between treatments.

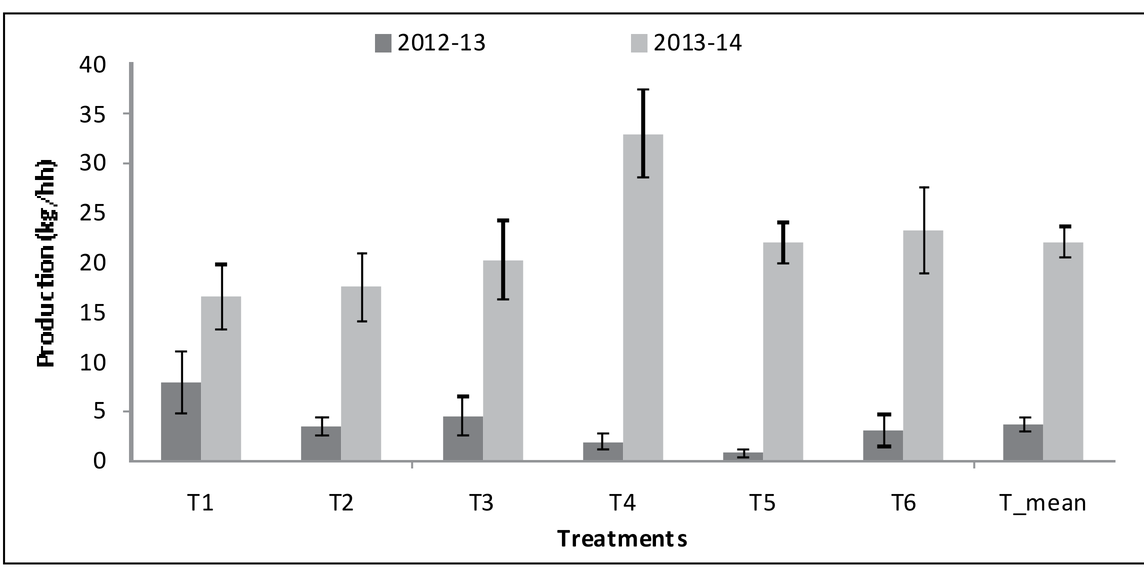


Fig. 3. Annual fish production (kg/hh) from homestead shaded ponds.

3.2 Consumption

Household fish consumption both in terms of amount consumed (Figure 4) and frequency of consumption increased significantly in 2013-14 compared to that of 2012-13 across all treatments in both the regions without much variation. In 2013-14 in the research ponds household members consumed an average 76.9% of the fish produced, ranging from 69.6% to 87.0% in different treatments. Similarly, mean household weekly fish consumption frequency from their own pond increased from 0.09 in 2012-13 to 1.93 in 2013-14.

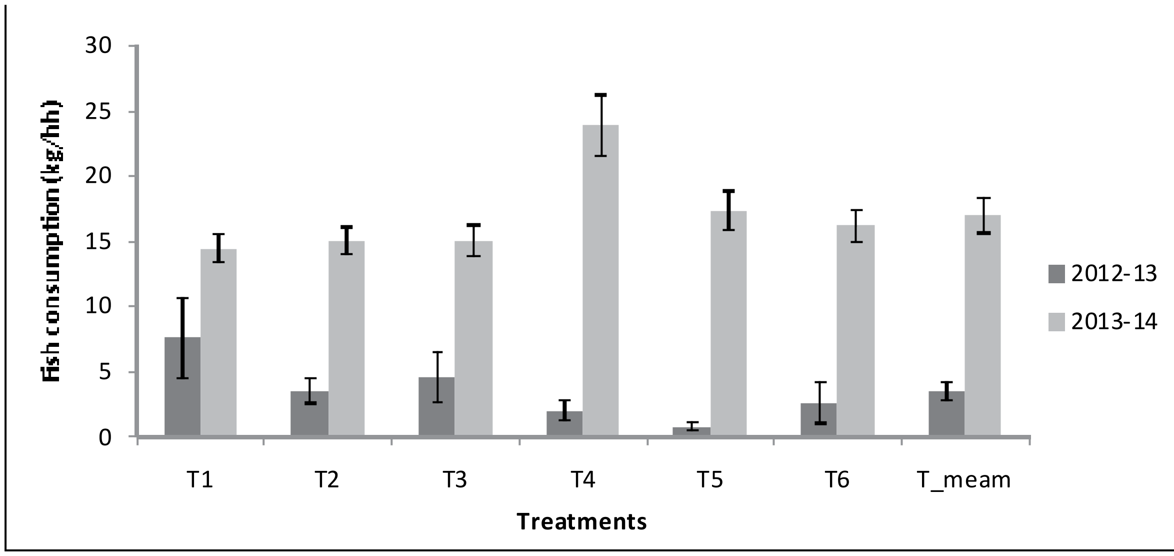


Fig. 4. Annual fish consumption (kg/hh) from homestead shaded ponds.

3.3 Pond water use

Regarding water use in regular household activities, 75% of households mentioned no problem in their pond record book and meeting registrar, as well as in impact surveys. The remaining 25% of women mentioned that due to use of lime, water quality in their ponds had improved compared to previous years and thus there were benefits for household use. While exploring the impact of aquaculture on other homestead farming components 50% of women mentioned there was no water use conflict or problem with other farming system components and the rest (50%) mentioned that engaging in aquaculture research was rather helpful for them to manage other parts of the homestead farm. According to the latter 50%, women farmer researchers visited ponds more frequently to take care of fish during which time they also could water and take care of their vegetable and fruit gardens, which resulted in increased yields.

3.4 Decision-making capacity

The collaborative nature of this PAR approach greatly increased women farmer's decision-making capacity on aquaculture management, though relatively less advancement was observed on other agriculture- and income-related areas. The least progress was made on making decisions for marketing (Table 2). There was not much variation among the treatments in building farmers' decision-making capacity. Only 1% of farmers reported decreased decision-making capacity and that was on another agricultural input selection.

Table 2. Change in farmers' decision-making capacity on different activities related to homestead farming

Decision-making activity	Increased		No change		Decreased	
	#	%	#	%	#	%
Daily pond management	95	99.0	1	1.0	0	0
Harvesting of fish	89	92.7	7	7.3	0	0
Selling of fish	36	37.5	60	62.5	0	0
Income from sold fish	31	32.3	65	67.7		0
Going to market	8	8.3	88	91.7		0
Other agricultural input selection (especially for homestead agriculture)	52	54.2	43	44.8	1	1.0

3.5 Learning

At the start of the project, farmers had limited knowledge on the context of research and aquaculture management in shaded ponds. At the end of the first cycle, the major learning as a result of conducting action research in conjunction with researchers was mainly about shaded pond management, research capacity and leadership (Table 3). There was not much variation among treatments in the process of learning.

Table 3. Different aspects of farmers learning and number of farmers who acquired that learning

Area of learning	Area of learning	Number of farmers
	Importance of stocking quality fish seed	93
Pond management	Importance of regular feeding	92
	Net fencing to prevent escape of fish & prevent entry of predator	71
	Selection of species in shaded pond aquaculture	67
	Selection of stocking density based on pond management	53
	Removal of predatory fish	38
	Advantages of liming in pond water quality management	36
	Regular fish harvesting technique for cat fish	29
	Sampling for examination of fish disease	11
	Advantage of using light trap	7
Research	Comparison and result analysis	89
	Importance of record keeping	88
	Sharing new learning with neighbors	72
	Prioritizing problems	61
	Planning for solving the problem	58
	Explaining result with reason	49
Research	Sharing with community (providing advice)	96
	Facing visitors	56
	Organizing meetings	31

3.6 Challenges

Limited access to markets and inputs were identified as major challenges by 88 of the farmers. While 31 farmers mentioned an increased workload, they enjoyed the activity. One farmer mentioned poaching as a threat of increased production.

Some challenges were more technical and encountered by less than 10 farmers. Those reported included a lack of natural food in the pond, predators (e.g. snake, frog, reptiles), falling tree leaves and worsening pond water quality, higher feed price and flooding of the pond.

3.7 Evaluation of farmers' capacity to analyze research findings

Scoring and voting tools used during the workshop led farmers to conclude there was not much difference among the treatments; GIFT Tilapia was considered the best species in terms of production and recruitment and increased fish consumption was their most important benefit. Learning on how to solve aquaculture problems through PAR and improved importance at the household level was also considered important.

By contrast, scientist analysis of the data showed that production was significantly higher in T4 and other treatments were similar in terms of fish production. Production and recruitment was best in GIFT Tilapia.

4. Discussion

Engaging rural women in shaded pond aquaculture greatly increased fish production, household consumption and advanced women's decision-making capacity in many sectors relevant to aquaculture, and homestead farming more generally.

Fish production greatly increased from the baseline. This was due to selection of high yielding GIFT tilapia and other fast growing fish with the addition of regular feedings. Mamun (2007) mentioned GIFT can grow well, utilize feed under adverse environments and are stress tolerant. Feeding supplements low natural food in the rearing system and optimum feeding increases aquaculture production (Biswas 2012; Bosma 2011; Azim 2002). However, the production is still below national average production (Belton and Azad 2012), suggesting room for further improvement.

Most of the fish produced were consumed at the household level, which is expected to have a positive impact on human nutrition. Kabir (2015) also reported a strong correlation between homestead pond fish production and consumption. Other studies have also shown that increased production from pond aquaculture is closely linked to increased household consumption and nutritional benefits (Bushamuka et al. 2005; Taher et al. 2004).

Women's decision-making capacity regarding aquaculture management greatly increased. Less progress was observed in some areas, such as financial and marketing aspects (fish sales, income and going to market to buy inputs or sell fish). Women empowerment in the agricultural index under Feed the Future interventions in southwest Bangladesh shows an advancement of 39% and also indicates several socio-economic factors influencing this advancement (Alkire et al.2013). In the first year of this PAR a larger improvement was noticed. This might be due to the PAR approach as opposed to a conventional development intervention.

This research created an excellent partnership between scientists, experts of technology extension and farmers, and resulted in multidimensional learning for farmer researchers and their increased capacity to lead in a community. Other research has also concluded that PAR involves a (relatively) egalitarian partnership between expert researchers and other participants (Greenwood et al. 1993; Wallerstein 1999; Pain 2004).

In this PAR the farmers' research results were quite similar to those derived from the scientists. This suggests that PAR has the potential for transformative change from a farmer to a farmer researcher; such capacity building can help farmers become more effective in solving local farming problems.

5. Conclusions

As this research work has illustrated, the philosophy of participatory action research provides technological and methodological answers for participatory and sustainable development. The approach goes through dialectical processes that involve rural women, facilitators and scientists and can build new knowledge on topics not yet explored. Such learning can be observed in the next PAR cycle.

However, this requires sharing multiple understandings to co-generate knowledge and developing reciprocal understanding that invokes all forms of rationality, not just technical approaches. This study has already broadened cross-project learning and involved two-dimensional (technological and social) processes of development. However, sustainability targets can be achieved only after developing complete knowledge of the process and determinants of social change in addition to the technological aspects.

Acknowledgements

We are grateful to all participating farmer researchers and facilitators for conducting this research, keeping records, doing participatory analysis and supporting further analysis by sharing data and outcome stories. We would like to acknowledge the CGIAR Research Program on Aquatic Agricultural Systems (AAS) for providing the methodical and financial support to organize common learning events with the farmers. USAID-CSISA, the CGIAR Research Program on Aquatic Agricultural System, CGIAR Research Program on Climate Change Agriculture and Food Security, and USAID –AIN funded specific hubs of the research.

References

Abdullah, T., 1985. Women in rice farming in Bangladesh and how technology programs can reach them. Women in Rice Farming. Proceedings of a Conference on Women in Rice Farming Systems. International Rice Research Institute (IRRI), Philippines. Gower Publishing Co. Ltd., Aldershot, 26-30 September 1983.

ADB, 2004. An evaluation of small-scale freshwater rural aquaculture development for poverty reduction. Operations Evaluation Department. Asian Development Bank, Manila, Philippines.

Ahmed, A. U., Hill, R. V., Smith, L. C., Wiesmann, D. M., & Frankenberger, T. (2007). The World's most deprived: Characteristics and causes of extreme poverty and hunger. 2020 vision for food, agriculture, and the environment discussion paper 43.

Alam, M.F., Thomson, K.J., 2001. Current constraints and future possibilities for Bangladesh fisheries. Food Policy 26, pp. 297–313

Alkire, S., Meinzen-Dick, R., Peterman, A., Quisumbing, A., Seymour, G., Vaz, A., 2013. The Women's Empowerment in Agriculture Index. World Development Vol. 52, pp. 71–91

Azim, M.E., Verdegem, M.C.J., Khatoon, H., Wahab, M.A., Dam, A.A V., Beveridge, M.C.M., 2002. A omparison of fertilization, feeding and three periphyton substrates for increasing fish production in freshwater pond aquaculture in Bangladesh. Aquaculture. Volume 212, Issues 1–4, 23 September 2002, Pages 227–243

Belton, B., Azad, A., 2012. The characteristics and status of pond aquaculture in Bangladesh. Aquaculture 358–359: pp. 196–204

Belton, B., Karim, M., Thilsted, S., Jahan, K.M., Collis, W., Phillips, M., 2011. Review of aquaculture and fish consumption in Bangladesh. Studies and Reviews 2011–53. The WorldFish Center, Penang, p. 76.

Begum, S., 1985. Women and technology: rice processing in Bangladesh. Women in Rice Farming. Proceedings of a Conference on Women in Rice Farming Systems. International Rice Research Institute (IRRI), Philippines. Gower Publishing Co. Ltd., Aldershot, 26-30 September, 1983.

Biswas, G., De, D., Thirunavukkarasu, A.R., Natarajan, M., Sundaray, J.K., Kailasam, M., Kumar, P., Ghoshal, T.K., Ponniah, A.G., Sarkar, A., 2012. Effects of stocking density, feeding, fertilization and combined fertilization-feeding on the performances of striped grey mullet (Mugil cephalus L.) fingerlings in brackishwater pond rearing systems. Aquaculture. Volumes 338–341, Pages 284–292

Bloomer, J. 2012. Homestead Aquaculture in Bangladesh: Current Status and Future Directions. MSc dissertation in Aquatic Resource Management of King's College London. http://www.kcl.ac.uk/sspp/departments/geography/study/masters/dissertations/Dissertation-2012-Bloomer.pdf

Bosma, R.H., Verdegem, M.C.J., 2011. Sustainable aquaculture in ponds: Principles, practices and limits. Livestock Science. Volume 139, Issues 1–2, Pages 58–68

Bushamuka, V.N., S. de Pee, A. Talukder, L. Kiess, D. Panagides, A. Taher, and M. Bloem. 2005. Impact of a homestead gardening program on household food security and empowerment of women in Bangladesh. Food and Nutrition Bulletin 26 (1): 17-25.

Brunea, D.E. , Schwartza, G. , Eversoleb, A.G. , Colliera, J.A. , Schwedlerb, T.E., 2003. Intensification of pond aquaculture and high rate photosynthetic systems. Aquacultural Engineering. Volume 28,

CAARP. 2009. Socio-economic profile and aquaculture rehabilitation impact on farming performance and livelihoods of the Cyclone Sidr affected households in the southern region of Bangladesh. WorldFish ReportIssues 1–2,Pages 65–86

DOF.2013. National Fish Week 2013 Compendium (In Bengali). Department of Fisheries, Ministry of Fisheries and Livestock, Bangladesh. 144p.

Funtowicz, S., Ravetz, J., 1993. Science for the post-normal age. Futures 25 (7), 739e755.

Giovannini, P., Piedrahita, R.H., 1994. Modeling photosynthetic production optimization for aquaculture ponds. Aquacultural Engineering. Volume 13, Issue 2, Pages 83–100

GOB (Government of Bangladesh). 2000. Forestry master plan: 3rd forestry forum background paper. TA no. 1355-BAN Asian Development Bank (ADB), Dhaka, Bangladesh

Greenwood, D.J., Whyte, W.F., Harkavy, I., 1993. Participatory action research as a process and as a goal. Human Relations 46, 175–192.

Huda, K.M.S., Atkins, P.J., Donoghue, D.N.M., Cox, N.J., 2010. Small water bodies in Bangladesh. Area 42 (2), 217–227

Jahan, M.K., Pemsl, D.E. 2011. The impact of integrated aquaculture–agriculture on small- scale farm sustainability and farmers’ livelihoods: Experience from Bangladesh. Agricultural Systems 104:

Jahan, M.K., Ahmed, M., Belton, B., 2010. The impacts of aquaculture development on food security: lessons from Bangladesh. Aquaculture Research 41 (4), 481–495.

Kabir, K.A., Karim, M., Phillips, M., 2015. Homestead farming system in southern Bangladesh. WLE Technical Report

Kindon, S., Pain, R., Kesby, M., 2007. Participatory action research approaches and methods : connecting people, participation, and place. Routledge. ISBN 0-203-93367-2 Master e-book ISBN

Keatinge, J. D. H., Chadha, M. L., Hughes, J. d.'. A., Easdown, W. J., Holmer, R. J., Tenkouano,A.,Yang, R.-Y.,Mavlyanova, R., Neave, S.,Afari-Sefa, V.,Luther, G.,Ravishankar,M., Ojiewo,C., Belarmino, M., Ebert, A., Wang, J. F., & Lin, L. J. (2012). Vegetable gardens and their impact on the attainment of the millen- nium development goals. Biological Agriculture and Horticulture, 28(2), 71–85.

Kranzlin, I., 2000. Pond management in rural Bangladesh: problems and possibilities in the context of the water supply crisis. Natural Resources Forum 24, 211–223

Lewis, D., 1997. Rethinking aquaculture for resource-poor farmers: perspectives from Bangladesh. Food Policy, Vol. 22, No. 6, pp. 533–546

Little, D., Karim, M., Turongruang, D., Morales, E., Murray, F., Barman, B., Haque, M., Kundu, N., Belton, B., Faruque, G., Azim, E., Islam, F., Pollock, L., Verdegem, M., Leschen, W., Wahab, A., 2007. Livelihood impacts of ponds in Asia—opportunities and constraints. In: van der Zijpp, A., Verreth, J., Tri, L.Q., van Mensvoort, R. (Eds.), Fishponds in Farming Systems.Wageningen Academic Publishers, pp. 177–202.

Mamun, S.M., Focken, U., Becker, K., 2007. Comparison of metabolic rates and feed nutrient digestibility in conventional, genetically improved (GIFT) and genetically male (GMNT) Nile tilapia, Oreochromis niloticus (L.). Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology Volume 148, Issue 1, Pages 214–222392–402

Pain, R., 2004. Social geography: participatory research. Progress in Human Geography 28, 652–663.

Ottmann, G., 2005. Agroecología y Sociología histórica desde Latinoamérica: elementos para el análisis y potenciación del movimiento agroecológico: el caso de la provincia argentina de Santa Fe. Córdoba University, Cordoba.

Quisumbing, A. R., & Maluccio, J. A. (2003). Resources at marriage and intrahousehold allocation: Evidence from Bangladesh, Ethiopia, Indonesia, and South Africa. Oxford Bulletin of Economics and Statistics, 65(3), 283–327

Rahman, S., 2000. Women's employment in Bangladesh agriculture: composition, composition, determinants and scope. Journal of Rural Studies vol. 16. Pp 497-507

Taher, A., A. Talukder, N.R. Sarkar, V.N. Bushamuka, A. Hall, S. de Pee, R. Moench-Pfanner, L. Kiess, and M.W. Bloem. 2004. Homestead gardening for combating vitamin A deficiency: The Helen Keller International, Bangladesh, experience. In Alleviating malnutrition through agriculture in Bangladesh: Biofortification and diversification as sustainable solutions, ed. N. Roos, H.E. Bouis, N. Hassan, and K.A. Kabir, Washington, D.C.: International Food Policy Research Institute.

Wallerstein, N., 1999. Power between the evaluator and the community: research relationships within New Mexico's healthier communities. Social Science & Medicine 49, 39–53.

Worby, E. (1994) Hitting hairs and splitting targets: anthropological perspectives on fish culture technology transfer through NGOs in Bangladesh. Rockefeller Foundation Conference paper, Addis Ababa

Section 5

Aquaculture

Productivity, diversification and resilience of saline aquaculture systems in coastal southern Bangladesh

K.A. Kabir [1], S.B. Saha[2], M. Karim[1], C.A. Meisner[1] and M. Phillips[3]

[1] WorldFish, Bangladesh, k.kabir@cgiar.org, m.karim@cgiar.org, c.meisner@cgiar.org
[2] Bangladesh Fisheries Research Institute, Bangladesh, sbikashsaha@yahoo.com
[3] WorldFish, Malaysia, m.phillips@cgiar.org

Abstract

The CGIAR Challenge Program on Water and Food conducted research in high salinity areas of the lower Ganges delta of Bangladesh in 2012 and 2013 to increase the productivity, profitability, diversity and resilience of aquatic agricultural farming systems. This paper reports on research on the diversification of shrimp-dominated low productive *gher* farming systems by testing crop rotation and incorporation of fish into the farming systems. Farmers' existing practice was used as a control treatment and compared to two improved systems: rotational monoculture and polyculture systems in outdoor ponds (*ghers*). Tiger shrimp (*Penaeus monodon*) production in 2012 and 2013 in control, monoculture and polyculture treatment systems was 210, 556, 404 and 390, 857, 567 kg/ha, respectively. Fish production in those years was 728, 2,367, 3,322 and 659, 3,308, 3,560 kg/ha, respectively. Profitability in both of the improved systems was significantly higher than current farmer practice. The economic return from rotational polyculture was significantly higher than monoculture in 2012, but there was no significant difference in 2013. Species combination of shrimp-tilapia in the dry season and carp-catfish in the wet season appeared most profitable and resilient (as assessed against the risk of disease) providing new opportunities for diversification of farming systems in the area. The level of profitability increased from Bangladesh Taka (BDT) 2,000/ha/year under existing farmer practice to BDT 248,000/ha/year and BDT 265,000/ha/year in monoculture and polyculture systems, respectively. Water drainage and maintaining expected water depth were key challenges for implementing these improved systems.

Key message: Rotational polyculture offers an important opportunity for sustainable intensification of shrimp-dominated farming systems in the high salinity areas of the lower Ganges delta. Diversification of brackishwater aquaculture systems led to significant increases in productivity and profitability.

Keywords: shrimp, monoculture, polyculture, crop rotation, profitability, salinity

1. Introduction

Coastal aquaculture is not a recent practice in Bangladesh (Swapan & Gavin 2011). For centuries local people have practiced traditional coastal aquaculture to grow shrimp and fish (Ahmed et al. 2002; Alauddin and Akhter Hamid 1997). A number of chronological historical events were associated with the emergence of commercial shrimp farming in Bangladesh (Swapan & Gavin 2011). Favorable ecological and climatic conditions, availability of wild shrimp post larvae (PL), cheap labor, unused land and plenty of salt water have contributed to keeping shrimp farming investment costs very low. With strong international market demand, shrimp farming has become very popular in the coastal region of Bangladesh. For some, it appeared as a good source for quick money-making for the coastal community. As a result, shrimp farming became one of the key economic activities in the coastal districts of Cox's Bazar, Khulna, Bagerhat and Satkhira, and has been expanding in other districts too (Ministry of Water Resources 2006).

The development of shrimp farming has been accompanied by positive and negatives impacts. Rural households including small and marginal farmers and landless poor have benefited from shrimp production due to a wide range of livelihood opportunities (Ahmed et al. 2010). The favorable domestic policy environment and emerging global market opportunities reinforced the commercialization of shrimp culture in Bangladesh (Ahmed et al. 2002). The value of shrimp exports increased from about US$322 million in 2000 to around US$467 million in 2012 (DOF 2013), contributing 2% of total national export (DOF 2013). Shrimp stands as second largest export item of the country (Azad et al. 2009).

However, massive development of shrimp also had negative influences on livelihoods and ecological functioning (Paul & Vogl 2011). Several authors have already expressed doubts about the sustainability of current shrimp farming (Hein 2002; Paez-Osuna et al. 2003; Hall 2004; Chowdhury et al. 2006; Azad et al. 2009). In recent years disease outbreak has been recognized as the biggest obstacle to the development of shrimp aquaculture in Bangladesh, causing massive economic loss (Alam et al. 2007; Miah et al. 2010; Karim et al. 2012). Under this situation farmer field-based research is needed to find ways out to improve the saline aquaculture systems of Bangladesh.

The CGIAR Research Program on Water and Food collaborated with farmers and conducted field-based research in high salinity areas of southwestern Bangladesh between 2012 and 2013 to seek ways to make coastal brackishwater aquatic agricultural systems more productive, profitable, diversified and resilient. Experiments were designed considering changes in saline regimes to explore options to improve existing brackish water aquaculture systems, with a focus on rotational monoculture and polyculture aquaculture farming systems to allow for crop rotation and risk reduction.

The hypotheses underlying this research were:

- Annual productivity can be increased by improving management of shrimp-based farming systems.
- Rotational polyculture will diversify the system and reduce economic loss due to shrimp disease in the dry season.
- Species compositions can be improved to better utilize different pond niches and contribute to higher yield.

2. Methods

2.1 Study area

The study was carried out in the southern part of polder 3 under the administrative *upazila* of Kaliganj of Satkhira Districts (Figure 1). This is one of the major shrimp farming areas (Ministry of Water Resources 2006) that is categorized as a high salinity area (SRDI 2010).

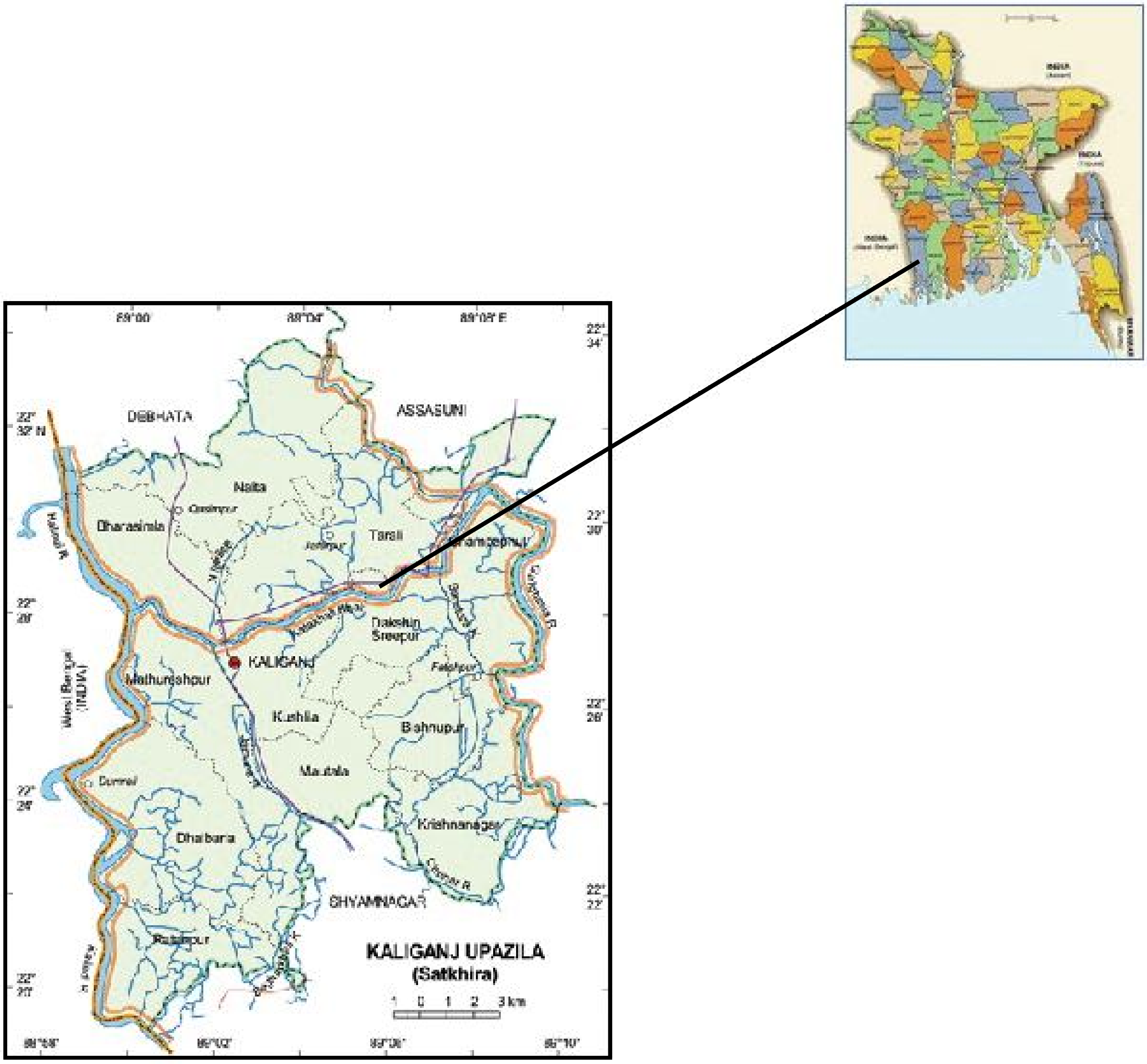


Fig. 1. Study area.

2.2 Experimental design

Three treatments—a control (farmers' existing practice), monoculture and polyculture—each with four replications were tested in 2012 and 2013. The control treatment was designed based on farmers' current management practice, developed through three consultation meetings with more than 50 shrimp farmers in the southern part of polder 3. The monoculture and polyculture treatments were developed considering crop rotation and species composition. A randomized concrete block design (Shieh 2004) was followed for distribution of treatments and replications within the experimental area.

2.2.1 Control treatment

The control treatment was based on existing farmer practices. Ponds were maintained at a water depth of 50 cm and the ponds were dried out at the end of each year. Multiple stocking of ghers was practiced starting in late February with *Penaeus monodon, Metapenaeus monoceros*, *Chelon subviridis, Rhinomugil corsula* and *Oreochromis mossambicus* at stocking densities of 2, 4, 0.25, 0.25 and 0.25 m^{-2}, respectively, followed by stocking of *Penaeus monodon* in each month until September at a density of 0.5 m^{-2}. Selective harvesting was carried out from April until the end of November. At the end of August *Labeo rohita, Catla catla, Cyprinus carpio* and *Cirrhinus mrigala* was stocked at a density *of* 0.25m^{-2} for each species.

2.2.2 Monoculture treatment

In this treatment, a greater water depth of 70-100 cm was maintained and the production cycle was divided into three crop sub-cycles allowing for crop rotation in response to changes in salinity. In 2013, the first cycle was *Penaeus monodon* stocked at a density of 3 m^{-2} followed by *Oreochromis niloticus* (monosex) and *Macrobrachium rosenbergii* at a density of 4 m^{-2} and 3 m^{-2} respectively. Based on the observation of disease outbreak and shrimp price in local markets in 2013, the dry season was subdivided into two short cycles of shrimp with a target of harvesting small-sized shrimps by growing at a relatively high density. So, *Penaeus monodon* was stocked at a density of 5 m^{-2} for 70 days in the first and second cycles followed by *O. niloticus* (monosex) at a density of 5 m^{-2} from August to November.

2.2.3 Polyculture treatment

This treatment was designed to maintain an improved water depth of 70-100 cm and the production cycle was divided into 3 crop sub-cycles allowing for crop rotation in response to changes in salinity. The treatment was intended to keep a backup crop if shrimp disease occured, thus reducing the economic loss and also producing fish for local consumption. In 2013 the first cycle was for 105 days starting from the end of February and was stocked with *Penaeus monodon* and *Oreochromis niloticus* (monosex) at a density of 3 m^{-2} & 2 m^{-2}, respectively. The second cycle for 90 days was stocked with *Oreochromis niloticus* (monosex) and *Mystus gulio* at a density of 3 m^{-2} & 2 m^{-2}, respectively. This was followed by *Macrobrachium rosenbergii* with *Mystus gulio* at a density of 2 m^{-2} for each. Like the monoculture treatment in 2013, the dry season was subdivided into two short cycles of shrimp with a target of harvesting small-sized shrimps by growing at a relatively high density. So, *Penaeus monodon* were stocked at a density of 5 m^{-2} for 70 days in the first and second cycles followed with *O. niloticus* (monosex) at a density of 3 m^{-2}. This was followed by *Labeo rohita*, *Clarius bactracus* and *Heteropneutes fossilis* at densities of 0.25 m^{-2}, 1 m^{-2} and 1 m^{-2}, respectively, from August to the end of November.

2.3 On farm experimental setup

A total of twelve ponds with area between 866 and 1,463 m^2 were prepared. Each pond had an independent water inlet. The control treatments were placed in a shallower part of the experimental area than the other eight ponds. Each year at the beginning of the production cycle pond bottoms were exposed to sunlight, allowed to sun-dry, plowed later on and treated with bleaching powder to disinfect the pond. Ponds were filled with tidal water by sieving through nylon net up to 50 cm for control treatment ponds and up to 100 cm for monoculture and polyculture ponds. Predatory and unwanted fishes were killed using rotenone at 1.5 ppm and removed from the ponds. Then water of the ponds was treated with dolomite at 20 ppm and fermented molasses at 25kg/ha. Water of the ponds was fertilized with urea at 5.00 ppm and TSP at 2.50 ppm. Water of the ponds was treated with dolomite and Zeolite and fertilized with urea and TSP whenever necessary. Evaporated and seepage water was replenished from the tidal water in 2012 and with treated water from the reservoir in 2013.

After each culture cycle ponds were dewatered for complete harvesting in monoculture and polyculture ponds and control treatment ponds were dewatered at the end of each year.

2.4 Source of shrimp and fish seed applied

Hatchery produced shrimp PL 15 was stocked in control treatment ponds and PCR tested, WSSV negative shrimp PL 15 were stocked in monoculture and polyculture treatments. Wild harvested *Metapenaeus monoceros*, *Chelon subviridis* and *Rhinomugil corsula* seed were collected from the local market. *Oreochromis mossambicus, Labeo rohita, Catla catla, Cyprinus carpio* and *Cirrhinus mrigala* for control treatment were collected from the local fry traders. The average weight of the carps varied from 80 to 100 g. *Mystus gulio* and *Macrobrachium rosenbergii* were obtained from the Bangladesh Fisheries Research Institute (BFRI) hatchery with an average weight of 0.33 g and 0.08 g respectively. *Oreochromis niloticus* (monosex) were obtained from a BRAC hatchery and *Labeo rohita*, *Clarius bactracus* and *Heteropneutes fossilis* were collected from Muktesawery Hatchery, Jessore and weighed on average 0.5 g, 100 g, 8 g and 5 g, respectively.

2.5 Nursing

In control treatments shrimp and fish were released directly into the grow out ponds without nursing. Shrimp and fish for monoculture and polyculture experiments were nursed either in earthen pond nurseries or an in-pond nursery for a period of 15 to 25 days. *Macrobrachium rosenbergii* was nursed for 60 days in an outdoor nursery built adjacent to the experimental ponds.

2.6 Feeding management

No supplementary feeding was provided in control treatments. Shrimps were fed with commercial shrimp pellets. *M. gulio*, *Clarius bactracus* and *Heteropneutes fossilis* were fed by commercial catfish feed and tilapia by floating feed. The quantity of feed applied was adjusted after estimating the total biomass of shrimp or fish at seven-day intervals. A feeding check tray was placed in shrimp and freshwater prawn ponds for monitoring feed intake and adjustment if needed. Feeds were applied every morning, noon and evening and spread evenly across the water surface.

2.7 Monitoring water quality and fish health and growth

Dissolved oxygen and pH were monitored daily morning and evening. Temperature, transparency and water depth were monitored daily at noon and alkalinity on a weekly basis. Sampling of shrimp and fish bodyweight was carried out at seven-day intervals.

2.8 Disease occurrence

Disease occurrence was also monitored and three characteristics were used to define a diseased pond: (i) symptoms of shrimp or fish disease were recorded; (ii) control measures did not work; and (iii) disease caused increasing mortality at more than 10% per day. Ponds meeting all three characteristics were declared as diseased ponds.

2.9 Economic data

Records of the quantities and costs of all inputs were recorded for each pond. Labor and land leasing cost was calculated based on the actual cost. Average sale value for *P. monodon, M. rosenbergii O. niloticus* , *M. gulio* , *C. bactracus, H. fossilis, M. monoceros*, *C. subviridis, R. corsula, O. mossambicus, L. rohita, C. catla, C. carpio* and *C. mrigala* was respectively Bangladesh Taka (BDT) 550, 500, 100, 250, 200, 350, 300, 250, 250, 70, 150, 150, 150 and 150. This price was set based on average market price for the study period. All economic data was in BDT (1 BDT = 0.013 USD in December 2014).

2.10 Data analysis

Data analysis was conducted using IBM SPSS Statistics 19. The first hypothesis was explored by comparing annual system production between the treatments and years. A suitable species combination was determined based on the profitability, risk of crop loss (defined as frequency of disease occurrence in two years study and the economic loss due to the disease), salinity level of the locality, preference of local farmers (as determined by farmer participatory consultation post harvest) and availability of inputs. Profitability was calculated including labor cost and excluding labor cost. The Duncan test, one-way ANOVA and one sample t test were used for statistical significance.

2.11 Initiative for green ghers

Observing the shift in salinity and salinity tolerance of local grass and medicinal plant *neem* (*Azadirachta indica*), an initiative was taken in the second year (2013) to integrate plant products into the aquaculture production facility by planting *neem* and local grass on gher dikes. Vegetables were also grown on dikes in the wet season. This was done in addition to the experimental research and the data were not analyzed critically. This additional component provided an interesting observation for its potential to further develop coastal aquaculture farming systems.

3. Results

3.1 System productivity

The experimental results from 2012 and 2013 clearly show that annual yield from brackishwater aquaculture system can be significantly increased by adopting improved management practices (Figure 2).

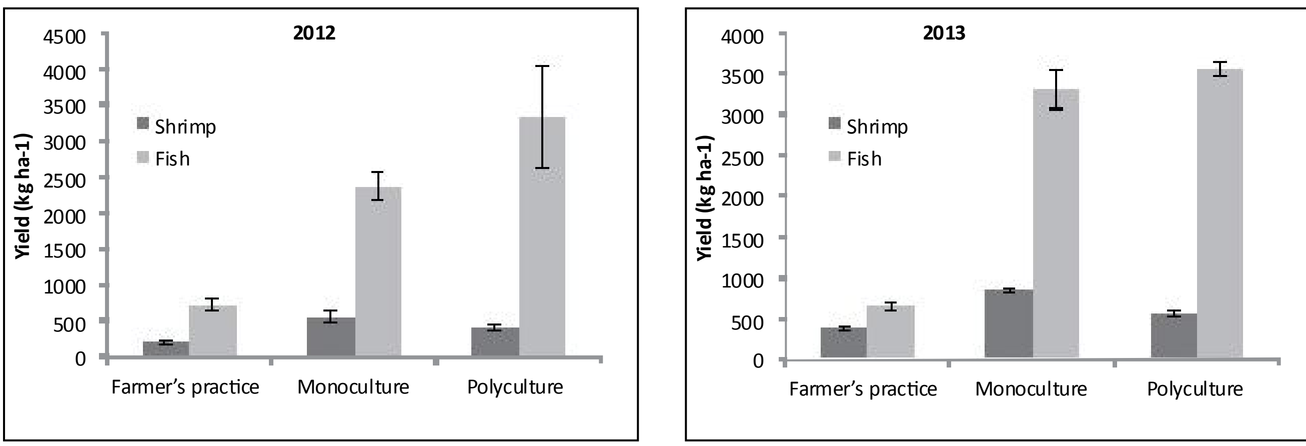


Fig. 2. Annual yield (kg $ha^{-1}year^{-1}$) of fish and shrimp in 2012 and 2013.

Shifting from year round shrimp-focused aquaculture to a season-specific annual production system not only increased fish production but also resulted in dry season-only shrimp production that was more productive than the yearround control treatments. (Table 1a and 1b). Shrimp together with freshwater prawn in 2012 and shrimp alone in 2013 was significantly higher than that of the control treatment and total fish production was also significantly higher in both the years.

Table 1a. Cycle-wise yield in kg ha^{-1} in 2012

Culture patterns	Cycle-1		Cycle-2		Cycle-3		Total annual yield	
	Shrimp	Tilapia	Tilapia	Tengra	Prawn	Tengra	Shrimp	Fish
Farmers' practice							*209.84	728.14
Monoculture	197.77	-	2367.48	-	363.63	-	556.40	2367.48
Polyculture	172.64	1163.41	1519.78	352.34	231.74	286.50	404.38	3322.04

Table 1b. Yield of the different components during each cropping cycle in kg ha^{-1} (from 2013)

Culture patterns	Cycle-1		Cycle-2		Cycle-3		Total annual yield	
	Shrimp	Tilapia	Shrimp	Tilapia	Magur + singh	Tilapia/ rohu	Shrimp	Fish
Farmers' practice							390.05	659.41
Monoculture	565.62	-	291.77	-	-	*3307.71	857.39	3307.71
Polyculture	373.64	1744.45	193.19	777.90	557.63	**480.05	566.83	3560.02

3.2 Suitable species combination

Shrimp-tilapia in dry season aquaculture and carp-catfish (*singh-magur*) in wet season had significantly higher yield ($p<0.05$) than other combinations. The farmers also ranked them higher during participatory evaluation following harvest.

3.3 Cost benefit analysis

Profitability was significantly higher ($p<0.05$) in recommended treatments (i.e. monoculture and polyculture) than that of the control treatment (i.e. farmers' practice) in both 2012 and 2013. Comparing profitability between the two recommended treatments, monoculture and polyculture, polyculture treatment was significantly higher ($p<0.05$) than monoculture treatment in 2012 (Figure 3) and there was no significant variation in 2013.

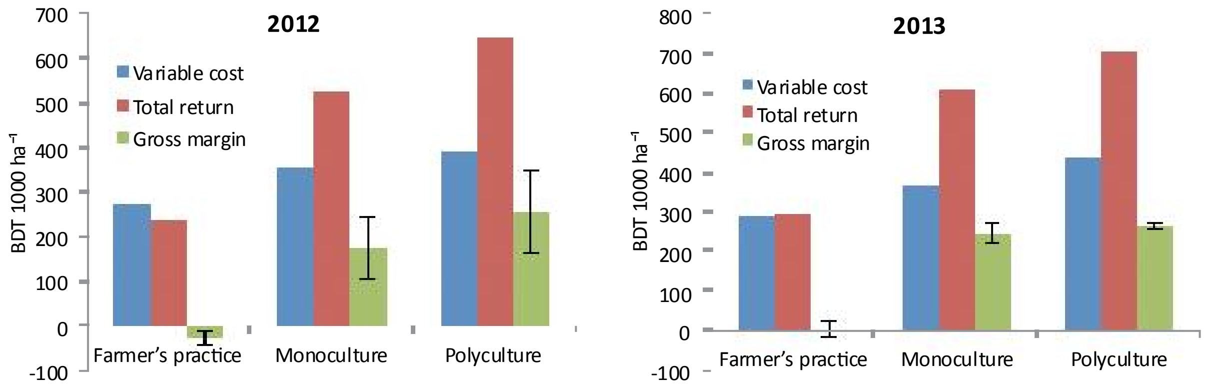


Fig. 3. Variable cost, total return and gross margin of different treatments in 2012 and 2013 including labor cost.

Profitability including labor cost for farmers' practice (i.e. control treatment) was negative in 2012, and significantly ($p<0.05$) increased in 2013. Profitability of control treatment excluding labor cost was 65,000 and 94,000 BDT $ha^{-1}year^{-1}$ respectively in 2012 and 2013.

3.4 Environmental consideration for aquaculture

Salinity is a major environmental factor for coastal aquatic agricultural systems and one of the determining factors for crop selection. There is a shift in salinity levels between dry and wet seasons (Figure 4), which provides plenty of opportunity to diversify coastal aquaculture and also provides opportunities to integrate aquaculture with dike cropping systems.

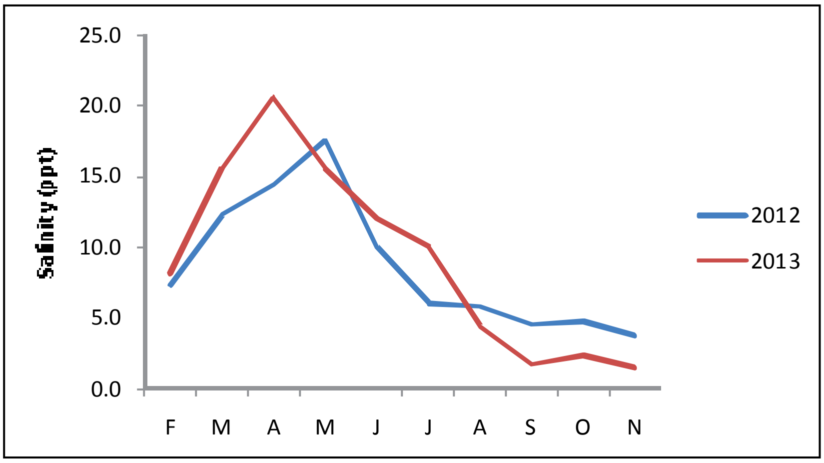


Fig. 4. Water salinity from February to November in 2012 and 2013.

Water depth and drainage, though critical for aquaculture, are difficult to maintain in practice for individual plots. In the improved management practice of the experimental setup the preparation was to keep one meter water in the ponds throughout the year; in practice from March to early July it was between 70-80 cm and from July to October it was between 90-105 cm. This further reduced in November to 65 cm in both the years.

In both years, dissolved oxygen at beginning of each cycle remained between 7-8 ppm and dropped even to <2 ppm in the morning in latter days of the culture period due to increased total biomass in the ponds. Under that limited dissolved oxygen level water exchange was not possible due to limited drainage facilities in the community level water management system.

Weekly average pH in fed ponds under monoculture and polyculture was always between 8.5 and 9.5 in the afternoon, showing highest fluctuations during the monsoon period. Water temperature in February remains below 15^{o}C and drops again to 20^{o}C in November. This makes aquaculture unfavorable from December to January due to low water temperatures.

Local varieties of grass and *neem* grew well on *gher* dikes. The grass grown on the *gher* dikes of 1 ha experimental plots provided sufficient fodder for four to five goats. Neem has potential for use in the herbal industry as a raw material. Based on rainfall from August to January, one to two crops of bottle gourd, ladies finger and cucumber can be grown on improved gher dikes with higher width and height. These initial experiments show potential for further crop production and overall system productivity.

4. Discussion

System productivity and profitability in brackishwater aquaculture systems can be increased significantly through diversification and better management. Rotational polyculture increases fish production for local market and reduces risk of economic loss from dry season crops. Crop rotation helps reduce water salinity.

Production of shrimp in both monoculture and polyculture systems was two to three times higher than the national average production mentioned by Belton et al. (2011), which was between 160 and 230 kg/ha/year. However, this level of intensification does not risk water pollution. An extensive system of shrimp production up to 1 mt/ha/year can neutralize the effluent through the natural process of the ecosystem (Wahab et al. 2003).

Though productivity of shrimp systems increased it was still much lower than that of other Southeast Asian countries who produce 1.2 to 10 mt/ha/yr (FAO 2012). Environmental conditions including poor water management facility are important limiting factors for increased production and intensification of the system. Manjurul et al. (2014) also listed these factors as playing a role in shaping coastal aquaculture production including shrimp. However, further research is needed on the potential limits of sustainable intensification within brackishwater aquaculture systems in Bangladesh.

Crop rotation and polyculture provide opportunities for improving the sustainability of the coastal aquatic agricultural system. Other researchers (Nesar et al. 2008, Nesar et al. 2010; Wahab et al. 2012) has also provided similar findings, noting that such approaches can provide resilience against a changing climate (Nesar 2013).

5. Conclusions and recommendations

Considerable opportunities exist for improving productivity, diversification and resilience of brackishwater aquaculture in the coastal saline zone of Bangladesh. Technologies appear to be very “adoptable” by farmers, as indicated by the number of farmers around the experimental plots that were voluntarily adopting some of the practices (e.g. shrimp-tilapia polyculture in the dry season, mixed culture of carp and catfish in the wet season, growing vegetables on dikes).

Water management is also a key factor in improving aquaculture within the region, and adoption of community water management could further improve options for aquaculture. Preliminary experiments with growth of vegetables and fodder on dikes also suggests it is possible to integrate vegetable production on dikes in the wet season and support livestock by growing grass on the dikes. Saline water represents an asset to the country that needs to be more efficiently used, by both aquaculture and aquatic-agricultural farming systems. To meet growing fish demand (World Bank 2013) further intensification of such systems is needed in a sustainable way. Better understanding of market systems, improved access of farmers to quality inputs and capital investment also needs to be explored for scaling of improved farming systems and creating development outcomes and impact from this research.

Acknowledgements

We would like to acknowledge the CGIAR Challenge Program on Water and Food for providing fund for conducting this study and the CGIAR Research Program on Aquatic Agricultural Systems for further collaboration and support in analyzing these data. We also thank the WorldFish AIN project for providing additional funding for establishing experimental ponds. We are grateful to Mr. Habibur Rahman and Md. Faruk Hossen for participating in the research with their land, time and skills.

References

Ahmed, Asad, S., Mallick, D.L., Liaquat, A. M., and Rahman, A., 2002. Policy Research for Sustainable Shrimp Farming in Asia: Literature Review on Bangladesh Shrimp. Bangladesh Center for Advanced Studies, Dhaka.

Alam, S., Pokrant, B., Yakupitiyage, A., Phillips, M., 2007. Economic returns of disease- affected extensive shrimp farming in southwest Bangladesh. Aquacult. Int. 15, 363-370.

Alauddin, Mohammad, Akhter Hamid, M., 1997. Shrimp Culture in Bangladesh with Emphasis on Social and Economic Aspects.

Azad, A., Jensen, K., Lin, C., 2009. Coastal aquaculture development in Bangladesh: unsustainable and sustainable Experiences. Environ. Manag. 44, 800-809.

Belton, B., Karim, M., Thilsted, S., Jahan, K.M., Collis,W., Phillips,M., 2011. Review of aquaculture and fish consumption in Bangladesh. Studies and Reviews 2011–53The WorldFish Center, Penang 76.

Chowdhury, M.A., Shivakoti, G.P., Salequzzaman, M., 2006. A conceptual framework for the sustainability assessment procedures of the shrimp aquaculture industry in coastal Bangladesh. Int. J. Agric. Resour. Governan. Ecol. 5, 162-184.

DOF.2013. National Fish Week 2013 Compendium (In Bengali). Department of Fisheries, Ministry of Fisheries and Livestock, Bangladesh. 144p.

FAO, 2012. FAO yearbook. Fishery and Aquaculture Statistics. http://www.fao.org/3/a-i3740t/index.html

Hall, D., 2004. Explaining the diversity of Southeast Asian shrimp aquaculture. J. Agrar. Change 4, 315-335

Hein, L., 2002. Toward improved environmental and social management of Indian shrimp farming. Environ. Manag. 29, 349-359.

Karim, M., Sarwer, R.H., Brooks, A.C., Gregory, R., Jahan, M.E., Belton, B., 2012. The incidence of suspected white spot syndrome virus in semi-intensive and extensive shrimp farms in Bangladesh: implications for management. Aquac. Res. 43 (9), 1357–1371.

Karim, M., Sarwer, R.H., Phillips, M. and Belton, B., 2014. Profitability and adoption of improved shrimp farming technologies in aquatic agricultural systems of southwestern Bangladesh. Aquaculture 428-429 (2014) 61-70

Miah, M.G., Bari, M.N., Rahman, M.A., 2010. Resource degradation and livelihood in the coastal region of Bangladesh. Front. Earth Sci. China 4, 427-437.

Ministry of Water Resources, 2006. Coastal Development Strategy.Water Resources Planning Organisation, Dhaka.

http://www.mowr.gov.bd/Documents/COASTAL%20DEVELOPMENT%20STRATEGY%20%28English%29.pdf

Nesar, A., Demaine, H., Muir, J.F., 2008. Freshwater prawn farming in Bangladesh: history, present status and future prospects. Aquaculture Research 39, 806e819.

Nesar, A., Allison, E.H., Muir, J.F., 2010. Rice-fields to prawn farms: a blue revolution in southwest Bangladesh? Aquaculture International 18, 555e574.

Nesar, A., 2013. Linking prawn and shrimp farming towards a green economy in Bangladesh: Confronting climate change. Ocean & Coastal Management 75 (2013) 33-42

Paez-Osuna, F., Gracia, A., Flores-Verdugo, F., Lyle-Fritch, L.P., Alonso-Rodraguez, R., Roque, A., Ruiz-Fernandez, A.C., 2003. Shrimp aquaculture development and the environment in the Gulf of California ecoregion. Mar. Pollut. Bull. 46, 806-815.

Paul, B.G. and Vogl, C.R., 2011. Impacts of shrimp farming in Bangladesh: Challenges and alternatives. Ocean & Coastal Management 54 (2011) 201-21

Shieh, G. 2004. The effectiveness of randomized complete block design. Statistica Neerlandica. Vol. 58, nr. 1, pp. 111–124

SRDI 2010. Soil Salinity Report 2010 of Bangladesh, Soil Resources Development Institute, Dhaka, Bangladesh

Swapan, M. S. H., and Gavin, M. 2011. A desert in the delta: Participatory assessment of changing livelihoods induced by commercial shrimp farming in Southwest Bangladesh. Ocean & Coastal Management 54 (2011) 45-54

Wahab, M.A., Bergheim, A. and Braaten, B., 2003. Water quality and partial mass budget in extensive shrimp ponds in Bangladesh. Aquaculture 218 (2003) 413-423

Wahab, M.A., Nahid, S.A., Ahmed, N., Haque, M.M., Karim, M., 2012. Current status and prospects of farming the giant river prawn (Macrobrachium rosenbergii) in Bangladesh. Aquaculture Research 43, 970-983.

World Bank, 2013. Annual Report.

http://web.worldbank.org/WBSITE/EXTERNAL/EXTABOUTUS/EXTANNREP/EXTANNREP2013/0,,menuPK:9304895~pagePK:64168427~piPK:64168435~theSitePK:9304888,00.html

Community-based fisheries management: Improving fish biodiversity in inland fisheries of Bangladesh

M. G. Mustafa

WorldFish, Bangladesh, g.mustafa@cgiar.org

Abstract

The Community Based Fisheries Management (CBFM) approach in Bangladesh aims to promote the sustainable use of inland fisheries by empowering fisher communities to manage their resources. An investigation into the impact of this approach underscored the strong dependence of multispecies and abundance on fisheries management. Using data compiled for impact assessment, fish production, abundance and biodiversity were examined in detail for different habitats. When comparing CBFM sites with control sites trends in fish production, abundance and biodiversity with time were found to be significantly higher ($p<0.01$) for the former. Of the 64 project sites, 49 of them showed an upward trend in production, 46 showed an upward trend in fish abundance and 48 demonstrated an upward trend in biodiversity. Ten of the 16 control sites showed a declining trend in production, abundance and biodiversity with time. In 2005, significant differences ($p<0.05$) in species assemblages were found in two out of five regions for two types of habitats at CBFM and control sites. Species assemblages in floodplain habitats in the north and river habitats in the east regions were found to be richer and more abundant at CBFM sites compared to control sites. Considered together, this evidence suggests that the CBFM approach also benefits wetlands biodiversity and resource sustainability.

Key message: The community-based fisheries management approach might be considered to improve fish production, abundance and biodiversity in inland fisheries.

Keywords: community-based fisheries management, biodiversity, abundance, assemblages, floodplain

1. Introduction

The importance of Bangladesh's inland fisheries for the livelihoods and food security of the poor and landless is widely acknowledged. Fish from Bangladesh's vast inland waters are vital to millions of poor people but landings and species diversity are believed to be declining (Ahmed et al. 1997). Fishers and experts have identified potential causes for this decline including habitat degradation due to siltation and change-over to agriculture, increasing fishing pressure, destructive fishing practices and an acute shortage of dry season wetland habitat (Hughes et al. 1994; Ali 1997). There are 260 indigenous species of finfish living in and around the freshwater habitats of Bangladesh (Rahman 1989). Rural families in Bangladesh consume up to 73 species of small indigenous fish during the course of a year, harvested mostly by the families (Minkin 1993). According to IUCN (2000) 54 freshwater fish species out of 260 species are threatened in Bangladesh.

The short-term leasing practice of small water bodies provides little incentive to leaseholders to harvest aquatic resources in a sustainable manner and often acts as an obstacle to access by poorer members of the community (Craig et al. 2004). Co- management and community-based management approaches have long been advocated for as a means to address common failures associated with conventional 'top-down', government-driven approaches to fisheries management but few studies have quantitatively demonstrated their benefits.

The present study employed data collected from 64 project sites and 16 control sites representing a range of different habitat types and geographic locations, and many river sections, floodplains and depressions (*beels*) located in the lower Indo-Gangetic Plains. To assess the status of fisheries resources and to test alternative local fishery management practices that might increase biodiversity this study covered fishing activities, fisher's participation, overall fish abundance and biodiversity data analysis. This paper also evaluates management performance and resource sustainability to determine the benefits of community-based fisheries management (CBFM) in the inland fisheries of Bangladesh. It does so by looking at qualitative indicators in a variety of wetlands (i.e. fish production, abundance and biodiversity) and studying their changes with time at project and control sites.

2. Methods

The Community Based Fisheries Management (CBFM) project began in September 2001. This five-year project, funded by the UK Government's Department for International Development (DFID), was implemented jointly by WorldFish and the Government of Bangladesh's Department of Fisheries in partnership with 11 Non-Governmental Organizations (NGOs). These field-based partner NGOs were responsible for organizing about 23,000 poor fishing households around 120 sites representing a range of different habitat types (*beel* - a permanent water body; *haor beel* - a large, low-lying depression in a floodplain; river section) and located in regions throughout Bangladesh (Figure 1).

The CBFM project was designed as an action research project to test and assess alternative local fishery management arrangements that might achieve greater efficiency, equity and sustainability. Partner NGOs have helped the fishers to develop *Beel* Management Committees, River Management Committees and Cluster Management Committees for fishery resources management. Management committees were formed in all project sites through election or selection of members by stakeholders and each site has its own resource management plans and rules. Committees have generally adopted simple conservation-based measures such as reserve harvest (small fish sanctuary), gear regulation, closed season and habitat restoration under CBFM.

The present study employed data collected since 2002, representing a range of different habitat types and geographic locations. This study was conducted by using species data for project and control sites to determine productivity (catch per unit area - CPUA), catch per day (CPD) and the Shannon-Weiner biodiversity Index (H') trends with time, species assemblage, abundance and sites' similarities.

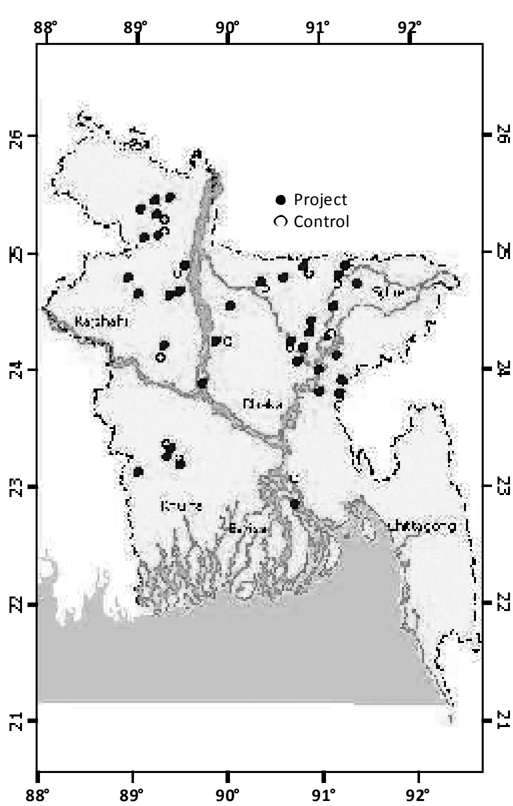


Fig. 1. Location of surveyed sites, CBFM projects and control sites in Bangladesh.

3. Data

Fishing activity was observed for four days per month per site. Gear surveys involved a regular spot survey for a sample of gear in operation, and the total catch from each gear type. A gear census covered the number and types of gear operating in the study sites. Species-wise catch statistics for each gear type were recorded between 2002 and 2005 (split year, June to May) for productivity (catch per unit area-CPUA) and abundance (catch per day-CPD) analysis.

Catch data from 2002 to 2005 on species and gear was collected from a maximum of 64 project sites (5 closed *beel*, 14 river sections, 21 ppen *beel*, 6 *haor beel*, 18 floodplain *beel*) and 16 control sites (2 closed *beel*, 4 river section, 4 open *beel*, 3 haor *beel*, 3 floodplain *beel*). At least three years worth of data were available for each site and used for biodiversity (H') and univariate analysis. The monitoring of control sites began in 2002 and the gill net CPUE was estimated for August and September (peak monsoon) to maximize the sample size. The gill net CPUE was considered during August and September to avoid the effects on CPUE of variation in gear catchability and only similar months were compared between years to get consistent diversity of species for the inland water systems.

The species data in this study was examined in two ways: for biodiversity analyses (H'-Shannon biodiversity Index) and trends with time at each site (slope ±*b* value); and for determining species assemblage and abundance between project and control sites. The trend (average annual change) in performance indicator (biodiversity) was first estimated for each site using the general linear model (GLM) where the performance indicator formed the dependent variable and time (year) was treated as covariate. The slope coefficient (*b*) of the linear (regression) model provided an estimate of the magnitude of performance indicator trend and whether it was upward (+ *b* value) or downward (- *b* value). Only sites with at least three years of observation were included.

3.1 Univariate measure of fish diversity

Management performance was quantified using indicators of production and resource sustainability. Annual multispecies catch per unit area (CPUA) was employed as a measure of production at each site:

$$CPUA_{s,y} = \frac{\sum_{m=June}^{m=May} \sum_{g=1}^{n} Catch_{s,y,m,g}}{MaxArea_s} \quad \text{Equation 1}$$

Where ***Catch***$_{s,y,m,g}$ is the estimated multispecies catch landed by gear type g, during month m and year y at site s measured in kg ha^{-1} y^{-1}, and $MaxArea_s$ is the mean maximum area of the site.

Fish abundance indicated by multispecies catch $fisher^{-1}$ day^{-1} or 'catch per day' (CPD) expressed as kg day^{-1} was employed as a measure of resource sustainability:

$$CPD_{s,y} = \frac{Catch_{s,y}}{Annual\ Fishing\ Days_{s,y}} \quad \text{Equation 2}$$

Where ***Annual Fishing Days***$_{s,y}$ is the estimated total number of days spent fishing by the fishers at site s during year y, irrespective of the gear type employed.

The Shannon-Weiner biodiversity Index (H') (Shannon 1948) was employed as a univariate indicator of fish diversity and used for species-wise catch from 2002 to 2005 (Equation 3).

$$H' = -\sum_j p_j (\ln p_j) \quad \text{Equation 3}$$

\Where p_j is the proportion of the total biomass arising from the *j*th species. Here p_j was estimated using the average gillnet catch rate for species *j* between August and September at site *s*, during year *y* (Equation 4):

$$\overline{GNCPUE}_{j,s,y} = \frac{\sum_{i}^{n} GNCPUE_{j,i,s,y}}{n} \quad \text{Equation 4}$$

Where

$$GNCPUE_{j,i,s,y} = \frac{Catch_{8-9,j,i,s,y}}{NetArea_{8-9,i,s,y} \cdot Hours_{8-9,i,s,y}} .1000 \quad \text{Equation 5}$$

Where $GNCPUE_{i.s.y}$ is the catch rate of the *i*th gillnet sampled at site *s* between August (month 8) and September (month 9) of year *y*, and $NetArea_{i.s.y}$ is the area of *i*th net sampled at site *s*, in year *y*. $Houre_{i.s.y}$ is the fishing hours. The ratio was multiplied by 1000 because units (kg m^{-2} hr^{-1}) were typically very small.

3.2 Multivariate comparisons of diversity

Multivariate comparisons of fish diversity were performed by comparing abundance indices (gill net catch per unit effort in August and September ($GNCPUE_{8-9}$) from 2002 to 2005) of species forming the multispecies assemblage between CBFM and control sites. Only testable habitat and region combinations containing control sites were used for multivariate analysis. The year 2005 was selected, as the year with maximum numbers of control site data available from different habitats for multivariate analysis. Data recorded for floodplain *beel* habitat in the north (FPB-N), *haor beel* habitat in the east (HB-E), open *beel* habitats in the north (OB-N) and north-west (OB-NW), and river habitat in the east (R-E) of the country were used for multivariate analysis. Similarities in the species assemblages at CBFM and control sites were summarized in two-dimensional space using nonparametric multidimensional scaling (MDS) ordinations (Clarke 1993). The approach aims to construct a map or ordination of sites (samples) such that their placement reflects the rank similarity of their species assemblages. Sites positioned in close proximity to each other in the ordination have very similar species assemblages, whilst sites that are far apart share few common species or have the same species but at very different levels of abundance. A “stress” measure indicates how well the ordination satisfies the (dis)similarities between sites. Stress values <0.2 indicate acceptable fits to the data. The null hypothesis [H_0: There are no differences in species assemblages between CBFM and control sites] was tested using a nonparametric permutation test (analysis of similarity or ANOSIM) based on the difference in average rank within and between the CBFM and control site groups (*r* statistic). The significance level of the test is calculated by referring the observed value of the *r* statistic to its permutation distribution generated from randomly sampled sets of permutations of site labels.

The species most responsible for the site groupings were then determined by computing the average contribution of each species to the overall average dissimilarity between all pairs of intergroup sites. The MDS and ANSOSIM analyses were performed with the PRIMER software (Clarke and Gorley 2006) on fourth-root transformed data and employing the Bray-Curtis (Bray and Curtis 1957) similarity coefficient as the measure of similarity between pairs of sites.

4. Results

4.1 Univariate trend analysis

The relative frequencies of the upward and downward trends indicate that the CBFM activities have significantly (p<0.01) benefited production (CPUA), fish abundance (CPD) and biodiversity (H’) at the majority (70-80%) of CBFM sites. At control sites, downward trends in CPUA, CPD and H’ were more frequent than upward trends.

Trends in fish production (CPUA) through time were upward at 77% of the 64 project sites that were monitored monthly for at least three years without data gap. At these sites annual fish production (kg ha^{-1}) increased on average by 13% a $year^{-1}$. Taking account of habitat type, annual fish production ha^{-1} $year^{-1}$ increased on average by 22%, 29%, 12%, and 22% for closed *beel*, floodplain, open *beel* and river habitats, respectively. In contrast, production decreased by 19% ha^{-1} $year^{-1}$ for *haor beel* habitats.

Trends in fish abundance as indicated by the annual average of fishers' daily catch rates increased at 72% of the 64 project sites, with an average increase of 17% per $year^{-1}$. When we consider this annual average increase for habitat types we see that closed *beel*, floodplain, *haor beel*, open *beel* and river habitats experienced an increased annual average of daily catch per fisher of 22%, 12%, 9%, 21% and 19%, respectively.

Forty-eight of the 64 project sites for which three or more years' estimates were available showed an upward trend in biodiversity (H') with time. Six of the 16 control sites for which three or more estimates were available also showed an upward trend in biodiversity (H') with time and the remaining ten showed downward trends. Distribution of b values for trends in biodiversity (H') with time for habitat types at project sites are shown in Figure 2a and for control sites in Figure 2b. The positive values of slope b indicate that biodiversity (H') increased at those sites and the negative values of slope b indicate that biodiversity (H') decreased with time.

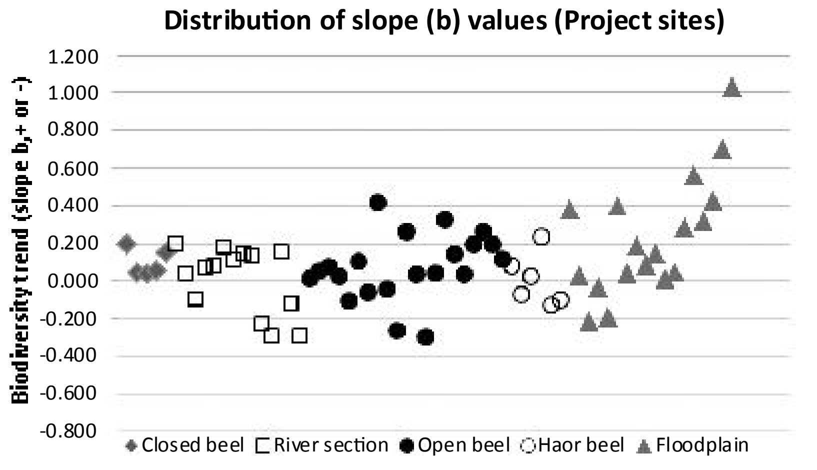


Fig. 2a. Distribution of slope (b) values for trend (up or down) in biodiversity index (H') with time for project sites.

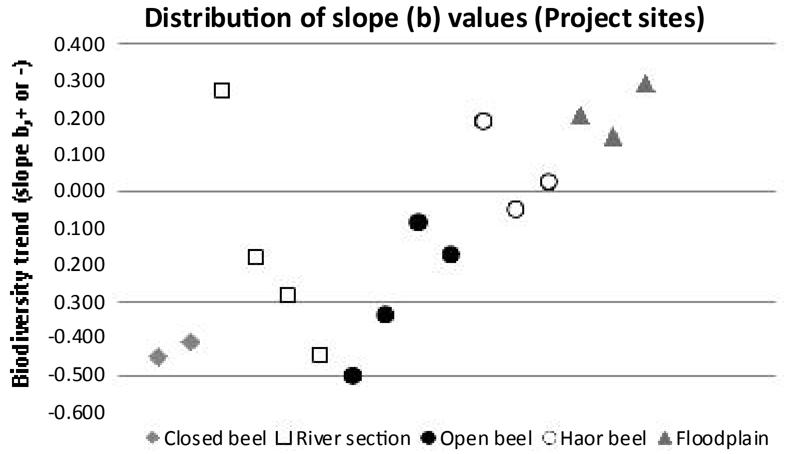


Fig. 2b. Distribution of slope (b) values for trend (up or down) in biodiversity index (H') with time for control sites.

4.2 Multivariate analysis

Differences in species assemblages between CBFM and control sites were tested within the same habitat and region. Significant ($p<0.05$) differences in species assemblages at CBFM sites and control sites were found only for floodplain *beel* habitat in the north (FPB-N) in 2004, and river habitat in the east (R-E) in 2004 and 2005 (Table 1 and Figure 3). One-way ANOSIM showed the R-statistics, where an R value of +1 indicates that the most similar samples are within the same groups and value of -1 indicates that the most similar samples are outside of the groups. The R statistics were higher in 2005 compared to the baseline survey in 2002 for river habitat in the east (R-E), and compared to the survey in 2003 for floodplain *beels* in the north (FPB-N) and open *beels* in the north (OB-N). However, R-statistics were lower in 2005 compared to the baseline survey in 2002 for *haor beels* in the east (HB-E) and open *beels* in the northwest (OB-NW). Only testable habitat and region combinations containing control sites were used.

Table 1. Results showing the one-way ANOSIM between CBFM and control sites

Habitat and Regions	Years	R-Statistic	Permutations	Significant Level %
Floodplain North (FPB-N)	2002	No control	No control	No control
	2003	0.119	105	25.7
	2004	-0.187	105	86.7
	2005	0.250	560	**4.5**
Haor *beel* East (HB-E)	2002	-0.148	84	75
	2003	0.037	35	42.9
	2004	-0.111	84	71.4
	2005	-0.021	35	71
OPEN *beel* North (OB-N)	2002	No control	No control	No control
	2003	-0.229	28	85.7
	2004	0.154	120	20
	2005	0.102	91	34
Open *beel* North-West (OB-NW)	2002	-0.393	15	80
	2003	-0.196	9	77.8
	2004	-0.140	165	74.5
	2005	-0.246	55	87
River East (R-E)	2002	-0.222	35	91.4
	2003	0.037	35	42.9
	2004	0.685	35	**2.9**
	2005	0.824	35	**2.9**

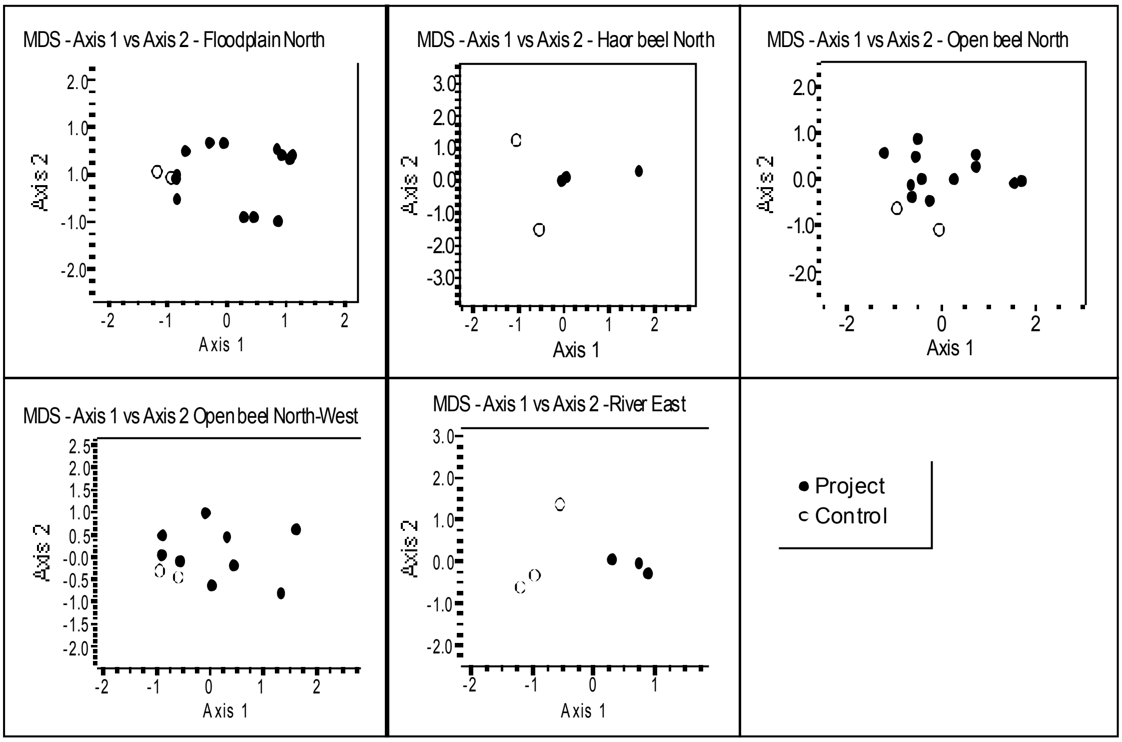


Fig. 3. MDS ordinations: comparing species assemblages at CBFM and control sites in each habitat or region combination.

4.2.1 Floodplain beel habitat in the north (FPB-N) region

For floodplain-*beel* habitat in the north region, more than 30 representative species were either absent or less abundant at the two control sites compared to the 13 CBFM sites in 2005 (Figure 4). Species are arranged in descending order of their contribution to the average dissimilarity between the two groups of sites (CBFM or control). Only those species contributing to 90% of the cumulative average dissimilarity are shown. Of the 36 recorded species 10 were more abundant at CBFM sites. These included, in descending order of their contribution to the average dissimilarity between the two groups of sites: *Nandus nandus, Cirrhinus cirrhosus, Labeo rohita, Anabas testudineus, Puntius sophore, Channa punctatus, Puntius chola, Macrobrachium macolmsonii, Heteropneustes fossilis* and *Macrognathus puncalus.* Only six species were more abundant at control sites compared to CBFM sites: *Labeo calbasu, Mastacembelus armatus, Cyprinus carpio, Mystus cavascius, Puntius gonionotus* and *Mytus bleekeri.* However, given the potential difficulty in selecting comparable control sites, these differences in species assemblages may simply reflect differences in site habitat.

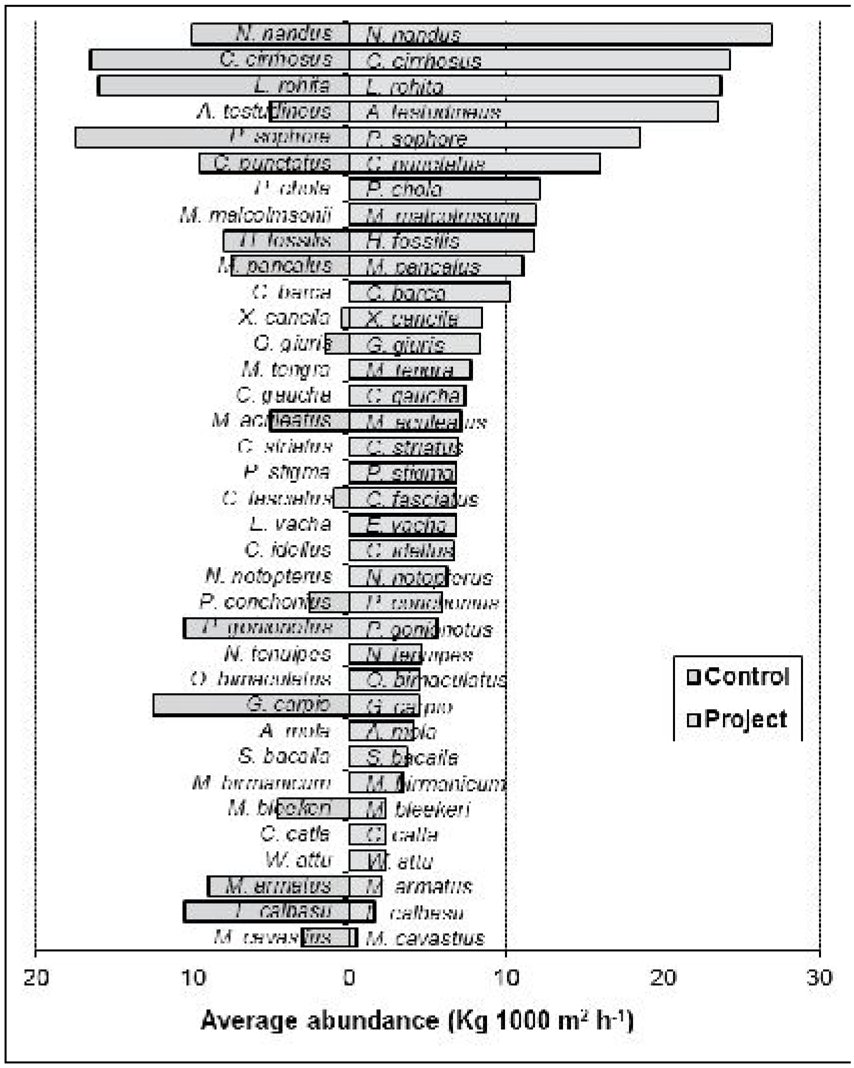


Figure 4. Average abundance [gillnet catch per unit effort (kg 1000 m^2 h^{-1})] of species caught from CBFM and control sites exploiting floodplain-*beel* habitat in the north (FPB-N) region of the country.

4.2.2 Haor beel habitat in the east (HB-E) region

Species assemblages at the CBFM and control sites were very similar in 2005. Species are arranged in descending order of their contribution to the average dissimilarity between the two groups of sites (Figure 5). Only those species contributing to 91% of the cumulative average dissimilarity are shown. Of the 16 recorded species, six were more abundant at CBFM sites. These included, in descending order of their contribution to the average dissimilarity between the two groups of sites: *Anabas testudineus, Nandus nandus, Puntius sophore, Heteropneustes fossilis*, *Mystus tengra* and *Wallago attu.* However eight species were more abundant at the control sites: *Puntius sophore, Wallago attu, Nandus nandus, Macrognathus aculeatus, Xenentodon cancilia, Aorichthys seenghala, Rohtee cotio* and *Puntius conchonius*. The latter two were absent from the CBFM sites.

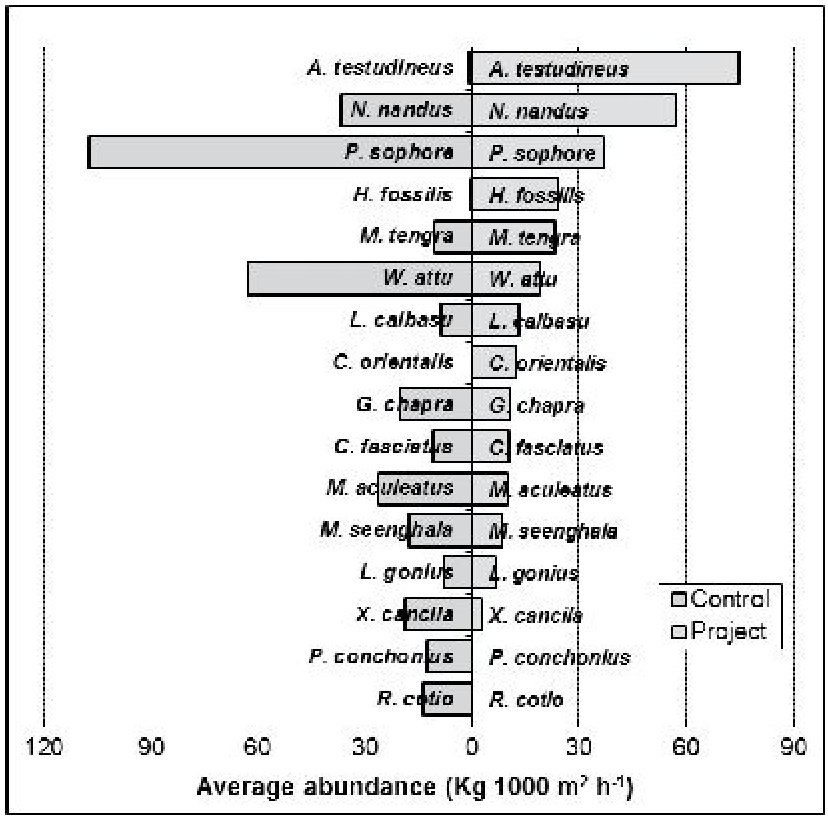


Fig. 5. Average abundance [gillnet catch per unit effort (kg 1000 m^2 h^{-1})] of species caught from CBFM and control sites exploiting *haor-beel* habitat in the north (HB-E) region of the country.

4.2.3 Open beel habitat in the north (OB-N) and northwest (OB-NW) region

Diversity of species assemblages at the CBFM sites was almost double those of the control sites in 2005. Only those species contributing to 91% of the cumulative average dissimilarity in the open *beel* habitat (OB-N) are shown in Figure 6. Of the 23 recorded species, 10 were more abundant at CBFM sites. These included, in descending order of their contribution to the average dissimilarity between the two groups of sites: *Aanbas testudineus*, *Aorichthys seenghala*, *Puntius gonionotus*, *Channa striatus*, *Heteropneustes fossilis*, *Channa punctatus*, *Macrognathus aculeatus*, *Nandus nandus*, *Mystus aor* and *Hypophthalmiichthys molitrix*. Ten species were absent at the control sites. Only two species were more abundant at the control sites: *Macrobrachium birmanicum* and *Puntius ticto*.

Species assemblage at CBFM sites increased with time in two habitats, but remained unchanged in the remainder. Biodiversity at control sites remained unchanged in all habitats. Species assemblages are richer and more abundant at CBFM compared to control sites in floodplain *beel* and river habitat in the north and east regions of the country, respectively. Considered together, this evidence suggests that CBFM benefits biodiversity.

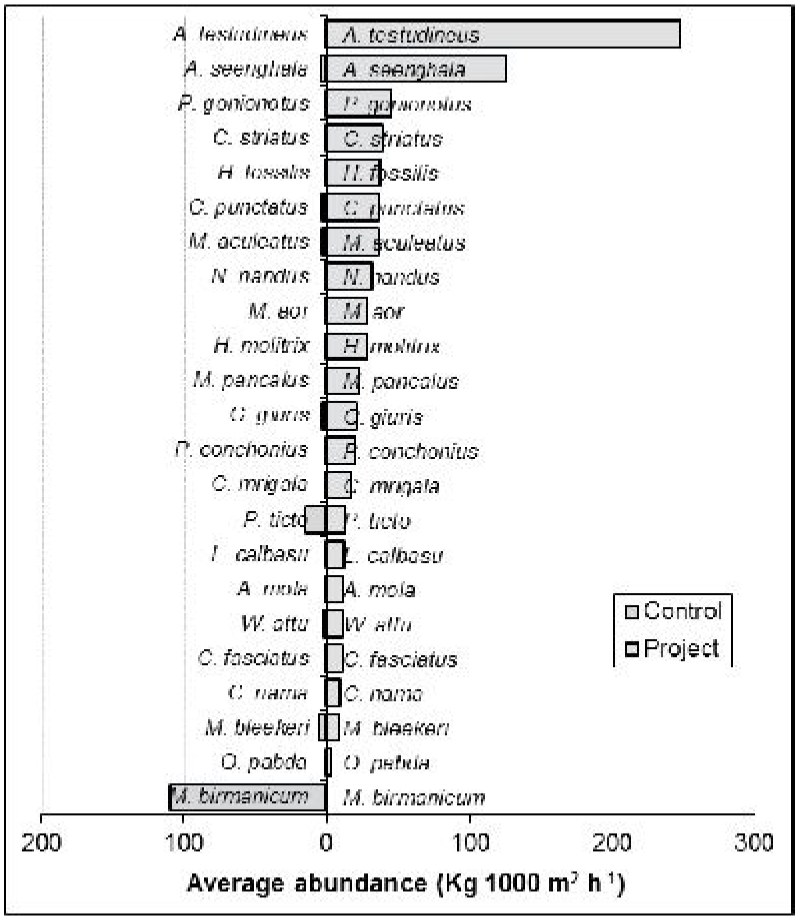


Fig. 6. Average abundance [gillnet catch per unit effort (kg 1000 m^2 h^{-1})] of species caught from CBFM and control sites exploiting open-*beel* habitat in the northwest (OB-N) region of the country.

4.2.4 River habitat in the east (R-E) region

Species assemblages at the CBFM sites comprised almost three times more species than those of the control sites in 2005. Species are arranged in descending order of their contribution to the average dissimilarity between the two groups of sites (Figure 7). Only those species contributing to 91% of the cumulative average dissimilarity are shown. Of the 14 recorded species, 11 were present or more abundant at CBFM sites. These included, in descending order of their contribution to the average dissimilarity between the two groups of sites: *Wallago attu, Pama pama, Labeo bata, Puntius sophore, Mastacembelus armatus, Glossogobius guiris, Nandus nandus, Mystus bleekeri, Aorichthys seenghala, Clupisoma garua* and *Macrognathus pancalus*. Only four species were more abundant at the control sites: *Aorichthys seenghala, Labeo calbasu, Cluposoma garua* and *Labeo gonius*. The latter three were absent from the CBFM sites.

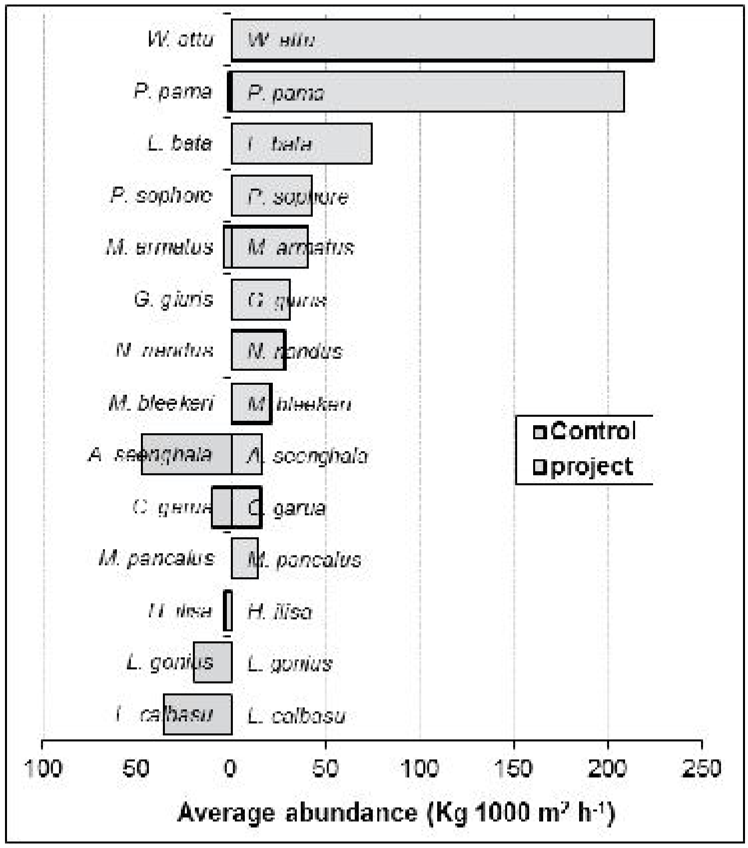


Fig. 7. Average abundance [gillnet catch per unit effort (kg 1000 m^2 h^{-1})] of species caught from CBFM and control sites exploiting river habitat in the eastern (R-E) region of the country.

5. Discussion

According to the relative frequency of upward and downward trends in performance indicators at CBFM and control sites, the CBFM project appears to have benefited fish production (CPUA), abundance (CPD) and biodiversity (H') at participating sites. Mean annual increases in fish abundance, indicated by CPD, were significantly greater at CBFM compared to control sites. Furthermore, the mean change in fish abundance at control sites was not significantly different from zero. Rates of change in biodiversity (H') were found to vary significantly among habitat and were on average also significantly greater at CBFM sites than control sites. Improvements in biodiversity at CBFM sites through time were significant in closed and floodplain *beel* habitat. Significant improvements in biodiversity were also detected for control sites belonging to only floodplain *beel* habitat. Closed season appears significant but explains only 24% of variation in biodiversity (Halls and Mustafa 2006; Mustafa and Halls 2007). Habitat restoration may be more appropriate in improving the availability of resources (Payne and Cowan 1998). Unlike the annual perspective of the CPD indicator, GNCPUE provides an index of fish abundance only during a two month period during the flood season when gillnets tend to target migratory whitefish species (Welcomme 1985). Improvements in fish abundance were strongly linked to reductions in fishing intensity and destructive fishing effort (Halls and Mustafa 2006). The co- and community-based management approaches have long been advocated as a means to address the failures associated with conventional 'top down' approaches to management (Pomeroy and Williams 1994; Hoggarth et al. 1999; Wilson et al. 2003), but few studies have quantitatively demonstrated their benefits. The CBFM project has already demonstrated that Community Based Organizations (CBOs) are motivated to share and disseminate their knowledge and experiences through meetings, exchange visits and newsletters (Halls et al. 2005).

The potential difficulty in selecting comparable control sites creates uncertainty for determining which management interventions may be responsible for possible differences between river habitat in the east and floodplain *beel* habitat in the northern regions. These differences in species assemblages may therefore simply reflect differences in site habitat.

6. Conclusions and recommendations

The present study clearly reveals that in project sites managed according to the CBFM regime, fishers have over time established appropriate fisheries management regimes. Rates of change in species abundance were found to vary significantly among habitats and were on average also significantly greater at CBFM sites than at control sites. Improvements over time in species abundance at CBFM sites were significant in floodplain and river habitats. On the basis of the results presented here, it is concluded that the practices implemented under community-based fisheries management in Bangladesh have improved, or at least sustained, fish abundance and biodiversity without significant loss compared to those at the control sites. However, further research is needed to determine why species abundance is more enhanced in floodplain and river habitats than in *haor beel* and open *beel* habitats.

The community-based management approach shows considerable promise and should be considered for wider scaling out within sustainable management initiatives in the Indo-Gangetic Plains.

Acknowledgements

The authors acknowledge Alan Brooks, Robert Arthur, Susana Hervas Avila and Neil Andrew for their valuable suggestions and helpful comments on the manuscript. Thanks also to Ashley Halls, Mohammod Ilyas, Khalilur Rahman, Susmita Choudhury and Ismat Ara for their valuable contributions towards the compilation, analysis and interpretation of the data. This research and dissemination was funded by the Department for International Development (DFID). The views expressed here are not necessarily those of DFID.

References

Ahmed, M., A.D. Capistrano, and M. Hossain. 1997. Experience of partnership models for the co-management of Bangladesh fisheries. *Fisheries Management and Ecology*. **4** (3), 233-248.

Ali, M. Y. 1997. *Fish, Water and People: Reflection on Inland Open Water Fisheries Resource of Bangladesh*. The University Press Limited. Dhaka.

Bray JR. and JT. Curtis. 1957. An ordination of the upland forest communities of southern Wisconsin. *Ecol. Monogr*. 27, 325-349.

Clarke, K. R. 1993. Non-parametric multivariable analysis of changes in community structure. *Aust. J. Ecol*. 18, 117-143.

Clarke, K. R. and R. N. Gorley. 2006. *PRIMER v6: User Manual/Tutorial*. PRIMER-E, Plymouth.

Craig, JF., A. S. Halls, J. Barr and C.W. Bean. 2004. The Bangladesh Floodplain Fisheries. *Fish. Res.* **66**, 271-286.

Halls, A.S. and M.G. Mustafa. 2006. Final Assessment of the Impact of the CBFM Project on Community-Managed Fisheries in Bangladesh. Report to the WorldFish Center, Bangladesh.

Halls, A. S., Arthur, R., Bartley, D., Felsing, M., Grainger, R., Hartmann, W., Lamberts, D., Purvis, J; Sultana, P., Thompson, P., Walmsley, S., 2005. Guidelines for Designing Data Collection and Sharing Systems for Co-Managed Fisheries. Part I: A Practical Guide. FAO Fish. Tech. Pap. 494/1&2.

Hoggarth, D.D., V.J. Cowan, A.S. Halls, M.T. Aeron, A. J. McGregor, C. A. Garaway, A. I. Panye, and R. R. Welcomme. 1999. Management Guidelines for Asian Floodplain River Fisheries. FAO Fish. Tech. Pap. 384/1&2.

Hughes R., S. Adnan, and B. Dalal-Clayton. 1994. *Floodplains or flood plans*: London: International Institute for Environment and Development, and Research and Advisory Services.

IUCN. 2000. Red Book of Threatened Fishes of Bangladesh. The World Conservation Union (IUCN), Dhaka, Bangladesh, 116p.

Minkin, F. 1993. Food control and nutritional consequence of biodiversity of fisheries. FAP-16. Environmental Study.

Mustafa, M.G. and S.A. Halls. 2006. Community Based Fisheries Management: Fisheries yields and sustainability. Malcolm Dickson and Alan Brooks (ed.), Policy Brief 2. The WorldFish Center, Bangladesh and South Asia Office, Dhaka, Bangladesh.

Mustafa, M.G. and S.A. Halls. 2007. Impact of the Community-Based Fisheries Management on sustainable use of inland fisheries in Bangladesh. Conference Proceedings 75. Conference paper 3, Dickson M. and A. Brooks (ed.). International Conference on Community Based Approaches to Fisheries Management, the WorldFish Center. Bangladesh and South Asia Office, Dhaka, Bangladesh.

Payne, A.I. and V.J. Cowan. 1998. Review of stock enhancement in the floodplains of Bangladesh. In J. Petr (Ed.). FAO/DFID Expert Consultation on Inland Fisheries Enhancements. FAO Fisheries Technical Paper 374. Rome, FAO.

Pomeroy, R.S. and M.J. Williams. 1994. Fisheries Co-management and small scale fisheries: a policy brief. International Centre for Living Aquatic Resources Management (ICLARM), Manila.

Rahman, A.K.A. 1989. Freshwater fishes of Bangladesh. Zoological Society of Bangladesh, Dhaka, 352pp.

Shannon, C.E. 1948. A mathematical theory of communication. *Bell. System. Tech. J.* 27, 379-423.

Welcomme, R.L. 1985. *River Fisheries*. FAO Fish. Tech. Pap. 262.

Wilson, D.C., J.R.Nielsen and P. Degnbol. 2003. The Fisheries Co-management Experience: Accomplishments, Challenges and Prospects. *Fish & Fisheries Series*. Vol: 26, Springer, New York.

Section 6

Rice-Based System
Intensification and Diversification

Promising rice genotypes for the wet and dry seasons in coastal West Bengal

S.K. Sarangi[1], D. Burman[1], S. Mandal[1], B. Maji[1], E. Humphreys[2], T.P. Tuong[2], B. K. Bandyopadhyay[1] and D. K. Sharma[1]

[1]Central Soil Salinity Research Institute, Regional Research Station, Canning Town, West Bengal and Karnal, Haryana, India, sksarangicanning@gmail.com, burman.d@gmail.com, subhasis2006@gmail.com, b.maji57@gmail.com, bimalbkb@gmail.com, dineshksharma@rediffmail.com
[2]International Rice Research Institute, Philippines e.humphreys@irri.org, t.tuong@irri.org

Abstract

Agricultural productivity of the coastal lands of West Bengal is very low. Rice is grown on most of the agricultural land during the rainy season, but the majority of the land remains fallow during the dry season due to water scarcity and salinity. Due to water stagnation, the average yield of the wet season crop in the coastal zone of West Bengal (< 2.0 t ha^{-1}) is below both the national average (2.4 t ha^{-1}in 2011-12) and the average of West Bengal (2.6 t ha^{-1}). Therefore, the development and dissemination of improved *boro* (irrigated rice grown during the dry season) and *aman* (rainy season crop) cultivars is necessary to increase and stabilize rice production and alleviate food insecurity and poverty in the coastal region. This study sought to identify improved *aman* and *boro* rice varieties in on-farm experiments in South and North 24 Parganas Districts of West Bengal, India, from 2011 to 2014. The performance of elite lines and varieties from the Central Soil Salinity Research Institute, International Rice Research Institute, and government agencies of India and Bangladesh was evaluated and compared to that of local cultivars. During each dry season, 17 entries were tested in soils with a range of salinities. The Bangladeshi varieties BRRI dhan47 and Binadhan-8, and the variety WGL 20471 (released from Warangal, Andhra Pradesh) produced the highest average grain yields of 5.0, 4.8 and 4.5 t ha^{-1}, respectively. These yields were 40 to 60% higher than that of the local cultivars (3.2 t ha^{-1}). During the wet seasons, 13 entries were evaluated at locations that experienced a range of water depths. The improved *aman* varieties yielded ~4 t ha^{-1}, about 20% more than the local cultivars (3.4 t ha^{-1}) across all water depths. The best performing entries across all water depths were Amal-Mana, Swarna-Sub1 and CSRC(D) 7-0-4 and CSRC(D) 12-8-12. The performance of the shorter statured Bangladeshi varieties declined as water depth increased. The results demonstrate the great potential for increasing the productivity of the coastal zone through adoption of improved rice varieties. The shorter duration of the improved wet season varieties may also facilitate cropping intensification. Some of the best performing varieties in the dry season came from other countries, highlighting the importance of collaboration and germplasm exchange among neighboring countries.

Key message: There is considerable potential for increasing rice production in the coastal zone of West Bengal through replacement of locally grown wet and dry season varieties with existing improved, stress tolerant varieties.

Keywords: aman, boro, improved varieties, salinity, waterlogging

1. Introduction

The saline coastal zone of India stretches over a length of 8,129 km along the eastern and western fringes of the country, with a total area of about 3.1 Mha (Table 1). The largest area of saline coastal soils is in West Bengal, with 0.82 Mha located in four out of 20 districts (South 24 Parganas, East Midnapore, North 24 Parganas and Howrah). Rice is the predominant crop in the coastal areas of West Bengal during both the wet (*kharif*) season from June to November, and during the dry (*rabi*) season from November to April. The dry season crop is almost entirely dependent on irrigation using groundwater. Farmers in the region are predominantly marginal landholders; the rest are either small farmers or landless (ICAR-CSSRI 2014). They prefer to follow a rice-rice cropping system for a range of reasons including meeting family food requirements, use of rice crop byproducts for domestic purposes, and unfavorable environmental conditions for growing other crops. During the rainy season, farmers typically grow traditional, photoperiod-sensitive, low yielding *aman* cultivars, whereas during the dry season high yielding *boro* varieties with moderate tolerance to salinity are grown. The single largest problem during the *aman* crop is waterlogging of varying depth and duration. This problem is also compounded by occasional natural disasters (cyclones, seawater intrusion, drought). The *boro* crop faces problems of lack of fresh water and soil and water salinity.

Table 1. Distribution of coastal saline soils in India (source: Yadav et al. 1983)

State	Area (Mha)
West Bengal	0.82
Gujarat	0.71
Orissa	0.40
Andhra Pradesh	0.28
Tamil Nadu	0.10
Karnataka	0.09
Maharashtra	0.06
Kerala	0.03
Goa	0.02
Andaman & Nicobar Islands	0.02
Pondicherry	0.001
Total	2.52
Area under mangroves	0.57
Total	3.09

Several high yielding (4-5 t ha^{-1}) *aman* varieties with improved tolerance to flooding have been developed recently by various Indian institutions including the Central Soil Salinity Research Institute (CSSRI) Regional Research Station at Canning Town, West Bengal and the Central Rice Research Institute (CRRI) at Cuttack, Odisha. Furthermore, the Sub-1 genes for submergence tolerance have been introgressed into some major varieties. These improved varieties have the potential to substantially improve and stabilize rice production in flood-prone environments (Singh et al. 2009; Sarangi et al. 2015b).

For the dry season, *boro* cultivars of shorter duration with greater tolerance to salinity are needed (Sarangi et al. 2014). Where fresh water is available, short duration varieties are preferred by farmers to reduce the water requirement and thus the pumping cost. Salt-tolerant *boro* varieties developed by the Bangladesh Rice Research Institute (BRRI) for the adjacent coastal zone region in Bangladesh could also fit into the cropping system in West Bengal (Hossain 2003).

While there has been good progress in the development of improved varieties for the wet and dry seasons in the coastal zone of West Bengal, these varieties have not been evaluated in farmers' fields. Therefore, the objective of the work presented here was to evaluate the performance of promising *aman* and *boro* varieties for the wet and dry seasons, respectively, in the coastal area of West Bengal.

2. Methods

2.1 Study sites

On-farm evaluation of *aman* and *boro* varieties was conducted at representative sites in Gosaba Block in South24 Parganas District ($22^0\,08'56''$ N, $88^0\,48'26''$E) and in Sandeshkhali II Block in North 24 Parganas District ($22^0\,18'00''$ N, $88^0\,49'36''$E) of West Bengal, India. The region has a tropical monsoon climate with an average annual rainfall of 1830 mm, of which about 89% occurs from June to October. At Sandeshkhali the source of irrigation water during the dry season was groundwater at a depth of 110-116m. At Gosaba the source was rainwater conserved in ponds and ditches. The depth of fresh groundwater (275 m) at Gosaba is too deep to use for irrigation because of the high cost of installation and pumping of deep tubewells.

The soil (10-15 cm layer) was sampled prior to the start of the first *boro* and *aman* experiments and analyzed for texture (hydrometer method), salinity (electrical conductivity of saturation extract, ECe), pH (1:2.5 soil:water), organic carbon (Walkley and Black 1934), available nitrogen (Subbiah and Asija 1956), available phosphorus (Olsen et al. 1954) and available potassium (Hanway and Heidel 1952).The soils at all sites are heavy textured (silty clay loam to silty clay), slightly acidic, with medium organic carbon (0.50–0.75%), low available nitrogen (<280 kg ha^{-1}), high available potassium (>300 kg ha^{-1}), and medium available phosphorus (11-25kg ha^{-1}) (Tables 2 and 3). The soils were moderately saline shortly prior to transplanting both the *boro* and *aman* crops.

Table 2. Initial soil and irrigation water properties at the *boro* experimental sites in January 2012 (mean ± s.e.)

	Soil		Water		N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	% OC
	ECe (dS m^{-1})	pH	EC (dS m^{-1})	pH				
Sandesh khali (n=18)	4.1±0.1	5.6±0.2	1.9±0.2	8.2±0.1	222±5.1	19.0±0.9	450±6.9	0.7±0.1
Gosaba (n=18)	5.4±0.1	5.9±0.8	2.5±0.1	8.7±0.1	185±5.1	20.6±1.7	468±13.2	0.7±0.1

Note: OC = Organic Carbon

Table 3. Initial soil properties at the *aman* experimental sites in June 2012 (mean ± s.e.)

	Soil		N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	% OC
	EC (dS m^{-1})	pH				
Sandeshkhali (n=9)	5.8±0.2	5.8±0.1	198±6.8	18.2±1.1	450±6.9	0.7±0.1
Gosaba (n=9)	6.5±0.1	6.7±0.4	189±5.3	19.4±1.9	468±13.2	0.7±0.1
Basanti (n=9)	5.3±0.3	5.5±0.2	203±7.1	22.1±1.3	390±8.3	0.6±0.2

Note: OC = Organic Carbon

2.2 Experimental design

The experimental design for evaluation of *aman* and *boro* varieties was a randomized block with three replicates at each site (farmers' field) and a gross plot area of 60 m^2 (12 m× 5 m).

2.2.1 Boro season

Evaluation of eight to ten *boro* varieties and advanced breeding lines ("entries") was conducted for three consecutive *boro* seasons (2011-12, 2012-13 and 2013-14) (Table 4). The evaluation was done in farmers' fields at two locations: 'Sandeshkhali' in Daudpur village (in Sandeshkhali II Block, North 24 Parganas District), and 'Gosaba' in Pakhiralay South, Jatirampur, Dulki and Pakhiralay villages (in Gosaba Block, South 24 Parganas District). At each location there were one to six sites (farmers' fields) each year.

Desirable rice variety attributes for the dry season include salinity tolerance, short duration, fine grain for higher market price and bold grain for home consumption, and high straw yield for domestic uses and animal fodder. Salinity tolerance of the entries varied from moderate to high and all were photoperiod insensitive, with duration ranging from about 110 to 150 d. Some of the entries were common over the three years, however, some were deleted and new entries added depending on performance and availability of new promising ones, respectively. Most entries were developed in India, but three Bangladeshi varieties (BRRI dhan47, BRRI dhan55 and Binadhan-8) and three IRRI lines (IR 87938, NSIC RC 238, NSIC RC 222) were also included. Old and traditional varieties often grown by farmers in the study areas (Canning-7, Parijat, N. Sankar, S. Sankar) were also included in the second year.

Table 4. Characteristics of the entries evaluated during the *boro* season over three years

Entry	**Salinity tolerance (dSm^{-1})**	**Plant height (cm)**	**Duration (days)**	**Grain yield (t ha-1)**	**Grain type1**	**Year released In India**	**Year evaluated**
Canning 7	6-8	95-105	130	4.0-4.5	LB	1989	2011-12 2013-14
CSR4	6-8	95-100	135	3.5-4.0	LB	1985	2011-12
WGL 20471 "Lal-minikit"	6-8	95-105	130	5.0-5.5	LS	1991	2011-12, 2012-13, 2013-14
IET 4786 "Sada-minikit"	4-6	80-95	135	3.5-5.6	LS	2000[3]	2011-12, 2012-13, 2013-14
Annada	4-6	95-105	135	3.5-4.5	SB	1987	2011-12, 2012-13, 2013-14
Boby	4-6	100-105	145	4.0-4.5	LB		2011-12
Lalat	2-4	102	135	4.0-4.5	LS	1988	2011-12, 2013-14
BRRI dhan47[2]	4-6	105	152	6.0	MB	2007	2012-13, 2013-14
Binadhan-8[2]	10	95	145	6.0	MB	2010	2012-13, 2013-14
BRRI dhan55[2]	4-6	100	145	7.3	LS	2011	2012-13
Bidhan 2	6-8	105-110	135	4.0-5.0	LS		2011-12
Parijat	4-6	85-95	135	3.5-4.0	MS	1976	2012-13
N. Sankar	2-4	95-100	140	3.0-4.0	LS	TV[4]	2012-13
S. Sankar	2-4	95-100	140	3.0-4.0	LS	TV	2012-13
IR 87938	2-4	95-100	140	3.0-4.0	MS	-	2013-14
NSIC RC 238	2-4	100-105	140	3.0-4.0	MS	-	2013-14
NSIC RC 222	2-4	100-105	140	4.0-4.5	MS	-	2013-14

[1]LB: long bold, MB: medium bold, SB: short bold LS: long slender, MS: medium slender

[2] Varieties developed and released in Bangladesh; characteristics are for conditions in Bangladesh

[3]Year of notification

[4]TV: traditional variety

2.2.2 Aman

Aman variety evaluation (nine to ten entries) was conducted at three sites in 2012 and 2013 (Table 5). Most (around 85%) of the land is low-lying, therefore varieties that are generally tall, high yielding, stress tolerant (tolerant to flash/stagnant flooding, lodging, diseases and pests) with long slender grains having good cooking quality are preferred during this season. All varieties evaluated had moderate salinity tolerance, and all were tall or very tall and photoperiod sensitive except for Swarna-Sub1, a submergence-tolerant variety developed by IRRI (Ismail et al., 2013). All varieties were also long duration except for Swarna-Sub1, which was medium maturity. The CSRC (D) series are promising lines developed at ICAR-CSSRI RRS Canning Town for low-lying coastal lands. BRRI dhan47 and Binadhan-8 are medium statured, salt tolerant and photoperiod insensitive varieties from Bangladesh.

Table 5. Characteristics of the entries evaluated during the *aman* season over two years

Variety	Salinity tolerance (dSm^{-1})	Plant height (cm)	Duration (days)	Grain yield ($t\ ha^{-1}$)	Grain type	Year released
SR 26B	4-6	130-145	165	3.5-4.0	MS	TV[1]
Sabita	4-6	180-190	210	3.5-4.0	LS	1986
Geetanjalli	4-6	160-170	165	4.0-4.5	LS	TV
Amal-Mana	6-8	160-170	165	5.0-5.5	LS	2008
Patnai 23	4-6	160-170	165	3.0-3.5	MS	TV
NC 678	4-6	165-170	160	2.0-2.5	MS	TV
CSRC (D) 7-0-4	4-6	160-175	170	4.0-4.5	MS	2008
CSRC (D) 13-16-9	4-6	160-175	170	4.0-4.5	MS	2008
CSRC (D) 12-8-12	4-6	160-175	170	4.0-4.5	MS	2008
CSRC (D) 2-17-5	4-6	155-175	165	4.0-4.5	MS	2008
Swarna-Sub1	-	95-105	140	4.5-5.0	MS	2009
BRRI dhan47	4-6	105	152	6.0	MB	2007
Binadhan-8[2]	10	95	145	6.0	MB	2010

[1]TV: traditional variety

2.3 Crop management

2.3.1 Boro

Nursery sowing was done during the second week of December and 30 d old seedlings were transplanted at a spacing of 20 cm x 10 cm with 1-2 seedlings per hill. A fertilizer dose of 120-20-0 ($N:P_2O_5:K_2O$) kg ha^{-1} was applied to each plot as urea, single super phosphate and muriate of potash, respectively. All of the P and K and 25% of the N were applied prior to leveling. Half of the N was broadcast 21 d after transplanting (DAT) and the remaining 25% was broadcast at 60 DAT. Hand weeding was done twice at 20 and 40 DAT to remove all weeds. Chloropyriphos @ 2 ml l^{-1} water and tricyclazole @ 0.6 g l^{-1} water were used to control insects and diseases, respectively, as recommended. The plots were kept flooded (2.5-7.5 cm) throughout the season until about 20 d before harvest maturity.

2.3.2 Aman

Nurseries were sown in mid-June and 40 d old seedlings were transplanted in the last week of July using two seedlings per hill spaced at 15 cm × 15 cm. All plots in the field received similar management, including 5 t ha^{-1}

of farmyard manure applied one month before transplanting, and inorganic fertilizers applied at 50-20-10 ($N-P_2O_5-K_2O$) kg ha^{-1}. P and K were incorporated before transplanting, whereas N in the form of urea was applied in three equal splits at 7 DAT, maximum tilering (45 DAT) and at initiation of flowering (75 DAT). Hand weeding was done twice at 30 and 60 DAT to remove all weeds. Chloropyriphos @ 2 ml l^{-1} water and tricyclazole @ 0.6 g l^{-1} water were used to control insects and diseases, respectively, as recommended.

2.4 Monitoring

2.4.1 Water depth

The depth of water in the field during each *aman* season was monitored daily using a meter stick installed in each plot. The mean data for all the plots was considered as the flood water depth (FWD) of that location.

2.4.2 Soil and irrigation water salinity

Soil samples were collected from the root zone (10-15 cm) before transplanting the *boro* experiments each season, and at monthly intervals during the crop growth period. The samples were processed as per standard procedure (Gupta 2006) and the electrical conductivity (EC) of saturation extract (ECe) was determined. Water samples were collected from the irrigation sources for EC determination at the same time as soil sampling.

2.4.3 Crop data

The date of physiological maturity was taken as the date when the grains had turned a golden yellow color and there was senescence of lower leaves. Grain and straw yields were determined in a 5m x 2m area at the center of each plot. The grain and straw were weighed, subsamples were dried at 60ºC to determine moisture content, and grain yield (14% moisture) and straw yield (dry) were determined. Plant height (from base to tip of the panicle) and the number of panicles $hill^{-1}$ were determined on three hills at each corner of the yield area. Ten panicles were randomly selected from each plot to determine the number of grains $panicle^{-1}$. The panicles were hand-threshed, filled (grains) and empty spikelets (chaff) were separated by submerging the threshed spikelets (floating spikelets considered empty) in tap water, then counted, weighed and dried to determine grain moisture content and 1000-grain weight at 14% moisture content.

2.5 Weather data

Daily rainfall, maximum and minimum temperature and bright sunshine hours (BSH) were collected from the meteorological observatory at Canning Town.

2.6 Statistical analysis

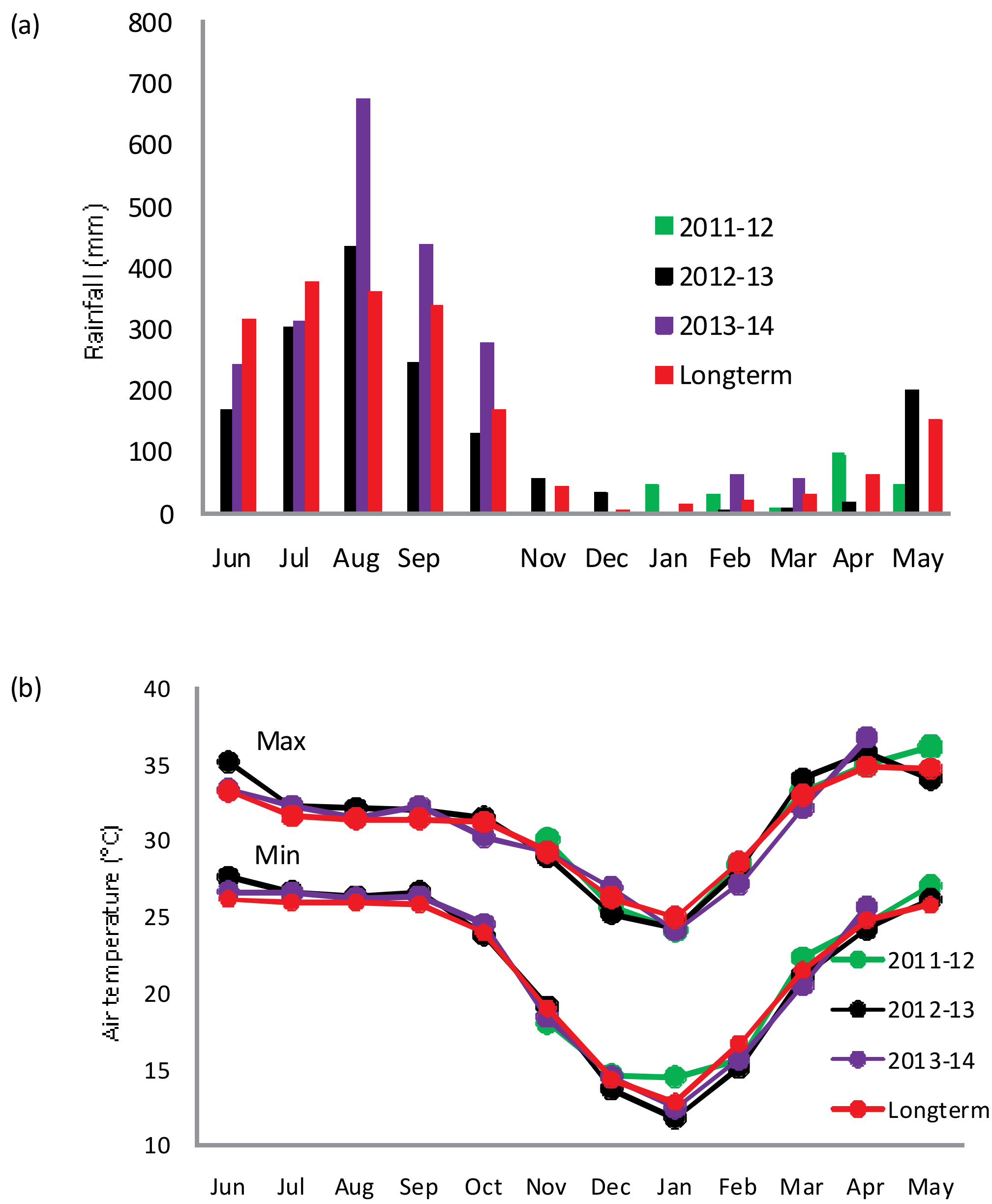
The data were subjected to analysis of variance (ANOVA, Gomez and Gomez 1984) using MS Excel and the STAR statistical package developed by IRRI. In the first *boro* season there were several sites (farmers' fields with replicated experiments) at both locations, and the mean of the treatments within each farmers' field was considered as one replicate. In the other two *boro* seasons there was only one replicated experiment at each location. During both rainy seasons there were three farmers' fields with replicated experiments, and each farmer's field was considered as one replicate. Treatment means were compared using the least significant difference (LSD) at p=0.05 level of significance. The interactions between variety, year and site were also determined by ANOVA for the four entries in common across all years for both the *boro* and *aman* seasons.

To determine the relationship between yield and variety, average soil salinity from transplanting to maturity was regressed against grain yield for each *boro* variety grown in more than one year. For the rainy season, average water depth during August (shortly after transplanting, when the crop is most sensitive to deep water) was regressed against yield. The similarity of the regressions for different varieties was determined using the minimum significant difference (MSD) method (Howell 2013). A pair of regression coefficients, bi and bj, are declared significantly different at the experiment wise error rate α if and only if their difference equals or exceeds the critical difference MSD_{ij}. That is, if [bi-bj]>MSD_{ij}, where $MSD_{ij} = Q'_{0.05[k,v]}$ max (s_{bi}, s_{bj}) and Q' is a value from the studentized augmented range distribution, k = no. of items, and v = degrees of freedom.

3. Results and discussion

3.1 Weather

Rainfall was generally well distributed during each *aman* season and little rain fell during the maturity period (November and December). Rainfall was much higher during the 2013 *aman* season (1936 mm from June to October) compared with 2012 (1272 mm), and higher than the long term average during this period (1554 mm) (Fig. 1a). The monthly temperature trends were similar in all three years with the exception of unusually high minimum temperature in January 2012 (Fig. 1b). This anomaly was also observed in the coastal zone of Bangladesh (Mondal et al. 2015).



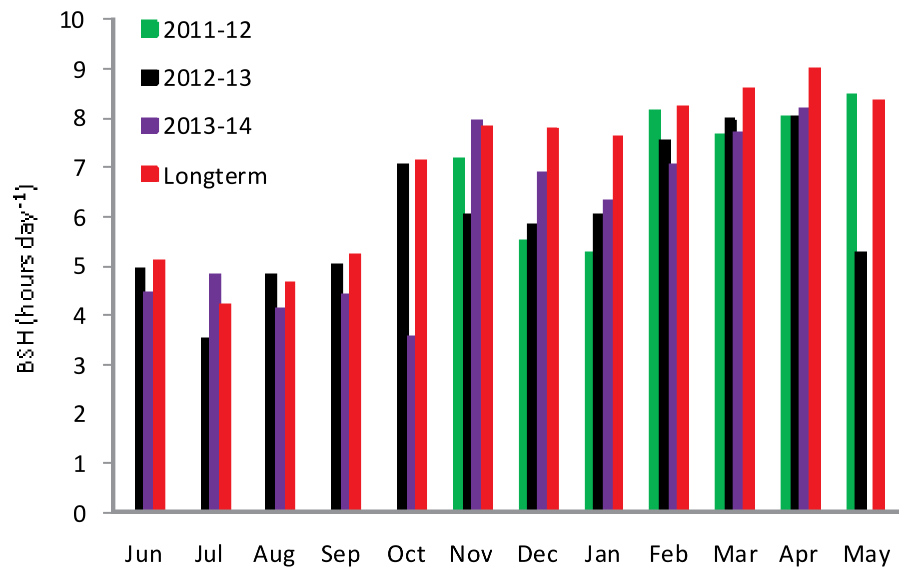


Fig. 1. Rainfall (a), maximum (max) and minimum (min) air temperature (b), and bright sunshine hours (BSH) (c) during the experimental period at ICAR-CSSRI RRS Canning Town. Long-term averages are for 1984-85 to 2013-14.

3.2 Boro variety evaluation

3.2.1 Soil and water salinity

At Sandeshkhali, initial soil salinity ranged from 2.1 to 7.9 dS m^{-1} across fields and years (Table 6). Initial soil salinity at Gosaba was higher (3.4 to 9.3 dS m^{-1}). At both locations, soil salinity increased with time after transplanting, by around 3dS m^{-1} between January and April each year (Fig. 2a). Salinity was consistently higher at Gosaba than at Sandeshkhali. Irrigation water salinity also increased during the *boro* season, more so at Sandeshkhali where irrigation was from groundwater (Fig. 2b), consistent with the findings of Burman et al. (2015) over several sites and years.

Table 6. Initial and final soil salinity (dS m^{-1}) in *boro* fields over three years. Values are mean and range (in parentheses)

Location	2011-12		2012-13		2013-14	
	Initial	Final	Initial	Final	Initial	Final
Sandeshkhali	4.1 (2.1-7.8)	7.2 (4.7-9.4)	4.5 (3.2-6.1)	7.7 (5.3-9.8)	4.4 (3.5-7.9)	6.8 (4.8-8.4)
Gosaba	5.4 (3.4–9.9)	8.9 (7.8-10.6)	6.2 (4.7-9.3)	9.7 (6.4-13.3)	5.8 (4.1-8.7)	8.1 (6.5-10.8)

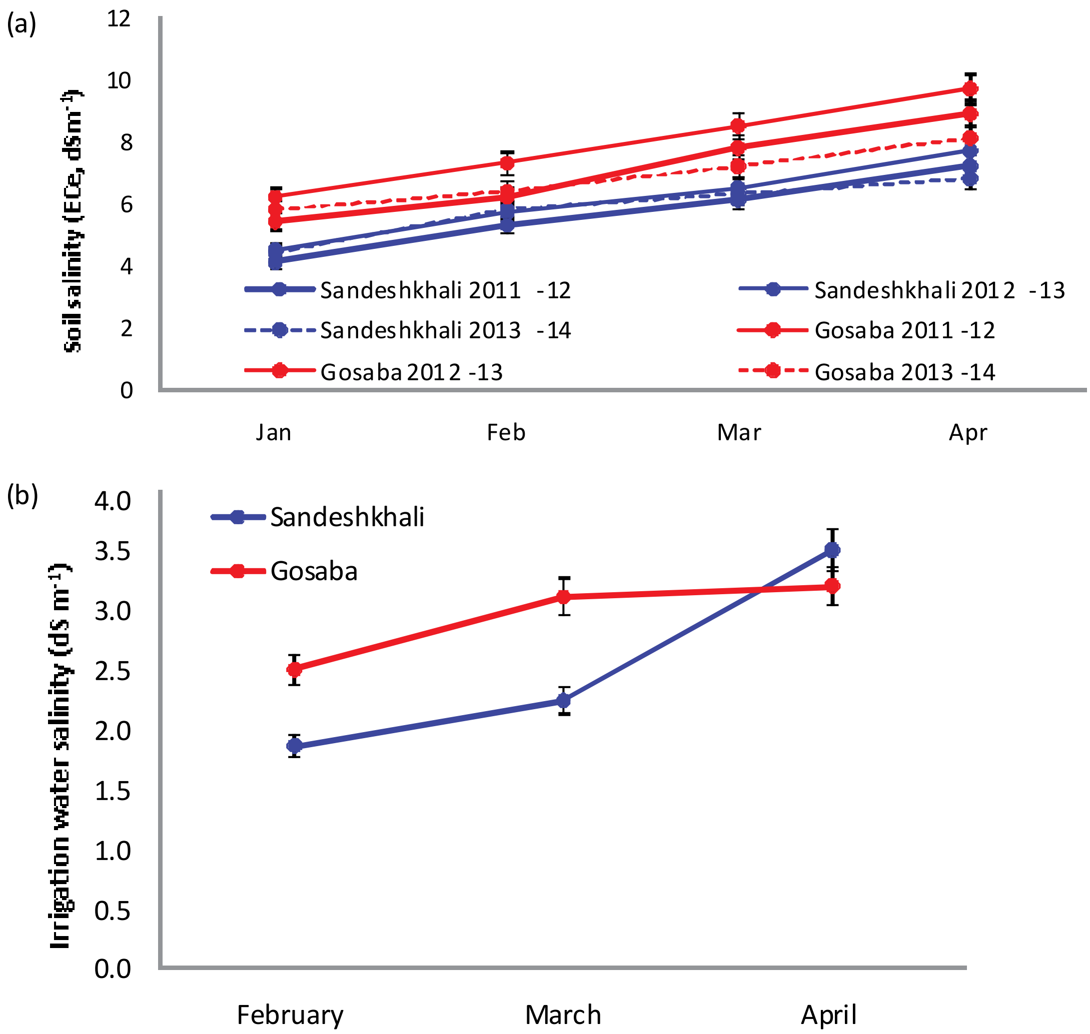


Fig. 2. Average soil salinity during the *boro* crop each year (a) and irrigation water salinity during the 2011-12 *boro* crops (b), at Gosaba and Sandeshkhali. Vertical bars indicate standard error.

3.2.2 Performance of boro varieties

The duration of most of the rice entries during the *boro* season was about 140 d. The Bangladeshi varieties had shorter duration ranging from 120 d (BRRI dhan55) to 130 d (BINAdhan-8) to 135 d (BRRI dhan47). The Indian variety Canning7 was also slightly shorter duration (135 d) than most of the Indian varieties, while Lalat was slightly longer duration than most at 145 d.

The interactions between variety, year and site were determined by analyzing the data for the four entries that were common across all three years (WGL 20471, IET 4786, Annada and Bidhan 2). The interactions were not significant for any of the measured parameters (Table 7). The effect of year was not significant for parameters like duration, plant height, panicles hill^{-1}, grains panicle^{-1} and test weight. Site had a significant effect on these parameters. However, since the varieties were different in different years, the analysis for grain yield was done year-wise and location-wise (Table 8).

Table 7. Level of significance of crop duration, plant height, yield and yield components as affected by variety, year and site. *Boro* results are for the four varieties in common over the three years (2011-12, 2012-13, 2013-14) (WGL 20471, IET 4786, Annada and Bidhan 2). *Aman* results are for the four varieties in common over the two years (2012 and 2013) (Amal-Mana, Sabita, CSRC (D) 7-0-4 and CSRC (D) 2-17-5)

Effects	Duration (days)	Plant height (cm)	Panicles $hill^{-1}$	Grains $panicle^{-1}$	1000 grain weight
Boro	P>F	P>F	P>F	P>F	P>F
Variety (V)	0.981	<0.05	0.335	<0.05	<0.05
Year (Y)	0.602	0.621	0.756	1.000	0.778
V and Y interaction	0.981	0.919	0.960	1.000	0.456
Site (S)	0.954	0.848	0.756	<0.05	<0.05
V and S interaction	0.962	0.886	0.782	0.767	0.879
S and Y interaction	0.328	0.959	0.536	1.000	0.925
V, Y and S interaction	0.594	0.999	0.941	0.377	0.970
Aman					
Variety (V)	0.007	<0.05	<0.05	<0.05	<0.05
Year (Y)	0.899	<0.05	0.729	0.188	0.962
V and Y interaction	0.909	<0.05	0.517	0.805	0.389
Field water depth (D)	0.704	<0.05	<0.05	0.052	0.277
V and D interaction	0.740	<0.05	0.720	0.548	0.820
D and Y interaction	0.527	<0.05	0.302	<0.05	0.763
V, Y and D interaction	0.951	<0.05	0.720	<0.05	0.706

Relative yield of the entries varied over the three years and two sites (Table 9). The most consistently high yielding variety was WGL 20471, which yielded an average of 4.6 to 5.8 t ha^{-1} in all three years at both sites, except at Sandeshkhali in 2011-12. In 2011-12, grain yield of all varieties was low at Sandeshkhali due to damage by rodents. The higher yield of WGL 20471 than the other three common varieties over the three years was due to higher grain weight in comparison with the other three varieties, more grains per panicle in comparison with IET 4786 and Annada, and slightly higher panicle density in comparison with Annada and Bidhan2 (Table 8). Yield of BRRI dhan47 was similar to that of WGL 20471 in 2012-13 at both sites, and at Gosaba in 2013-14, with the added benefit of slightly shorter duration. However, WGL 20471 has the locally preferred grain type (long slender grains), whereas BRRI dhan47 grain is medium bold. Yield of BRRI dhan55 was relatively low at both sites, probably reflecting its much shorter duration. The performance of the local varieties (Parijat, N. Sankar, S. Sankar) was always inferior to that of the improved varieties at both sites.

Table 8. Mean maturity duration, plant height and yield components of boro rice entries

Effects	Duration (days)	Plant height (cm)	Panicles $hill^{-1}$	Grains $panicle^{-1}$	1000 grain weight (g)
WGL 20471	140	98.4	16	95	20.47
IET 4786	140	95.8	16	81	19.28
Annada	140	97.2	15	82	19.32
Boby	140	102.4	13	93	20.83
Lalat	145	102.1	13	85	21.87
BRRI dhan 47	135	100.1	17	83	25.85
BINA dhan 8	130	100.5	14	81	25.45
BRRI dhan 55	120	82.7	10	74	21.57
Bidhan 2	140	105.6	15	95	19.41
Parijat	140	87.8	13	70	19.68
N. Sankar	140	97.1	14	56	17.06
S. Sankar	140	97.9	10	55	16.80
IR 87938	140	98.6	15	58	21.64
NSIC RC 238	140	103.7	12	71	23.22
NSIC RC 222	140	101.0	15	81	21.46
Canning 7	135	99.8	14	94	19.35
CSR 4	140	92.2	14	94	18.98

Table 9. Yield of *boro* entries over three seasons

Varieties	**2011-12**		**2012-13**		**2013-14**	
	Sandesh-khali[1]	**Gosaba**	**Sandesh-khali**	**Gosaba**	**Sandesh-khali**	**Gosaba**
WGL 20471	3.9^{ab}	5.4^{a}	5.4^{a}	5.8^{a}	4.7^{a}	4.6^{a}
IET 4786	3.8^{bc}	4.8^{abc}	4.8^{abc}	5.2^{b}	4.0^{c}	4.1^{b}
Annada	3.6^{c}	4.6^{abc}	4.6^{abc}	4.6^{cd}	4.2^{bc}	4.3^{ab}
Bidhan 2	4.0^{a}	4.7^{abc}	4.7^{abc}	4.8^{bc}		
Boby	3.1^{de}	5.5^{a}				
Lalat	2.9^{e}	5.0^{ab}			3.9^{c}	4.0^{b}
Canning 7	3.6^{c}	3.9^{bc}			4.5^{ab}	4.4^{ab}
CSR 4	3.3^{d}	3.7^{bc}				
BRRI dhan47			5.5^{a}	5.8^{a}	4.2^{bc}	4.2^{ab}
BINAdhan-8			5.0^{ab}	5.2^{b}	4.4^{ab}	4.4^{ab}
BRRI dhan55			3.9^{bc}	4.2^{de}		
Parijat			3.7^{bc}	3.8^{ef}		
N. Sankar			3.6^{bc}	3.3^{g}		
S. Sankar			3.4^{c}	3.4^{fg}		
IR 87938					3.4^{d}	3.4^{c}
NSIC RC 238					3.4^{d}	3.5^{c}
NSIC RC 222					4.4^{ab}	4.4^{ab}
LSD 0.05	0.1	0.1	0.8	0.5	0.8	0.5
Mean	*3.5*	*4.7*	*4.5*	*4.6*	*4.1*	*4.1*

[1]Rat damage reduced yield

The relationship between soil salinity and grain yield varied between varieties, but there was a trend for yield of most varieties to decline with increasing salinity (Table 10). Lalat was the most sensitive variety, with yield declining by 336 kg ha^{-1} per unit increase in average soil salinity, which accounted for 56% of the variation in yield (P<0.1). The least sensitive varieties were BRRI dhan47, BINAdhan-8 and Bidhan 2. BRRI dhan47 was not affected by salinity up to the maximum experienced across the sites (season mean ECe 7-8 dS m^{-1}).

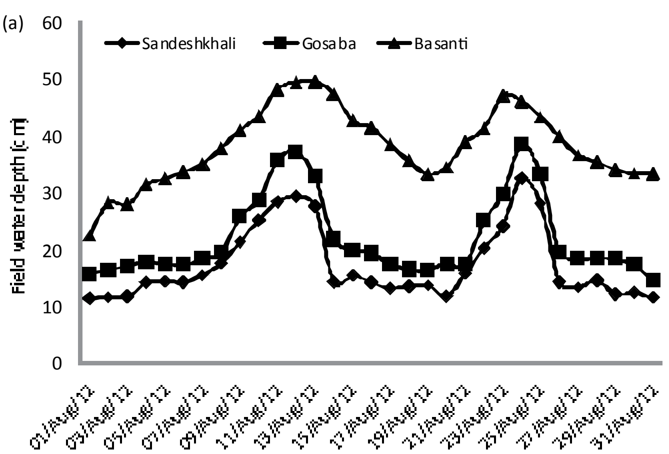
The *boro* entries were divided into two groups (those more sensitive to salinity (group A) and those less sensitive to salinity (group B)) based on the size of the regression co-efficient, P value and R^2 for further analysis. The responses of WGL 20471, IET 4786, Annada, Boby and Lalat were statistically similar (MSD 1.9), and the combined regression showed yield declining by 241 kg ha^{-1} per unit increase in average soil salinity. The response of BRRI dhan47, BINAdhan-8 and Bidhan 2 was also statistically similar (MSD 1.1) and for this group there was no significant response to salinity up to the degree experienced across the experimental sites. Thus, these varieties are more suited to higher salinity situations, and BINAdhan-8 has the advantage of about 10 d shorter duration than the less salt tolerant entries.

Table 10. Results of the analysis of the regression of average soil salinity against grain yield for individual varieties, and for the groups (A and B)

Group	Variety	n	Reg.coeff.	SEm	P>F	R^2
A	WGL 20471	9	-0.25	0.31	0.18	0.24
A	IET 4786	9	-0.22	0.24	0.14	0.28
A	Annada	9	-0.20	0.20	0.08	0.38
A	Boby	6	-0.20	0.19	0.06	0.64
A	Lalat	6	-0.34	0.33	0.09	0.56
A	*ALL*	*39*	*-0.24*	*0.13*	*<0.01*	*0.25*
B	Bidhan 2	7	-0.11	0.16	0.29	0.22
B	BRRI dhan47	5	-0.01	0.40	0.96	0.00
B	Binadhan-8	5	-0.18	0.33	0.47	0.19
B	*ALL*	*17*	*-0.15*	*0.18*	*0.15*	*0.13*

3.3.3 Aman variety evaluation

The floodwater was much deeper at Basanti than at Gosaba or Sandeshkhali in August 2012 (Fig. 3a). However, in 2013, depth was similar at Basanti and Gosabi and higher than at Sandeshkhali (Fig. 3b). There were two peaks in floodwater depth in 2012 at all three sites due to heavy rains, with depth reaching 50 cm at Basanti. In 2013, depth gradually increased to about 50 cm at Basanti and Gosaba, and to about 45 cm at Sandeshkhali. At Sandeshkhali, the crop was submerged from 8 to 13 August 2012 due to a flash flood, with adverse effects. Swarna-Sub1 and Amal-Mana recovered well due to submergence tolerance and performed better than the other entries. During 2013, there was stagnant flooding of >25 cm for a longer period starting from mid-August to the end of August, at all locations.



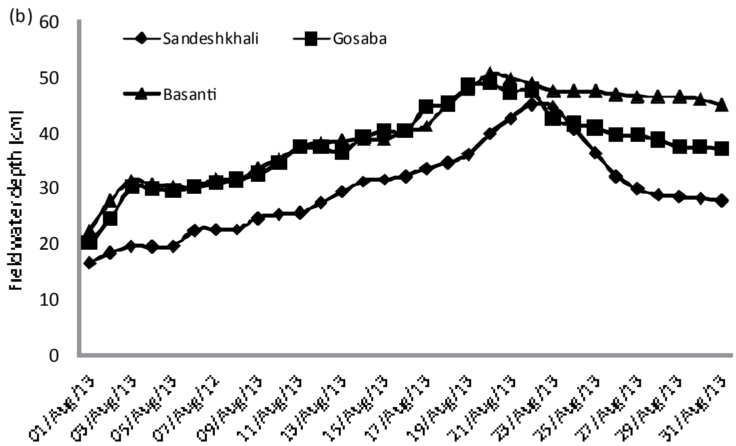


Fig. 3. Field water depth during August 2012 (a) and 2013 (b).

The interactions between variety, site and year were not significant for any of the parameters monitored except for plant height, for the four entries grown in both years (Table 7). Within site and year, there were significant differences in plant height between varieties (Table 11). Swarna-Sub1, BRRI dhan47 and Binadhan-8 were much shorter than all other varieties, at around 100 cm. Within variety, plant height varied across sites due to differences in water depth. However, the response varied greatly with variety. Regression analysis showed that Amal-Mana, CSRC(D) 2-17-5, CSRC(D) 12-8-12, Sabita and Patnai 23 responded the most strongly (R^2>0.9) to field water depth.

Table 11. Plant height (cm) of *aman* rice entries with different water depths and years

Entries	2012			2013		
	Sandeshkhali	Gosaba	Basanti	Sandeshkhali	Gosaba	Basanti
Amal-Mana	139	141	168	162	176	169
Sabita	128	144	172	161	173	178
CSRC (D) 7-0-4	128	130	173	143	163	150
CSRC (D) 2-17-5	145	152	167	165	175	173
CSRC (D) 12-8-12	130	136	177	-	-	-
CSRC (D) 13-16-9	146	152	157	-	-	-
Swarna-Sub 1	95	105	107	-	-	-
Geetanjali	-	138	147	-	-	-
NC 678	-	141	143	152	184	176
SR 26 B	-	130	138	149	168	157
Patnai 23	-	-	-	140	161	164
BRRI dhan47	-	-	-	98	102	101
Binadhan-8	-	-	-	99	102	101
LSD 0.05 (variety×year×site): 2.7						

The duration of most *aman* varieties was around 160-165 d (Table 12). However, the duration of Swarna-Sub1 (140 d), BRRI dhan47 (130 d) and BINAdhan-8 (125 d) was much less. Shorter duration means earlier harvest and the possibility of earlier establishment of the subsequent *boro* crop, reducing irrigation requirement for land preparation and resulting in earlier *boro* maturity, meaning that the crop is exposed to lower soil salinity (Sarangi et al. 2015a). The highest number of panicles hill^{-1} (9) and grains panicle^{-1} (121-128) were observed in Amal-Mana and CSRC (D) 12-8-12.

Table 12. Mean maturity duration and yield components of *aman* rice entries

Entries	Duration (days)	Panicles $hill^{-1}$	Grains $panicle^{-1}$	1000 grain weight (g)
Amal-Mana	155-175	9	121	29.00
Sabita	160-210	7	119	27.17
CSRC (D) 7-0-4	155-175	8	115	26.50
CSRC (D) 2-17-5	155-175	9	112	27.17
CSRC (D) 12-8-12	155-175	9	128	26.33
CSRC (D) 13-16-9	155-175	8	107	27.50
Swarna-Sub 1	140-145	8	89	25.50
Geetanjali	160-175	8	80	27.50
NC 678	165-185	7	123	28.00
SR 26 B	160-175	8	102	23.50
Patnai 23	160-175	7	96	24.00
BRRI dhan47	130-145	7	93	26.93
Binadhan-8	125-140	7	93	26.38

There were significant differences in yield of the *aman* varieties within site x year (Table 13). Relative yield varied with site and year. Amal-Mana consistently performed well across sites and years, with yield ranging from 4.4 to 5.0 t ha^{-1}. Swarna-Sub1 also performed well across all sites in the one year that it was evaluated (4.2 to 4.4 5.0 t ha^{-1}). The two Bangladeshi varieties performed well at Sandeshkhali where water depth was least, but poorly at the higher water depth sites. The results of regression analysis suggested that the entries fell into three groups. For group A varieties, yield increased with water depth. For group B, there was no effect of water depth on yield, and in group C yield decreased with water depth (Table 14).

Table 13. Grain yield (t ha^{-1}) of *aman* rice entries at different water depths

Entries	2012			2013		
	Sandeshkhali	Gosaba	Basanti	Sandeshkhali	Gosaba	Basanti
Amal-Mana	3.80^{ab}	4.55^{a}	4.40^{b}	4.96^{a}	4.51^{a}	4.50^{a}
Sabita	2.70^{c}	2.15^{e}	2.43^{d}	3.34^{d}	4.63^{a}	3.01^{c}
CSRC (D) 7-0-4	3.70^{b}	3.70^{cd}	3.70^{c}	4.86^{ab}	4.36^{a}	4.79^{a}
CSRC (D) 2-17-5	3.05^{c}	3.60^{d}	3.60^{c}	4.73^{ab}	4.57^{a}	4.24^{ab}
CSRC (D) 12-8-12	3.52^{b}	4.15^{bc}	4.80^{a}	-	-	-
CSRC (D) 13-16-9	3.50^{b}	3.50^{d}	3.50^{c}	-	-	-
Swarna-Sub 1	4.15^{a}	4.38^{ab}	4.20^{b}	-	-	-
Geetanjali	-	3.96^{c}	3.82^{c}	-	-	-
NC 678	-	3.45^{d}	3.50^{c}	3.85	3.91^{b}	4.58^{a}
SR 26 B	-	3.42^{d}	3.60^{c}	4.51^{b}	3.85^{b}	4.12^{b}
Patnai 23	-	-		4.13^{c}	3.86^{b}	3.81^{b}
BRRI dhan47	-	-		4.26^{bc}	3.31^{c}	2.95^{c}
Binadhan-8	-	-		4.23^{bc}	3.32^{c}	2.91^{c}
LSD 0.05	0.36	0.35	0.36	0.37	0.42	0.59

Note: Means with the same letter in a column are not significantly different at the 5% level by LSD

Table 14. Results of the analysis of the regression of average field water depth against grain yield of *aman* varieties for individual varieties, and for the groups (A, B, C)

Group	Variety	n	Reg.coeff.	SEm	P>F	R^2
A	CSRC(D) 12-8-12	9	2.4	0.37	0.20	0.99
A	Sabita	18	2.1	0.36	0.40	0.98
A	Patnai 23	9	2.3	0.10	0.05	0.98
A	CSRC(D) 2-17-5	18	1.2	0.27	0.21	0.93
A	Amal-Mana	18	1.6	0.15	0.39	0.91
A	ALL	72	0.03	0.16	0.12	0.11
B	CSRC(D) 13-16-9	9	0.46	0.01	0.37	0.88
B	BRRI dhan47	9	0.34	0.39	0.02	0.79
B	CSRC(D) 7-0-4	18	1.66	0.23	0.32	0.76
B	ALL	45	0.01	0.16	0.78	0.01
C	Swarna-Sub 1	9	0.46	0.07	0.93	0.60
C	Geetanjali	9	0.02	0.09	0.46	0.57
C	SR 26B	15	1.26	0.19	0.72	0.41
C	NC 678	15	1.62	0.20	0.31	0.39
C	ALL	48	0.004	0.09	0.73	0.008

4. Conclusions and recommendations

During the dry season, lack of fresh water and soil salinity are major constraints to rice production in the coastal zone of West Bengal. Several improved varieties performed better than the varieties commonly grown by farmers during the dry season. The most consistently high yielding variety across sites with varying soil salinity was WGL 20471, with yields usually in the range 4.6 to 5.8 t ha^{-1}. However, this line was more sensitive to soil salinity than the Bangladeshi varieties BRRI dhan47 and BINAdhan-8, and than the Indian variety Bidhan 2. BRRI dhan47 was the least sensitive variety to soil salinity, with no effect of soil salinity on yield up to the maximum salinity experienced in the trials in farmers' fields (season average ECe 7-8 dS m^{-1}).

During the rainy season, water depth (which reflects land elevation) is an important criterion for the selection of suitable varieties. Varieties varied in their response to water depth. Amal-Mana was consistently the best performer (3.8 to 5.0 t ha^{-1}) across all water depths experienced. The short statured Bangladeshi varieties (BRRI dhan47, BINAdhan-8) performed well at the shallowest water depth (which increased gradually from about 15 to 45 cm during the first three weeks of August), but performed poorly with deeper water. Swarna-Sub1, while also short statured, performed as well as Amal-Mana across the range of water depths in the one year that it was evaluated. The performance of several CSRC (D) lines was also encouraging across a range of water depths, although not always as good as Amal-Mana.

Acknowledgements

This paper presents findings from G2 project on "Productive, profitable, and resilient agriculture and aquaculture systems", a project of the CGIAR Challenge Program on Water and Food.

References

Burman, D., Mahanta, K.K., Sarangi, S.K., Mandal, Subhasis, Maji, B., Mandal, U.K., Bandyopadhyay, B.K., Humphreys, E. and Sharma, D.K. Effect of groundwater use on groundwater salinity, piezometric level and *boro* rice yield in the Sundarbans of West Bengal. These proceedings.

Gomez, K.A., and Gomez, A.A., 1984. Statistical procedures for agricultural research. John Wiley and Sons, New York.

Gupta, P.K., 2006. *Soil, plant, water and fertilizer analysis*. Jodhpur: Agrobios (India), Jodhpur.

Hanway, J.J., and H. Heidel. 1952. Soil analyses methods as used in Iowa State College Soil Testing Laboratory. Iowa Agric. 57:1-31.

Hossain, M., 2003. Development of boro rice cultivation in Bangladesh: Trends and policies.In: Boro Rice. R.K. Singh, M. Hossain and R. Thakur editors, IRRI-India Office, New Delhi, 25-42.

Howell, D.C., 2013. Statistical methods for pshychology. Wadsworth, Cengage Learning, Belmont, USA.

ICAR-CSSRI, IRRI-EC-IFAD, 2014. Final report of IRRI-EC-IFAD project on improved rice crop management for raising productivity in submergence-prone and salt-affected rainfed lowlands in South Asia. B. Maji, Sukanta K. Sarangi, D. K. Sharma and Sudhanshu Singh editors, ICAR-Central Soil Salinity Research Institute (ICAR-CSSRI), Regional Research Station (RRS), Canning Town – 743 329, South 24 Parganas, West Bengal, India. 72 p.

Ismail, A.M., Singh, U.S., Singh, S., Dar, M.H.,Mackill, D.J., 2013. The contribution of submergence-tolerant (Sub 1) rice varieties to food security in flood-prone rainfed lowland areas in Asia.Field Crops Res.152, 83-93 http://dx.doi.org/10.1016.j.fcr.2013.01.007.

Mondal, M.K., Saha, N.K., Ritu, S.P., Paul, P.L.C, Sharifullah, A.K.M., Humphreys, E., Tuong, T.P. and Rashid, M.A. 2015. Optimum sowing window for *boro* cultivation in the coastal zone of Bangladesh. These proceedings.

Olsen, S.R., C.V. Cole, F.S. Watanabe,and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939:1-19, Gov. Printingoffice Washington D.C.

Sarangi, S.K, Burman, D., Mandal, S., Maji, B., Tuong, T.P, Humphreys, E., Bandyopadhyay, B.K. and Sharma, D.K. 2015a.Reducing irrigation water requirement of dry season rice (*boro*) in coastal areas using timely seeding and short duration varieties. These proceedings.

Sarangi, S.K., Maji, B., Singh, S., Burman, D., Mandal, S., Sharma, D.K., Singh, U.S., Ismail, A.M., Haefele, S.M. 2015b. Improved nursery management further enhances the productivity of stress-tolerant rice varieties in coastal rainfed lowlands. Field Crops Res. 174, 61-70. http://dx.doi.org/10.1016/j.fcr.2015.01.011

Sarangi, S. K., Maji, B., Singh, S., Sharma, D.K., Burman, D., Mandal, S., Ismail, A.M., Haefele, S.M., 2014. Crop establishment and nutrient management for dry season (boro) rice in coastal areas. Agronomy Journal 106(6), 2013-2023. DOI: 10.2134/agronj14.0182.

Singh, S., Mackill, D.J., Ismail, A.M., 2009. Response of *SUB1* rice introgression lines to submergence in the field: Yield and grain quality. Field Crops Res. 113, 12-23. DOI: 10.1016/j.fcr.2009.04.003.

Subbaiah, G.V., Asija, G.L., 1956. A rapid procedure for the determination of available nitrogen in soils. Current Science 25: 259-260.

Walkley, A.J., and I.A. Black. 1934. Estimation of soil organic carbon by the chromic acid titration method. Soil Science 37:29-38.doi: 10.1097/00010694-193401000-00003.

Yadav, J.S.P., Bandyopadhyay, A.K., Bandyopadhyay, B.K., 1983. Extent of coastal saline soils in India. *Journal of the Indian Society of Coastal Agricultural Research* 1: 1-6.

Performance of improved *aman* rice varieties in the coastal zone of Bangladesh

M.R.A. Sarker[1], M.A. Rahman[1, 2], N. Sharma[1], M.R. Islam[2], M.K. Mondal[2], G.B. Gregorio[2], E. Humphreys[2] and T.P. Tuong[2]

[1]Bangladesh Rice Research Institute, Bangladesh, mrasbrri@yahoo.com, akhlas08@gmail.com, nirmal_brri@yahoo.com

[2]International Rice Research Institute, Bangladesh and Philippines, akhlasur.rahman@irri.org, m.mondal@irri.org, mr.islam@irri.org, g.gregorio@irri.org, e.humphreys@irri.org, t.tuong@irri.org

Abstract

Varying levels of salinity and water stagnation affect about 1 Mha of cultivable lands in coastal areas of Bangladesh. Most farmers grow traditional photoperiod sensitive, tall *aman* varieties that are well adapted to water stagnation but with low yield potential and long duration, resulting in late *rabi* crop establishment and precluding the ability to diversify to high yielding and/or high value *rabi* crops. Over the past decade, high yielding varieties of *aman* rice with tolerance to salinity, submergence and water stagnation, and with mild to no photoperiod sensitivity, have been developed. Therefore we sought to identify improved *aman* varieties suited to the coastal zone and their optimum sowing dates. Twelve rice varieties were tested in the *aman* season at low (polder 43/2F) and medium (polder 30) salinity locations in farmers' fields over three consecutive years and three seeding dates (24 June, 15 July, 6 August). Water depth across sites and seasons ranged from 0 (soil saturation) to 50 cm and salinity ranged from 0.2 to 2 dS/m.

At the low salinity site, the optimum seeding date for most varieties was late June to mid-July, and yield declined with a delay in sowing to early August. With sowing at the optimum time, BRRI dhan52 and BR11-Saltol (5.3-6.0 t/ha) were the most consistent and highest yielding varieties, followed by BRRI dhan51 (4.8 to 5.4 t/ha). The highest yielding varieties had duration of 130-146 d for the late June and mid-July sowings, meaning that they would reach maturity in mid- to late November. Given that the optimum sowing date for *boro* crops in the region is mid-November to mid-December the highest yielding varieties would be suitable for use in high yielding *aman-boro* cropping systems. However, their maturity is too late for *aman-rabi* systems in which the *rabi* crops should be sown in early December for maximum yield. The highest yielding *aman* varieties with short enough maturity for a high yielding *aman-rabi* system were BRRI dhan53 (~123 d, 4.7-5.1 t/ha) and BRRI dhan33 (110-120 d, 4.2-4.7 t/ha) for sowings on 24 June and 15 July.

At the medium salinity site there was little effect of sowing date on yield, in contrast with the low salinity site. The most consistent higher yielding varieties across years and sowing dates were BR11-Saltol (4.3-5.8 t/ha), BRRI dhan54 (4.1-5.8 t/ha) and BRRI dhan52 (4.1-6.0 t/ha). The durations of BR11-Saltol and BRRI dhan52 were suitable for intensification to *aman-boro*. BR11-Saltol and BRRI dhan52 would also be suitable for *aman-rabi* systems provided that the *aman* crops were sown early (late June). Yields of the shorter duration varieties most suited to *aman-rabi* systems (BBRI dhan53 and 57 and BINAdhan-8) were more variable across years and sowing dates, with yields ranging from 3.1 to 6.3 t/ha.

For the 24 June and 15 July sowing dates, yields were generally lower at the medium salinity site than at the low salinity site. This was particularly so for the long duration varieties (BR23 and BRRI dhan41), with yields in polder 30 at 73-80% of those in polder 43/2F. Yield of BINAdhan-8, a salt tolerant variety, was similar at both sites for 24 June sowings (4.6-4.7 t/ha) and 15 July sowings (4.7-5.0 t/ha). However, the other salt tolerant varieties generally performed better at the low salinity site than at the high salinity site.

The results demonstrate the great potential for increasing rice production in the coastal zone in the *aman* season by adoption of improved varieties. However, their earlier maturity meant that the crops were vulnerable to attack by rats and birds as the surrounding crops matured much later. Thus the adoption of improved varieties requires a synchronized community approach.

Key message: BRRI dhan44, BRRI dhan52, BRRI dhan53, BRRI dhan54, BR11-Saltol are the most suitable *aman* varieties in low and medium salinity areas of the coastal zone, and produced at least 50% higher yield than the popular local varieties when sown in mid-July.

Keywords: salinity, polder, synchronized community based approach

1. Introduction

The cultivation of tall (>130 cm), traditional, photoperiod sensitive and late maturing varieties is one of the major constraints to cropping intensification and diversification in low and medium salinity areas of the coastal zone of Bangladesh. These varieties are adapted to the hydrological conditions in the region during the rainy season when water stagnation of 20-60 cm prevails over much of the cultivable land area. The long duration and photoperiod sensitivity of traditional varieties means that they are generally unsuitable for cropping system intensification. While there has been great progress in the development of modern high yielding varieties of rice (HYV) with earlier maturity, many of the earlier HYV were not suitable for large parts of the coastal zone because of their short stature and thus poor performance as a result of submergence after transplanting and water stagnation, and because of high salinity in some areas.

Environmental conditions vary greatly over small distances in the coastal zone, in particular the incidence and severity of water stagnation and salinity. Furthermore, the preferred grain type varies with location. However, moderately salt tolerant (EC = 8 dS m^{-1}) rice varieties (BR23, BRRI dhan40, BRRI dhan41) have limited adaptability in the coastal zone due to short seedling height and sensitivity to prolonged water stagnation (Salam et al. 2010; Rahman et al. 2013). While drainage of water from the fields following excessive rains is possible by systematically opening the sluice gates at low tide (Mondal et al. 2015) the community coordination and infrastructure improvements required to reduce submergence and water stagnation across the coastal zone are not yet in place. Tolerance to water stagnation and submergence would thus be highly desirable to enable adoption of HYV, and also to reduce the drainage requirement and thus the investment in infrastructure and management.

Improved rice varieties have recently been developed which are able to give high yield under conditions of moderate water stagnation and/or low to medium soil salinity. Some of these varieties have little or no photoperiod sensitivity, and some are short or medium duration, and thus more suited to cropping system intensification. Moreover, potential yield of these varieties is roughly double that of traditional varieties. Therefore, experiments were undertaken to evaluate improved *aman* varieties to identify those most suited to the coastal zone and their optimum sowing dates to increase cropping intensity and diversity.

2. Methods

2.1 Site description

Replicated variety evaluation trials were conducted in farmers' fields at two sites in low and medium salinity regions of the coastal zone during three *aman* seasons (2011-2013). The low salinity site was located at Bazarkhali village in polder 43/2F, and the medium salinity site was at Hatbati in 2011, but was shifted to Kismat Fultola village (2012, 2013) in polder 30 due to uncontrolled flooding at Hatbati from an open flushing gate. All sites were located adjacent to a *khal.*

Bazarkhali is located in Amtali *Upazila* in Barguna District, near the Dalachara River, which has low salinity (EC <1 dS/m) throughout the year (Khan and Kamal 2015). Soil salinity (saturation extract, ECe) in Amtali *Upazila* varies from 2 to 8 dS/m (SRDI 1998). The major cropping patterns in Amtali *Upazila* are transplanted *aman*-fallow-transplanted *aus* and transplanted *aman*-grass pea-fallow. The *aman* crops are grown using tall, photoperiod sensitive local varieties.

Kismat Fultola and Hatbati are located in Batiaghata *Upazila* of Khulna District, beside the Kazibacha River. Soil salinity in Batiaghata *Upazila* varies from 3 to 12 dS/m and the river water salinity of Kazibacha River increases as the dry season progresses to a peak value of about 20 dS/m in June (Mondal et al. 2006). The river becomes too saline for irrigation (>4 dS/m) in early to mid-February. The major cropping pattern in Batiaghata is transplanted a*man*-fallow-sesame using local varieties of both crops.

2.2 Experimental design

Ten to eleven modern HYV and advanced lines were evaluated and compared with the popular local variety at each site (Table 1) for three sowing dates. The trial for each sowing date was in a separate block. There were three replicates in a randomized complete block design within each sowing date. Individual plot size was 25 m^2 in the first replicate and 12.5 m^2 in the second and third replicates.

2.2.1 Variety

Several HYV were in common to both sites, however some varieties were selected based on preferred grain type (bolder grain types preferred in Amtali, more slender types in Batiaghata). There was greater inclusion of salt tolerant varieties at Batiaghata where soil salinity is higher. The local check was Morichsail at Hatbati, Kumri at Kismat Fultola and Sadamota at Bazarkhali.

Table 1. Characteristics of *aman* genotypes used in the experiments (BRRI, 2013)

Genotype	Years evaluated in each polder		Varietal Characteristics					
	43/2F	30	Duration (days)	Plant height (cm)	Yield (t/ha)	Photo-period sensitivity	Stress tolerances	Grain type
BR23	2012-2013	2011-2013	150 (L)	120	5.5	Sensitive	Salinity slender	Medium
BRRI dhan30	2011		145 (L)	120	5.0	Weakly sensitive	-	Medium Bold
BRRI dhan33	2011-2013		118 (S)	100	4.5	Non-sensitive	-	Bold
BRRI dhan39	2011		122 (S)	106	4.5	Non-sensitive	-	Medium slender
BRRI dhan40	2011		145 (L)	110	4.5	Sensitive	Salinity	Medium bold
BRRI dhan41	2011-2013	2011-2013	148 (L)	115	4.5	Sensitive	Salinity	Long bold
BRRI dhan44	2011-2013	2011-2013	145 (L)	130	5.5	Sensitive	Tidal submergence	Bold
BRRI dhan49	2011-2013	2011-2013	135 (M)	100	5.5	Non-sensitive	-	Medium slender
BRRI dhan51	2011-2013		142 (L)	90	4.5	Weakly-sensitive	Flash flood submergence	Medium slender
BRRI dhan52	2011-2013	2011-2013	145 (L)	116	5.0	Weakly sensitive	Flash flood submergence	Medium Bold
BRRI dhan53	2011-2013	2011-2013	125 (S)	105	4.5	Non-sensitive	Salinity	Slender
BRRI dhan54	2011-2013	2011-2013	135 (M)	115	4.5	Sensitive	Salinity	Slender
BRRI dhan57	2012-2013	2012-2013	105 (S)	115	4.5	Sensitive	-	Long
BINAdhan-8	2011-2013	2011-2013	150 (L)	105	6.0	Non-sensitive	Salinity	Bold
IR84649-120-8-1-B (Saltol+Sub1)		2011	145 (L)	100	4.5	Non-sensitive	Salinity and Flash flood submergence	Bold
IR84645-34-9-1-B (Saltol+Sub1)		2011	145 (L)	98	4.5	Non-sensitive	Salinity and Flash flood submergence	Medium slender
BR11-Saltol (IR89574-7)	2012-2013	2012-2013	145 (L)	115	5.5	Weakly sensitive	Salinity	Medium bold
BRRI dhan28-Saltol (IR89573-84)		2012-2013	130 (M)	90	5.5	Non-sensitive	Salinity	Medium Slender
Sadamota (Local)	2011-2013		165 (L)	150	3.5	Sensitive	Tidal submergence	Bold
Morichsail (Local)		2011	165 (L)	160	3.5	Sensitive	Tidal submergence	Bold
Kumri (Local)		2012-2013	165 (L)	160	3.5	Sensitive	Tidal submergence	Bold

2.2.2 Seeding date

There were three target seeding dates at 21 d intervals at each location (24 June, 15 July, 6 August), but this was not always possible. In 2011 flooding as a result of heavy rain destroyed the seedling nurseries for the second and third sowings at Hatbati. Flooding also destroyed the seedbed for the third sowing in 2012 at Kismat Fultola.

Table 2. Seeding and transplanting dates

Year	Actual seeding date	Transplanting date	Seedling age at transplanting
Bazarkhali			
2011	24 Jun	15 July	21
	15 Jul	4 Aug	21
	16 Aug	5 Sep	21
2012	24 Jun	15 July	21
	15 Jul	13 Aug	29
	7 Aug	28 Aug	21
2013	24 Jun	15 July	21
	15 Jul	4 Aug	21
	6 Aug	27 Aug	21
Hatbati/Kismat Fultola			
2011	1 July	26 July	25
2012	24 Jun	15 July	21
	15 Jul	6 Aug	21
2013	26 Jun	16 July	21
	14 Jul	3 Aug	21
	6 Aug	27 Aug	21

2.3 Management

Pre-germinated seeds were sown at 16-20 kg/ha on the seedbed and urea was applied at 30 kg N/ha.

Land preparation involved three to four passes (cross plowing) in wet soil using a power tiller powered by a two-wheel tractor, followed by leveling using a ladder. Before land leveling, fertilizer was broadcast at 11:42:18:3.6 kg of P:K:S:Zn per hectare in the forms of triple super phosphate, muriate of potash, gypsum, and zinc sulphate (BRRI 2013). Urea was broadcast at 70 kg N/ha in three equal installments: 7 to 10 d after transplanting (DAT), 4 to 5 tiller stage, and 5 to 7 d before panicle initiation.

Twenty-one day-old seedlings were transplanted, except for the only sowing at Hatbati in 2011, and the second sowing at Bazarkhali in 2012 (Table 2) when transplanting was delayed by 4 and 8 d, respectively, because the water was too deep on the target date. The seedlings in the nursery for the third sowing in 2012 at Bazarkhali were partly damaged due to submergence and there were only sufficient viable seedlings to transplant two replicates. Two to three seedlings per hill were transplanted with 20 cm x 15 cm geometry in all experiments.

Hand weeding was done three times, prior to each topdressing with urea. Disease and insect pests were always well controlled using recommended practices (BRRI 2013). Early maturing varieties of the first sowing were severely damaged by rats at both sites in 2011 and at Bazarkhali in 2012, after which a plastic rat barrier was installed. Bird nets were also installed over the experimental field prior to grain filling to protect the crops from bird damage. These protection measures were needed due to the earlier maturity of most of the varieties in comparison with the farmers' varieties in surrounding fields.

2.4 Monitoring

2.4.1 Crop

Growth duration was calculated as the number of days from soaking of the seeds to physiological maturity (PM). Physiological maturity was taken as the time when 80% of the grains were hard or translucent. Grain yield was determined in a 5.1 m x 2 m area in the middle of each plot, moisture content was determined using a grain moisture meter, and yield was adjusted to 14% moisture content.

2.4.2 Water depth and salinity

Water depth was measured daily at 16 staff gauges installed across the experimental field. Water salinity (electrical conductivity, EC) was measured weekly using a portable EC meter.

3. Results and discussion

3.1 Bazarkhali

3.1.1 Water depth

The water depth in the rice field varied widely within and across years (Fig. 1) depending on the rainfall and river tides and management of the sluice gate. Generally water depth varied from 1 to 20 cm, except in the first week of August 2011 (data not presented) and September 2012. In August 2011, water depth increased to 40-45 cm 2 to 3 d after transplanting of the seedlings of the second sowing. The seedlings were submerged for about 5 d and the crops in replicate 3 and in half of the plots in replicate 2 were destroyed. In September 2012, water depth increased to almost 50 cm due to very high rainfall. This occurred about a week after transplanting of the third sowing, as a result of which the seedlings were submerged or almost submerged for about one week.

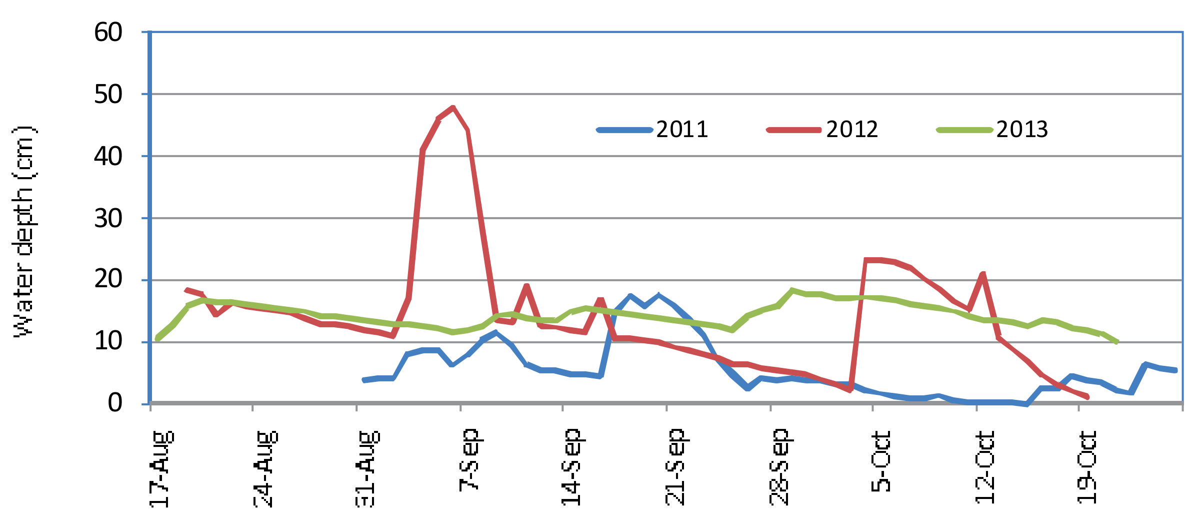


Fig. 1. Water depth in the rice field at Bazarkhali during *aman* 2011-2013.

3.1.2 Growth duration

Growth duration varied significantly among the varieties for all sowing dates each year and ranged from 98-105 d for BRRI dhan57 sown on 6 August to 161-181 d for the local variety (Sadamota) sown on 24 June (Table 3). The genotypes varied greatly in photoperiod sensitivity. Delaying sowing of Sadamota from 24 June to 6 August decreased its duration by 40-45 d, with PM of all sowing dates occurring in mid-December (Fig. 2). BR23, BRRI dhan41 and BRRI dhan54 were also highly photoperiod sensitive, with duration decreasing by

30-41 d with delay in sowing from 24 June to 6 August (when not affected by submergence). Most of the other HYV had some photoperiod sensitivity, except for BINAdhan-8 and BRRI dhan53. Submergence after transplanting of the second sowing in 2011 increased the duration of most HYV by 1-9 d, and it also increased the duration of the most photoperiod sensitive varieties in comparison with what it would have been in the absence of submergence.

Table 3. Growth duration (days) of *aman* varieties/genotypes at Bazarkhali

Variety	2011			2012			2013		
	24 Jun	15 Jul[1]	16 Aug	24-Jun	15-Jul	6-Aug	24-Jun	15-Jul	6-Aug
BR23				156	143	119	161	139	121
BRRI dhan30	137	142	124						
BRRI dhan33	117	121	111	RD[2]	110	112	121	117	101
BRRI dhan39	118	121	113						
BRRI dhan41	153	140	112	153	128	GF[3]	153	139	115
BRRI dhan44	138	142	120	138	127	125	141	139	118
BRRI dhan51	140	141	134	146	136	131	143	143	121
BRRI dhan52	135	140	126	144	129	126	141	139	118
BRRI dhan53	118	127	122	RD[2]	124	123	123	120	112
BRRI dhan54	140	135	132	142	126	112	136	125	107
BRRI dhan57				RD[2]	105	105	113	114	98
BINAdhan-8	113	118	118	RD[2]	130	126	125	122	116
BR11-Saltol				139	129	131	143	139	118
Sadamota	168	161	133	165	148	125	181	161	136
LSD (0.05)	0.9		0.3	1.7	1.5	1.8	0.3	0.3	1.3

[1] Submerged for 5 d shortly after transplanting

[2]RD=rat damage

[3]GF=Germination failure

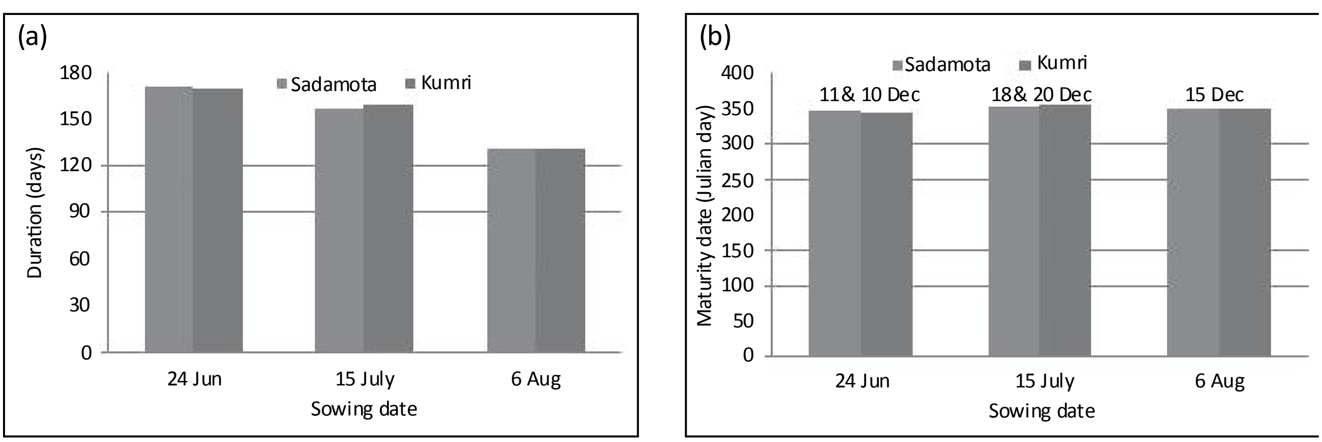


Fig. 2. Growth duration (a) and maturity date (b) of photosensitive local varieties at Bazarkhali (Sadamota) and Kismat Fultola (Kumri) as affected by seeding date.

3.1.3 Yield

There were significant differences in yield between varieties for all sowing dates in all years (Table 4). There was considerable damage of the earliest maturing varieties of the first sowing in 2011 and 2012 due to rats. In the first year, the first sowing also suffered from shading. As a result, yields of the first sowing were much lower than of the first sowing in later years. In 2011, the second sowing was completely submerged from 5-9 August, causing considerable damage. However the crops in replicate 1 and in most of the plots in replicate 2 survived and went on to yield 3.3 to 4.8 t/ha. The best performers were BRRI dhan44, which is tolerant to tidal submergence, and BRRI dhan51 and 52, which have the Sub-1 gene and are tolerant to flash flooding for up to two weeks after transplanting. Yield of the local variety was consistently lower than yield of the HYVs, except for similar yield with BRRI dhan33 and 57 (both short duration, 110 and 105 d) in the second sowing in 2012. In 2012 and 2013, yield of Sadamota was 73, 74 and 79% of the yield of the mean of all the HYV for the 24 June, 15 July and 6 August sowings.

The data from 2012 and 2013 were used to analyze the effect of sowing date. Yield of the third sowing was consistently lower than yield of the first two sowings (Fig. 3). The effect was least with the shortest duration varieties (BRRI dhan33 and 57). There was a general trend for slightly higher yield of the second sowing than the first sowing. Mean yield of the HYV for the 24 June, 15 July and 6 August sowings was 4.8, 5.1 and 3.9 t/ha, respectively. In comparison, mean yield of Sadamota was 3.5, 3.8 and 3.1 t/ha.

Table 4. Yield performance of *aman* varieties/genotypes at Bazarkhali

Genotype	2011			2012			2013		
	24-Jun	15-Jul[1]	16-Aug	24-Jun	15-Jul	6-Aug	24-Jun	15-Jul	6-Aug
BR23				5.1	5.5	3.7	4.1	4.6	4.9
BRRI dhan30	3.7	3.4	3.0						
BRRI dhan33	RD[2]	3.9	3.5	RD[2]	4.2	3.9	4.6	4.7	4.5
BRRI dhan39	3.2	3.8	3.5						
BRRI dhan41	2.8	3.3	3.3	5.5	5.3	GF[3]	3.9	5.2	3.7
BRRI dhan44	2.9	4.8	3.2	5.4	5.0	3.5	4.2	5.1	4.1
BRRI dhan51	4.3	4.1	2.3	4.8	5.3	3.6	4.9	5.4	4.2
BRRI dhan52	2.6	4.4	3.4	5.6	5.3	3.3	5.8	6.0	4.9
BRRI dhan53	RD[2]	3.9	3.2	RD[2]	4.7	4.0	5.0	5.1	4.3
BRRI dhan54	3.7	4.2	3.4	5.1	5.6	4.0	4.6	5.4	3.9
BRRI dhan57				RD[2]	4.2	2.8	3.4	4.2	3.3
BINAdhan-8	RD[2]	3.9	3.2	RD[2]	4.8	3.9	4.6	4.5	3.8
BR11-Saltol				5.5	5.8	3.4	5.3	6.0	4.4
Sadamota (L.)	1.5	2.4	1.8	3.5	4.2	2.5	3.5	3.3	3.7
LSD (0.05)	1.0		0.5	0.9	0.6	0.8	0.7	0.7	0.3

[1] Submerged for 5 d shortly after transplanting, results are for one or two plots only

[2]RD=rat damage

[3]GF=Germination failure

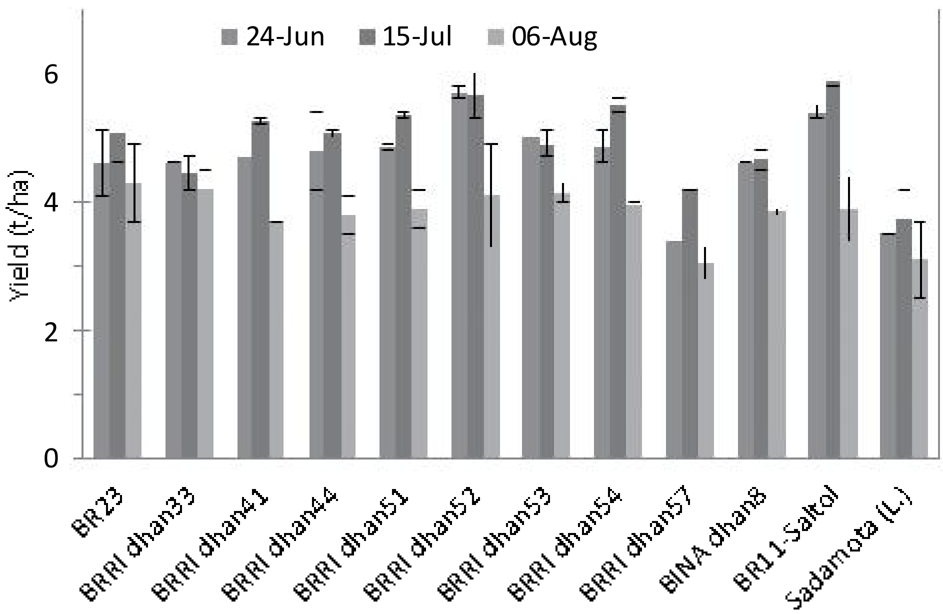


Fig. 3. Effect of sowing date on yield of *aman* genotypes at Bazarkhali (average of 2012 and 2013). Vertical capped bars are SE.

The results suggest that late June to early July is the optimum sowing window for both HYV and Sadamota at Bazarkhali. With sowing at this time, BRRI dhan52 and BR11-Saltol (5.3-6.0 t/ha) were the most consistent and highest yielding varieties, followed by BRRI dhan51 (4.8 to 5.4 t/ha). BRRI dhan41, 44 and 54 also had yields exceeding 5 t/ha for the first two sowing dates in 2012, and the second sowing date in 2013, while BRRI dhan53 yielded 4.7-5.1 t/ha. The highest yielding varieties had a duration of around 140 to 150 d for the first sowing, meaning that they would reach maturity in mid- to late November. Given that the optimum sowing date for *boro* crops in the region is mid-November to mid-December (Mondal et al. 2015), the highest yielding varieties would be suitable for use in an *aman-boro* cropping system. However, their maturity is too late for *aman-rabi* systems with high yielding varieties such as maize and sunflower, which need to be sown in early December for maximum yield (Bhattacharya et al. 2015; Rashid et al. 2015) and the soil needs to be drained in early to mid-November to enable it to dry sufficiently for tillage or dibbling. The highest yielding *aman* varieties with short enough maturity for a high yielding *aman-rabi* system were BRRI dhan53 (~123 d, 4.7-5.1 t/ha) and BRRI dhan33 (110-120 d, 4.2-4.7 t/ha) for sowings on 24 June and 15 July.

3.2 Hatbati/Kismat Fultola

3.2.1 Water depth

Water depth generally ranged from 0 to 20 cm each year (Fig. 4). In 2011, the 1 July sown crop was almost submerged for about 10 d about two weeks after transplanting, and the crop also experienced water stagnation during the grain filling period due to an uncontrolled flushing gate higher in the landscape, allowing tidal water to enter.

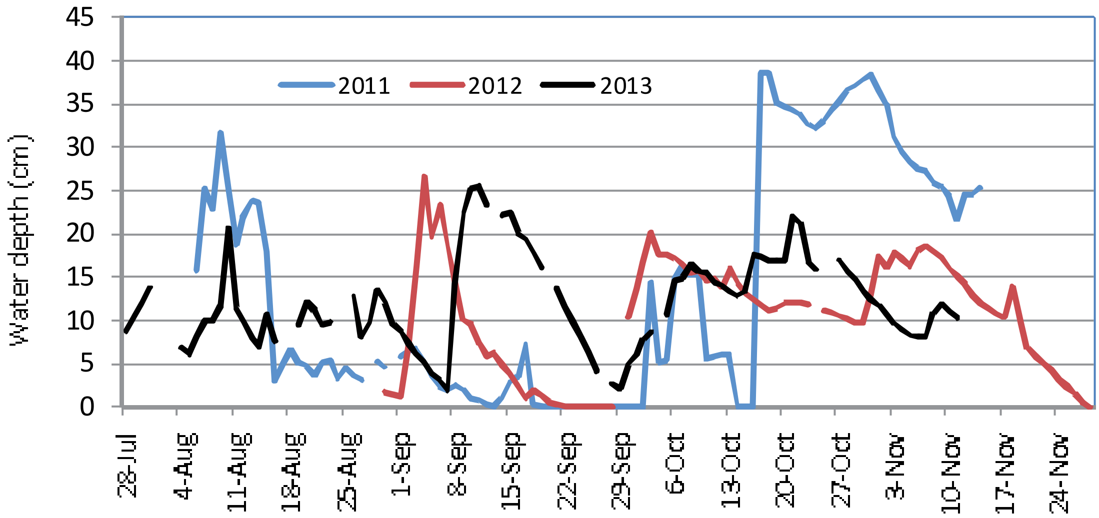


Fig. 4. Water depth in the rice field at Hatbati/Kismatfultola during *aman* 2011-2013.

3.2.2 Growth duration

Growth duration of the genotypes varied significantly for all sowing dates in all years, from 91 d for BRRI dhan57 sown on 6 August 2013 to 172 d for the local variety Kumri sown on 24 June 2012 (Table 5). Growth duration of all varieties was higher in 2011 due to prolonged water stagnation (Fig. 4) and this effect was more pronounced in the shorter duration varieties (BRRI dhan53, BINAdhan-8). As at Bazarkhali, there was a consistent trend for decline in duration with delay in sowing, with the highest photoperiod sensitivity in BR23, BRRI dhan41 and 54, and the local variety (Kumri). BR11-Saltol and BRRI dhan53 showed no and little photoperiod sensitivity, respectively, and BINAdhan-8 showed no photoperiod sensitivity in 2013.

Table 5. Growth duration* (days) of *aman* genotypes at Hatbati (2011) and Kismat Fultola (2012-13)

Genotype	2011	2012		2013		
	1-Jul	24-Jun	15-Jul	24-Jun	15-Jul	6-Aug
BR23	169	161	143	166	152	129
BRRI dhan41	154	149	138	155	143	121
BRRI dhan44	140	130	130	148	132	122
BRRI dhan49	140	132	131	134	122	114
BRRI dhan52	140	134	120	133	129	111
BRRI dhan53	158	120	115	112	111	106
BRRI dhan54	154	133	131	148	134	113
BRRI dhan57		108	102	107	102	91
BINA dhan-8	158	131	122	113	115	112
BR11-Saltol		131	135	134	125	121
BRRI dhan28-Saltol		117	115	107	101	93
IR84649-120-8-1-B (Saltol+Sub1)	158					
IR84645-34-9-1-B (Saltol+Sub1)	158					
Morichsail (L.)	169					
Kumri (L.)		172	166	168	155	131
LSD (0.05)	1	2	2	1.3	0.3	1

* Only one sowing in 2011 and third sowing in 2012 damaged by rainfall on seedbed

3.2.3 Yield

There were significant differences in yield between varieties for all sowing dates in all years. In 2011 rats damaged the early maturing varieties. Yields in excess of 4 t/ha were achieved by BR23 and BRRI dhan41 and 52 despite the prolonged water stagnation, while the local variety (Morischsail) only yielded 2.7 t/ha (Table 6). In 2012 and 2013, yields of the HYV ranged from 2.8 to 6.3 t/ha across years and sowing dates, while yield of the local variety (Kumri) ranged from 2.4 to 3.8 t/ha. Yield was generally unaffected by or increased with delay in sowing (Fig. 5), despite the general decrease in crop duration with delay in sowing at both sites. The effect of sowing date on yield was in contrast with the decline in yield of the last sowing at Bazarkhali. At Kismat Fultola, mean yield of the HYV was 4.4, 4.4 and 4.9 t/ha for sowings on 24 June, 15 July and 6 August, respectively, compared with 3.1, 3.1 and 2.8 t/ha, respectively, for the local variety. Yields of the 24 June and 15 July sowings were usually much lower in 2012 than 2013 (the exceptions being both sowings of BR23, and the 15 July sowing of BRRI dhan52 and 53 and BR11-Saltol). The most consistent higher yielding varieties over these two years across all sowing dates were BR11-Saltol (4.3-5.8 t/ha), BRRI dhan54 (4.1-5.8 t/ha) and BRRI dhan52 (4.1-6.0 t/ha). The durations of BR11-Saltol and BRRI dhan52 were suitable for intensification to *aman-boro*, given that the optimum sowing date for *boro* in this region is early November (Mondal et al. 2015). BR11-Saltol and BRRI dhan52 would also be suitable for *aman-rabi* systems provided that the *aman* crops were sown in late June. Yields of the shorter duration varieties most suited to *aman-rabi* systems (BBRI dhan53 and 57 and BINAdhan-8) were more variable across years and sowing dates, with yields ranging from 3.1 to 6.3 t/ha.

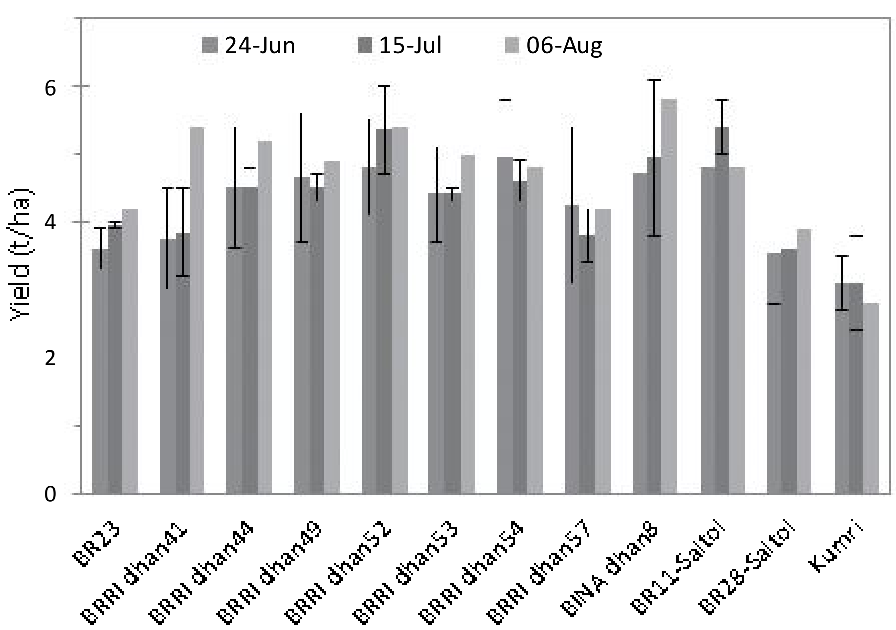


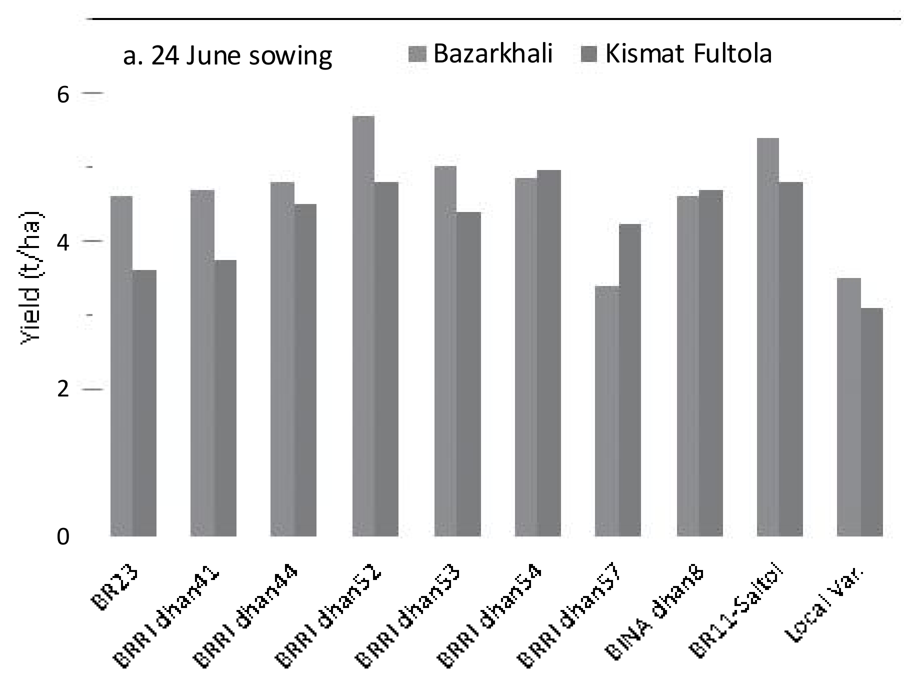
Fig. 5. Effect of sowing date on yield of *aman* genotypes at Kismat Fultola (average of 2012 and 2013). Vertical capped bars are SE.

Table 6. Yield of *aman* genotypes at Hatbati (2011) and Kismat Fultola (2012-13)

Genotype	2011	2012		2013		
	1-Jul	24-Jun	15-Jul	24-Jun	15-Jul	6-Aug
BR23	4.1	3.9	3.9	3.3	4.0	4.2
BRRI dhan41	4.1	3.0	3.2	4.5	4.5	5.4
BRRI dhan44	3.2	3.6	4.2	5.4	4.8	5.2
BRRI dhan49	3.3	3.7	4.3	5.6	4.7	4.9
BRRI dhan52	4.2	4.1	6.0	5.5	4.7	5.4
BRRI dhan53	RD[1]	3.7	4.3	5.1	4.5	5.0
BRRI dhan54	3.6	4.1	4.3	5.8	4.9	4.8
BRRI dhan57		3.1	3.4	5.4	4.2	4.2
BINA dhan-8	RD[1]	3.1	3.8	6.3	6.1	5.8
BR11-Saltol		4.3	5.8	5.3	5.0	4.8
BRRI dhan28-Saltol		2.8	2.9	4.3	4.3	3.9
IR84649-120-8-1-B (Saltol-Sub1)	RD[1]					
IR84645-34-9-1-B (Saltol+Sub1)	RD[1]					
Morichsail (L.)	2.7					
Kumri (L.)		3.5	2.4	2.7	3.8	2.8
LSD (0.05)	0.6	0.6	0.9	1.0	1.2	0.7

[1] RD=rat damage

For the 24 June and 15 July sowing dates, yields were generally lower at Kismat Fultola than at Bazarkhali, within variety (Figs 6a,b). This was particularly so for the long duration varieties (BR23 and BRRI dhan41), with yields (average of 2012 and 2013 within sowing date) at Kismat Fultola of 73-80% of those at Bazarkhali. Yield of BINAdhan-8, a salt tolerant variety, was similar at both sites for 24 June sowings (4.6-4.7 t/ha) and 15 July sowings (4.7-5.0 t/ha). However, the other salt tolerant varieties generally performed better at Bazarkhali than at Kismat Fultola. This suggests that factors other than salinity were the main cause of the poorer crop performance at Kismat Fultola.



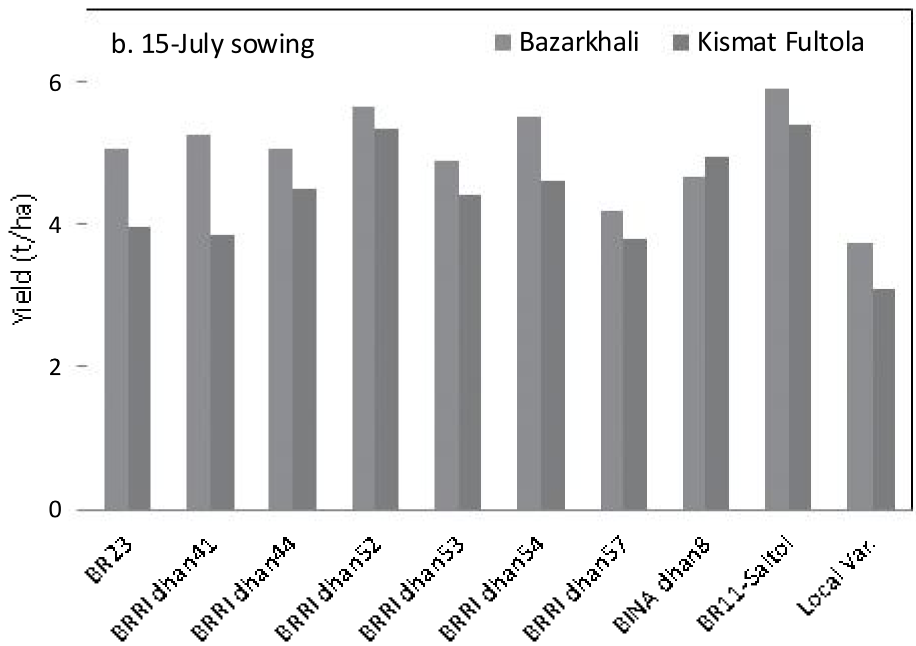


Fig. 6. Comparison of yield of *aman* genotypes at Bazarkhali and Kismat Fultola for sowing dates of 24 June (a) and 15 July (b) (average of 2012 and 2013).

4. Conclusions and recommendations

Aman variety evaluation trials conducted in low and medium salinity locations of the coastal zone show the feasibility of achieving high yields with modern high yielding varieties and with much earlier maturity than that of local varieties. In addition to higher yield (by up to two-fold), the earlier maturity of the HYV would allow for cropping intensification through timely establishment of *boro* or high yielding *rabi* crops. However, earlier maturing crops were vulnerable to attack by rats and birds as the surrounding farmers' crops (local varieties) matured much later. Thus, the adoption of improved varieties with earlier maturity would require a synchronized community approach.

Acknowledgements

This paper presents findings from G2 'Productive, profitable and resilient agriculture and aquaculture systems', a project of the CGIAR Challenge Program on Water and Food. We thank Atiqur Rahman, Swapan Bhadra, Amal Ray, Lincoln Ray, Tanmoy Ray and Mithun Ray for their technical assistance.

References

Bhattacharya, J., Mondal, M.K., Humphreys, E., Saha, N.K., Rashid, M.H., Paul, P.C. and Ritu, S.P. 2015. Rice-rice-*rabi* cropping systems for increasing the productivity of low salinity regions of the coastal zone of Bangladesh. These proceedings.

BRRI (Bangladesh Rice Research Institute) 2013. Adhunik Dhaner Chash (Modern Rice Cultivation). 17^{th} Edition. Gazipur-1701, Bangladesh.

Khan, Z.H. and Kamal, F.A. 2015. The Ganges coastal zone – current conditions, future projections. These proceedings.

Mondal, M. K., T. P. Tuong, S. P. Ritu, M. H. K. Choudhury, A. M. Chasi, P. K. Majumder, M. M. Islam and S. K. Adhikary 2006. Coastal water resource use for higher productivity: Participatory research for increasing cropping intensity in Bangladesh. In C. T. Hoanh, T. P. Tuong, J. W. Gowing and B. Hardy (Eds). Environmental and livelihoods in tropical coastal zones: Managing agriculture-fishery-aquaculture conflicts. Comprehensive Assessment of Water Management in Agriculture Series, no. 2. CABI Publishing p 72-85.

Mondal, M.K., Saha, N.K., Ritu, S.P., Paul, P.L.C, Sharifullah, A.K.M., Humphreys, E., Tuong, T.P. and Rashid, M.A. 2015. Optimum sowing window for *boro* cultivation in the coastal zone of Bangladesh. These proceedings.

Rahman, M. A., M. R. A. Sarker, N. Sharma, M. R. Islam, G. B. Gregorio and E. Humphreys. 2013. Turning adversity into opportunity. *CURE Matters* 3(1): page 16.

Rashid, M.H., Hossain, F., Nath, D.K., Sarker, P.C., Ferdous, A.K. M. and Russel, T. 2015. Oil seed crops in rice based cropping systems in southern Bangladesh. These proceedings.

Salam, M.A., M.R. Islam, M.S. Rahman, M.A. Rahman, M.A.R. Bhuiyan, Z.I. Seraj, T.L. Aditya, M.K. Uddin, M.K. Mondal, A.M. Ismail, D.L. Adorada, R.D. Mendoza, E. Tumimbang-Raiz and G.B. Gregorio. 2010. Rice varieties and cultural management practices for high and sustained productivity in the coastal wetlands of Southern Bangladesh. In: Tropical Deltas and Coastal Zones: Food production, Communities and Environment at the Land-Water Interface. CABI Publisher, Uk. Pp 183-198.

SRDI (Soil Resources Development Institute). 1998. Land and soil resources use guidelines of Amtali upazila, Barguna.

Challenges and opportunities for *aman* rice cultivation in *ghers* used for brackish water shrimp production

M. A. Rahman[1,2], M. R. A. Sarker[2], N. Sharma[2], M. K. Mondal[3], M. R. Islam[1], G. B. Gregorio[1], E. Humphreys[1] and T. P. Tuong[1]

[1]International Rice Research Institute, Philippines, akhlasur.rahman@irri.org, m.mondal@irri.org, mr.islam@irri.org, g.gregorio@irri.org, e.humphreys@irri.org, t.tuong@irri.org
[2]Bangladesh Rice Research Institute, Bangladesh, akhlas08@gmail.com, mrasbrri@yahoo.com, nirmal_brri@yahoo.com

Abstract

Brackish water shrimp production in *ghers* is a major source of livelihoods for many farming families in the more saline areas of the southwest coastal zone of Bangladesh. In some regions, farmers continue to grow *aman* rice during the rainy season after shrimp harvest. However, the productivity of rice in shrimp *ghers* is often hampered by salinity, submergence, and water stagnation as a result of high rainfall and lack of drainage. Therefore, experiments were conducted to evaluate the performance of modern, high yielding varieties with good tolerance to salinity and submergence in farmers' *ghers* from 2011 to 2013. The results showed that with current water management production of *aman* in shrimp *ghers* is highly risky, but that the risk can be reduced to some degree by the use of stress tolerant varieties. The best performing varieties were those with salinity tolerance (BRRI dhan47, 53, 54) or submergence tolerance (BRRI dhan52). With good water (drainage) management, yields of around 4 t/ha were achieved.

Key message: Improved drainage management is essential for stable and high productivity of *aman* rice in shrimp *ghers*.

Keywords: drainage, leaching, salinity, water stagnation, submergence, stress tolerance

1. Introduction

The traditional cropping system throughout the southwest coastal zone of Bangladesh was a single rice crop during the rainy season. However, in 1980, the introduction of brackish water shrimp farming in the more saline parts of the coastal zone changed not only cropping patterns, but also landholding sizes and land tenure systems (Barmon et al. 2004). The shrimp are cultivated in *ghers,* which are basically land surround by large levees to pond water for aquaculture. *Ghers* in the southwest coastal zone are typically 0.25 to 1 ha, but there are some very large *ghers*, up to several thousand hectares in size. Following the introduction of shrimp farming, cultivation of *aman* rice ceased in large areas, however, there are still significant areas where farmers prefer to grow *aman* rice in rotation with brackish water shrimp. The productivity of rice in *ghers* used for shrimp culture is often hampered by salinity, submergence and water stagnation as a result of high rainfall and lack of drainage. In addition, terminal drought stress and/or terminal salinity after the rains have ended is sometimes problematic for late maturing varieties such as BR23. Therefore, many *ghers* are fallowed during the rainy season. The high yielding BRRI variety BR23 is usually the preferred variety in the *ghers* of the southwest coastal zone. While BR23 has good yield potential (5.5 t/ha under favorable conditions), it is photoperiod sensitive and has a long duration (about 150 d) when sown at the optimum time. Also, BR23 has only moderate salinity tolerance and is sensitive to submergence.

The use of recently developed non-photoperiod sensitive high yielding varieties with tolerance to salinity at 8-10 dS/m (such as BR11-Saltol, BR28-Saltol, BRRI dhan47, BRRI dhan53 and BINAdhan-8) and with flash flood submergence tolerance (such as BRRI dhan52) (BRRI 2013) may provide an opportunity to increase the productivity of *aman* crops grown in rotation with brackish water shrimp in *ghers*. Therefore, experiments were undertaken to evaluate the performance of *aman* varieties with improved stress tolerance in farmers' *ghers* in the southwest coastal zone of Bangladesh.

2. Methods

2.1 Sites

Evaluations of high yielding *aman* varieties and advanced lines were conducted in farmers' *ghers* during the rainy seasons of 2011, 2012 and 2013. All *ghers* had a history of brackish water shrimp during the dry season and rice during the rainy season, but in some years rice was not grown due to the late onset of the monsoon and thus insufficient leaching of the *ghers*. All sites were in polder 3 at Sehara village in Kaliganj *Upazila*, Satkhira District. Different *ghers* owned and managed by different farmers were used each year.

2.2 Experimental design

All experiments involved evaluation of 10 or 11 released Bangladeshi varieties and usually one advanced line in farmers' *ghers*. There were three replicates in a randomized complete block design. Plot size in replicate 1 (25 m^2) was larger than in the other replicates, as these plots were also used for farmer participatory varietal evaluation. Plot size in replicates 2 and 3 was 12.5 m^2. Each year, there were two or three seeding/transplanting dates. In 2011, the experiments were repeated in two *ghers* owned by different farmers.

2.2.1 Varieties

The varieties were selected for evaluation each year based on tolerance to salinity, water stagnation and submergence in comparison with BR23, which is commonly grown in the region (Table 1).

Table 1. Characteristics of *aman* varieties and lines evaluated in *ghers* in Sehara, Polder 3, Kaliganj, Satkhira in 2011-2013

Genotype	Year	Varietal Characteristics					
		Plant height (cm)	Duration (days)[1]	Yield [2] (t/ha)	Photo-period sensitivity	Stress tolerances	Grain type
BR23	2011-2013	120	150 (L)	5.5	Sensitive	-	Medium slender
BRRI dhan40	2011	110	145 (L)	4.5	Sensitive	Salinity	Medium bold
BRRI dhan41	2011-2013	115	148 (L)	4.5	Sensitive	Salinity	Long bold
BRRI dhan44	2011-2013	130	145 (L)	5.5	Sensitive	Tidal submergence	Bold
BRRI dhan47	2011-2013	105	152 (L)	6.0	Non-sensitive	Salinity	Bold
BRRI dhan52							
(BR11-Sub1)	2011-2013	116	145 (L)	5.5	Moderately sensitive	Flash flood submergence	Medium bold
BRRI dhan53	2011-2013	105	125 (S)	4.5	Non-sensitive	Salinity	Slender
BRRI dhan54	2011-2013	115	135 (M)	4.5	Sensitive	Salinity and water stagnation	Long
BRRI dhan57	2012-2013	115	105 (S)	4.5	Sensitive	-	Long
BINA dhan8	2011-2013	105	155 (L)	6.0	Non-sensitive	Salinity	Medium bold
BR11-Saltol	2012-2013	115	145 (L)	5.5	Non-sensitive	Salinity	Medium bold
BR28-Saltol	2012-2013	90	130 (M)	5.5	Non-sensitive	Salinity	Medium slender
BR8371-4R-2	2012	115	145 (M)	5.5	Non-sensitive	Salinity	Long
IR8465-311-5-1-1-3	2011	105	135 (M)	4.5	Non-sensitive	Salinity	Bold

[1]L = long, M = medium, S= short duration;

[2]Under favorable conditions

2.2.2 Seeding and transplanting date

Two seeding/transplanting dates ("sets") were implemented in 2011, and three in 2012 and 2013 (Table 2). The original intention was to transplant 21 d-old seedlings, however, transplanting was always delayed because the water was too deep as a result of rainfall and inability to drain (the surrounding area was also flooded). The age of seedlings at the time of transplanting ranged from 26 to 64 d.

Table 2. Dates of seeding and transplanting of rice in the *ghers*

	Seeding date	Transplanting date	Seedling age (days)
2011	15 Jul	20 Aug	36
	30 Jul	25 Aug	26
2012	1 Jul	3 Sep	64
	16 Jul	3 Sep	49
	31 Jul	16 Sep	47
2013	1 Jul	19 Aug	49
	15 Jul	9 Sep	56
	30 Jul	14 Sep	46

2.3 Crop management

The farmers drained water from the *ghers* in July after harvesting the shrimp and fish. A basal dose of fertilizer (BRRI recommended dose for *aman*) was applied at 11:42:18:3.6 kg of P:K:S:Zn per hectare, using triple super phosphate, muriate of potash, gypsum, and zinc sulphate. The fertilizer was broadcast on the surface of the saturated, soft soil and mixed with the soil by hand. After mixing of fertilizer to soil the plot was leveled by hand. The rice seedlings were transplanted with two to three seedlings/hill and hill spacing was 20 cm x 15 cm. Nitrogen fertilizer (75 kg N/ha) was applied as 1.8 g urea super granules 7 to 10 d after transplanting. The granules were placed at a depth of about 8-10 cm below the soil surface, midway between four hills.

2.4 Monitoring

2.4.1 Water depth and salinity

Water depth and salinity were monitored weekly in each *gher*. Water depth was monitored using a vertical gauge fixed permanently in the floor of the *gher*. Salinity was monitored using a portable electrical conductivity meter.

2.4.2 Agronomic, grain yield and yield components

At maturity, plant height from the base to the tip of the panicle (cm) was determined from ten randomly selected plants for each replication. Crop duration was determined as the number of days from sowing of the seedling nursery to maturity. Maturity was taken as the date when 80% of the grains became physiologically mature, hard and translucent. Grain yield was determined by harvesting the entire area of each plot (replication 1=25 m^2 and replications 2 and 3=12.5 m^2). The grain was weighed, grain moisture content was determined on a sub-sample by grain moisture meter and yield at 14% moisture was calculated.

2.5 Data analysis

The height and yield data were analyzed by analysis of variance using MS, and the least significant difference at 5% probability (LSD) was used to compare the means.

3. Results and discussion

3.1 2011

Water management varied between the two *ghers* – one farmer implemented good drainage management to reduce salinity of the *gher* ("medium salinity *gher*") to provide more favorable conditions for the rice, while the other farmer preferred to retain saline water for longer to try and increase shrimp yield ("high salinity *gher*"). As a result, salinity was always below 4 dS/m in one *gher*, and ranged from about 5 to 7 dS/m in the other *gher* (Fig. 1).

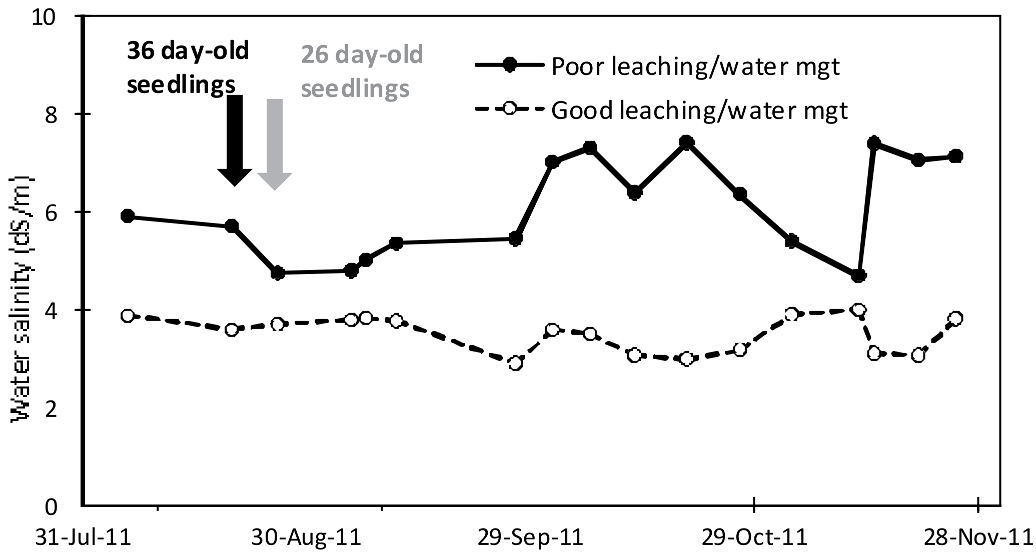


Fig. 1. Water salinity in medium (good leaching management) and high (poor leaching management) salinity *ghers* in 2011. Arrows indicate dates of transplanting.

Crop duration of the two sowing dates ranged from 114-119 d (BRRI dhan47, BINAdhan-8) and 149-154 d (BR23) in the medium salinity *gher* (Fig. 2). Duration of the second sowing was consistently a few days less than duration of the first sowing.

Plant height at maturity in the medium salinity *gher* ranged from around 90 cm for BRRI dhan47 and BINAdhan-8 to around 110 cm for BRRI dhan41, 44, 52 and 54 (Fig. 3). Plant height of the first and second sowings was similar within variety.

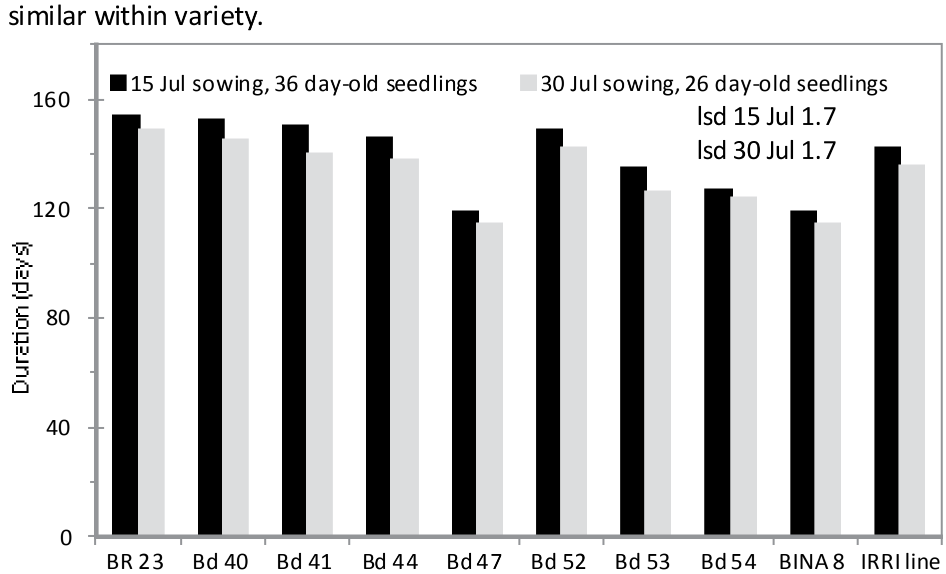


Fig. 2. Duration of *aman* varieties in the medium salinity *gher* in 2011 (Bd = BRRI dhan; BINA = BINAdhan). Lsd values are for comparing varieties within sowing date at p=0.05.

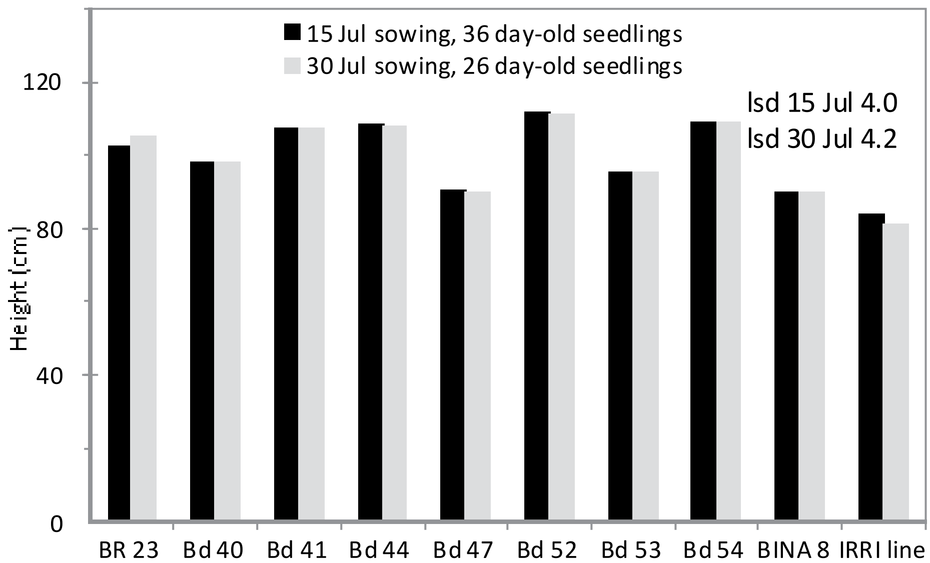


Fig. 3. Plant height at maturity of *aman* varieties in the medium salinity *gher* in 2011 (Bd = BRRI dhan; BINA = BINAdhan). Lsd values are for comparing varieties within sowing date at p=0.05.

Yields in the medium salinity *gher* were similar for the two seeding date/seedling age combinations and ranged from 2.7-4.3 t/ha (Fig. 4). The highest yielding varieties were BR23, BRRI dhan44 and BRRI dhan52, with yields consistently in the range of 3.9-4.3 t/ha. About 40% of the variation in yield was due to varietal duration (longer duration varieties tended to have higher yields). There was greater variation in yield in the more saline *gher* (Fig. 5). Especially notable was the much poorer performance of the younger seedlings (26 d old) that were transplanted just 5 d after the older seedlings (36 d old). The younger seedlings did not survive the combination of salinity (5 dS/m) and high (relative to the height of the seedlings) water depth (13 cm) at the time of transplanting and submergence for about a week in mid-September (Fig. 6) about three weeks after transplanting. Only four varieties produced any yield from the younger seedlings, the best being BINA dhan8 at almost 2 t/ha. However, with older seedlings, many of the varieties produced in excess of 3 t/ha, the best being BRRI dhan44 at 4.3 t/ha, compared with 3.4 t/ha from BR23. BRRI dhan40 (with good salt tolerance) completely failed in this situation due to the water being too deep after transplanting.

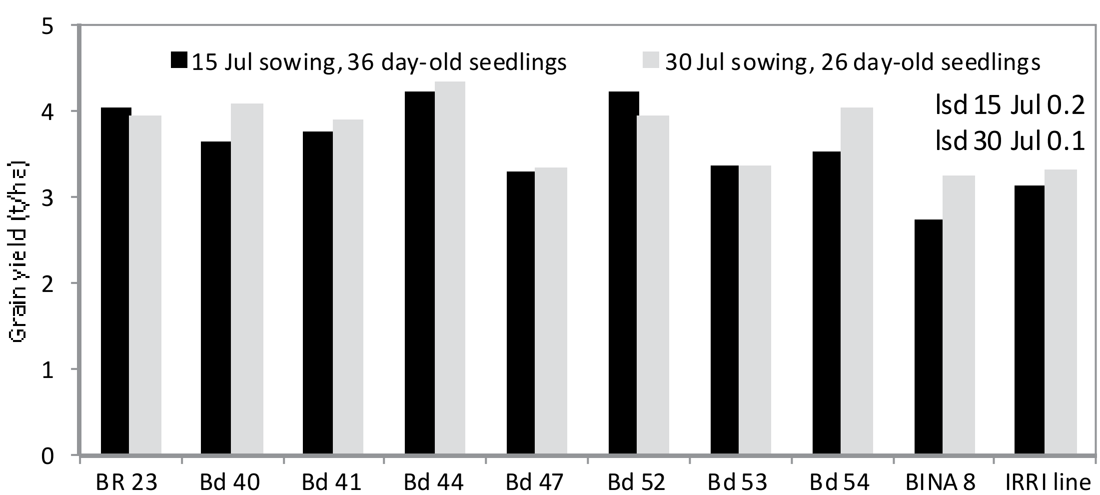


Fig. 4. Variety yields in the medium salinity *gher* with two sowing date/seedling age treatments in 2011 (Bd = BRRI dhan; BINA = BINAdhan). Lsd values are for comparing varieties within sowing date at p=0.05.

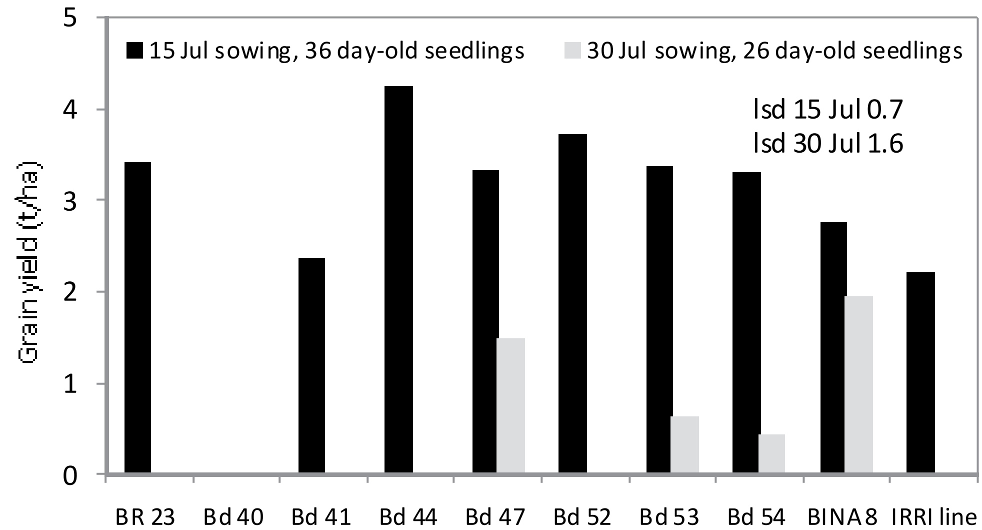


Fig. 5. *Aman* variety yields in the higher salinity *gher* in 2011 as affected by seedling age/transplanting date (Bd = BRRI dhan; BINA = BINAdhan). Lsd values are for comparing varieties within sowing date at p=0.05.

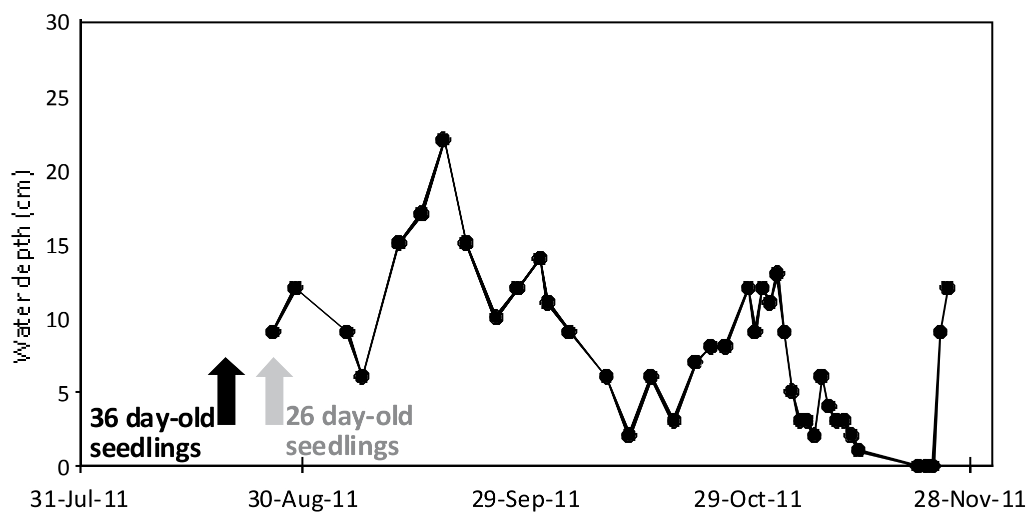


Fig. 6. Water depth in the high salinity *gher* in 2011.

3.2 2012

In 2012, transplanting of the first two sets was delayed to 3 September due to high water depth, with 64 and 49 d old seedlings. Water salinity was 6 dS/m at the time of transplanting (Fig. 7). The trial was completely submerged for 5 d (from 6-10 September as a result of heavy rainfall) starting 2 d after transplanting. Survival was poor for all varieties of both sets, apart from BRRI dhan52. Recovery rate after de-submergence (plant survival) varied from 10 to 90%. The third transplanting was done on 16 September with 47 d old seedlings, after the water depth had receded to about 20 cm, and while salinity was relatively low (~2.5 dS/m) as a result of the rainfall. Salinity gradually increased to almost 6 dS/m by the end of October and to 6 dS/m by mid-November.

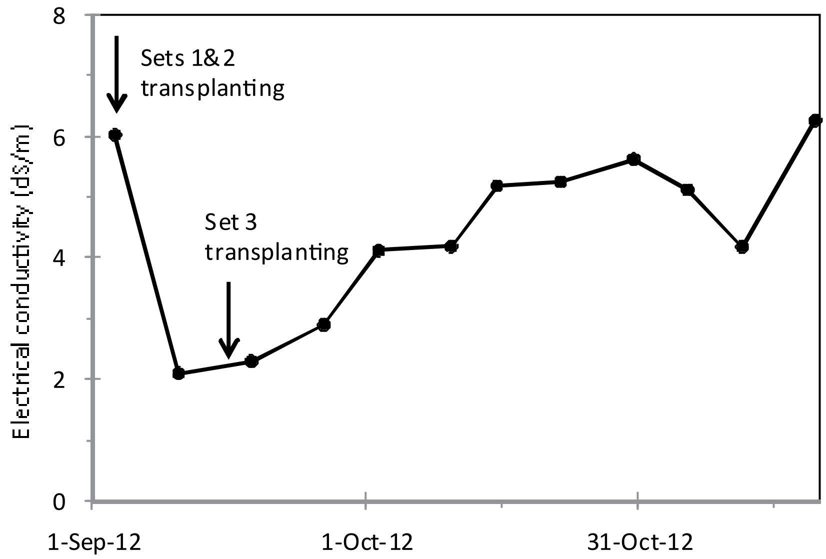


Fig. 7. Water salinity in the *gher* in 2012.

BRRI dhan41 and 44 did not survive due to submergence for 5 d immediately after transplanting. While BRRI dhan41 is moderately salinity tolerant it is sensitive to submergence. BRRI dhan44 is suitable for non-saline tidal water stagnation (diurnal fluctuations in water level), but is not tolerant to submergence. BRRI dhan52 produced the highest yield at 4.0 t/ha, followed by BRRI dhan47 at 3.4 t/ha (Fig. 8). Yields of all other varieties were between 2.3 and 2.8 t/ha. The good performance of BRRI dhan52 reflects the fact that it combines salinity tolerance with relatively tall height, conferring greater tolerance to water stagnation.

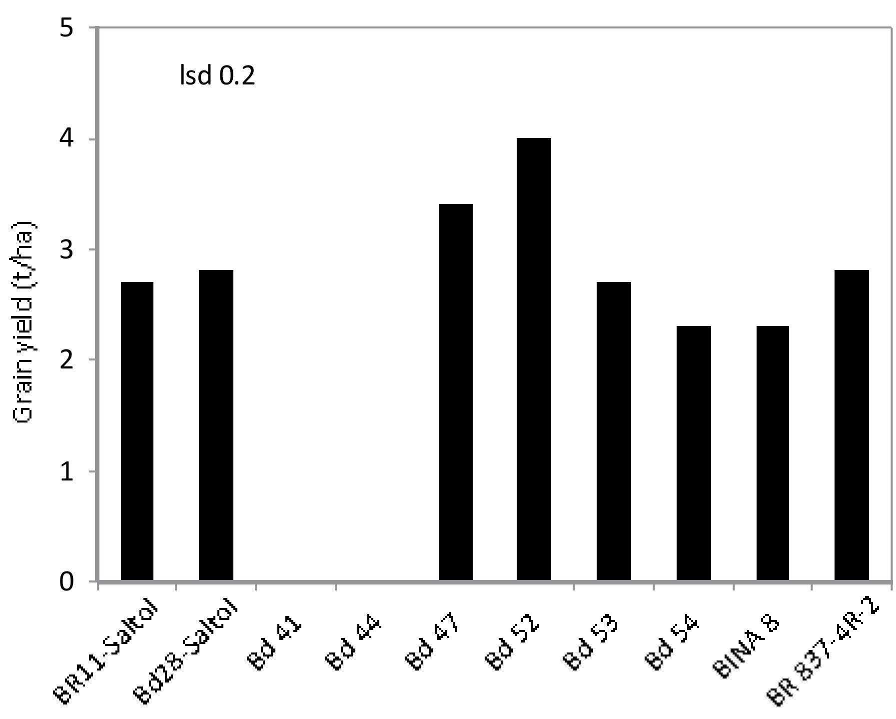


Fig. 8. *Aman* variety yields in the *gher* in 2012 (Bd = BRRI dhan; BINA = BINA dhan; BR8371-4R-2).

3.3 2013

In 2013, salinity fluctuated between 3 and 4 dS/m throughout the season (Fig. 9). Water depth was quite high at the time of the first transplanting of the 49 d-old seedlings on 19 August, and rain shortly after transplanting further increased water depth. As a result, the first transplanting failed. The second transplanting of 56 d-old seedlings was done on 9 September after water depth had declined to about 25 cm, but this was still too deep and the seedlings were damaged and ultimately died due to the combination of high water depth (which increased to almost 30 cm about four weeks after transplanting as a result of rainfall) and salinity. A third set of varieties was transplanted 5 d after the second set (14 September using 46 d-old seedlings). Seven of these varieties survived due to their tall stature combined with salinity tolerance and these varieties went on to produce 2.6-3.7 t/ha of grain (Fig. 10). Both the Saltol varieties (BR11-Saltol, BRRI dhan28-Saltol) failed due to their short stature. The best varieties, with yields of 3.6-3.7 t/ha, were BR23, BRRI dhan41, and BR8371-4R-2.

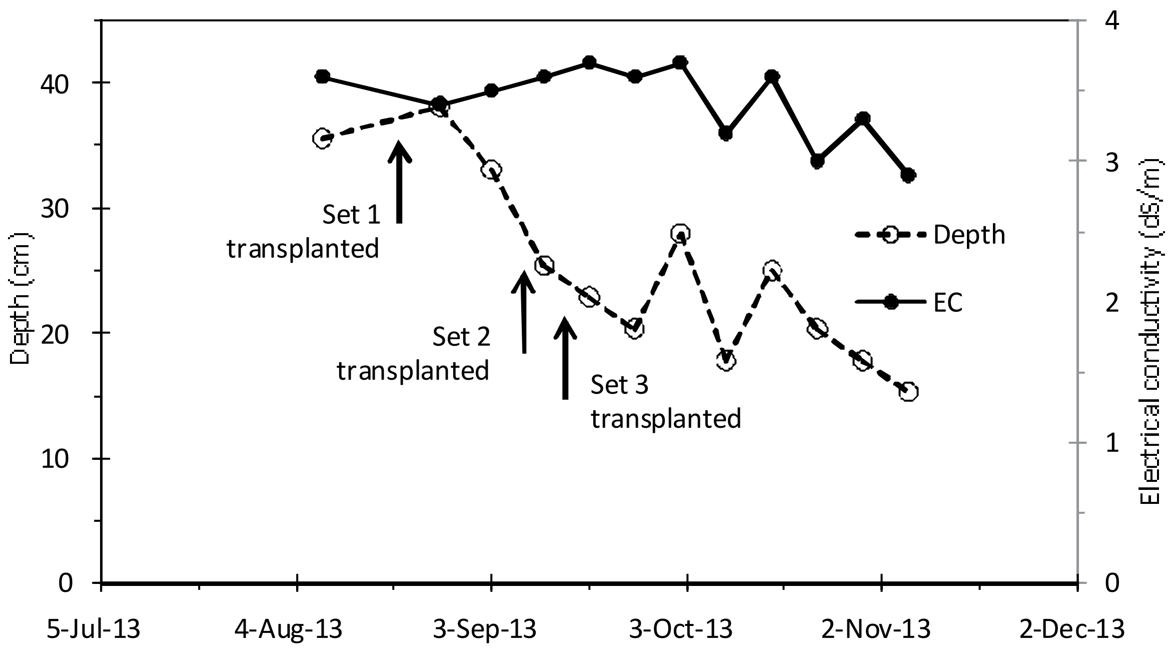


Fig. 9. Water depth and salinity (EC) in the *gher* in 2013.

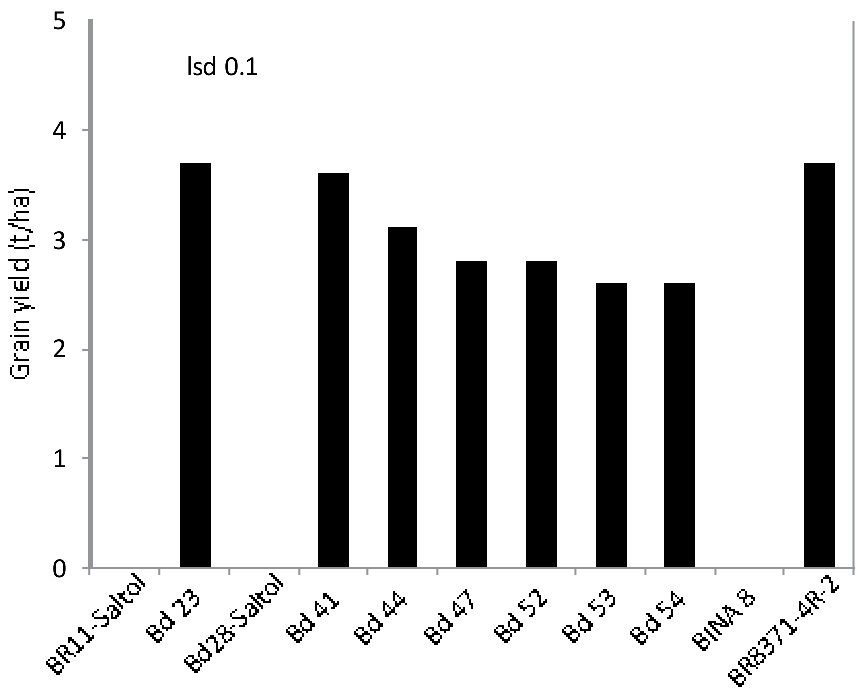


Fig. 10. *Aman* variety yields in the *gher* in 2013 (Bd = BRRI dhan; BINA = BINA dhan; BR8371-4R-2).

4. General discussion

The water depth and salinity data demonstrate the considerable challenges to *aman* production in shrimp *ghers* in the coastal zone of Bangladesh in terms of water depth and salinity. Both water depth and salinity are highly variable depending on drainage management by the farmers at the end of the shrimp season and the incidence and amount of rainfall. As a result, over the three years, there were many constraints to *aman* production including: (i) water too deep for transplanting at the desired time (all years for almost all target transplanting dates), (ii) the need to use older seedlings (beyond the optimal age for best crop performance, in all three years) because water depth was too high, (iii) submergence after transplanting (at least one set each year), (iv) high salinity at the time of transplanting (2011 in poorly leached *gher*, 2012), (v) high salinity during the second half of the season (2012), and (vi) a combination of moderately high salinity and high water depth (2011 in poorly leached *gher*, 2012, 2013). The most consistent performers under these difficult conditions were the varieties with salinity tolerance (BRRI dhan47, 53, 54) or submergence tolerance (BRRI dhan52). However, even these varieties failed when water depth and/or salinity were too high. With current water management, varieties with multiple tolerances (salinity, submergence, water stagnation) would probably be beneficial.

The findings highlight the need for improved drainage management for stability of *aman* yield in shrimp *ghers*. The results showed that with good water management, yields of 4 t/ha can be achieved with modern, high yielding varieties. Good water management requires timely drainage (and thus shrimp harvest) to facilitate leaching of salt from the topsoil by the early monsoon rains, and drainage throughout the season as needed to maintain a suitable water depth for the rice plants, with shallower depth after transplanting than later on. Implementation of drainage throughout the rainy season is biophysically feasible as the rivers are tidal, with low tide levels below land level in most locations (Khan et al. 2015). Furthermore, the *ghers* are connected to the rivers through a network of shallow canals as this is the means for bringing brackish water in from the rivers for shrimp production during the dry season. At present, the canals are primarily designed for water intake. However, slight deepening would facilitate drainage and leaching after shrimp harvest. Implementation of good drainage management would require a coordinated community approach and synchronization of cropping systems. For example, it would be important that all farmers in the same canal network harvest their shrimp around the same time; otherwise there would be conflicting needs, with some farmers wanting to bring in more river water to extend the shrimp phase and others wanting to drain to commence the leaching of salt in preparation for the rice season.

5. Conclusions

With current water management, production of *aman* rice in *ghers* used for brackish water shrimp production is risky due to salinity, submergence and water stagnation. Transplanting of seedlings much older than the optimum age (three to four weeks) for high yield under favorable conditions reduces the risk slightly, but also reduces yield potential. With modern high yielding varieties with salinity or submergence tolerance the risk is reduced somewhat and yields of 2.5 to 4 t/ha are feasible (although replanting may be required).

Improving drainage management is the key to improving yield and yield stability of *aman* crops in shrimp *ghers*, to enable better leaching of salt prior to rice establishment, and to maintain a suitable water depth for the rice crop throughout the season.

Acknowledgements

We thank Mustafa Kamal, Atiqur Rahman, Amal K. Roy and Masum Rana for their assistance during experiments. This paper presents findings from 'G2 Productive, profitable and resilient agriculture and aquaculture systems', a project of the CGIAR Challenge Program on Water and Food.

References

Barmon, B.K., Kondo, T., Osanami, F. 2004. Labor Demand for Rice Prawn *Gher* Farming in Bangladesh: A Case Study of Khulna District. *The Review of Agricultural Economics,* 60: 273-287.

BRRI. 2013. Modern Rice Cultivation, 17th Edition. 80p

Khan, Z.H. and Kamal, F.A. 2015. The Ganges coastal zone – current conditions, future projections. These proceedings.

Optimum sowing window for *boro* cultivation in the coastal zone of Bangladesh

M.K. Mondal[1], N.K. Saha[1,2], S.P. Ritu[3,4], P.L.C. Paul[3], A.K.M. Sharifullah[5], E. Humphreys[1], T.P. Tuong[1], and M.A. Rashid[3]

International Rice Research Institute, Bangladesh and Philippines m.mondal@irri.org, n.saha@irri.org, e.humphreys@irri.org, t.tuong@irri.org
[2]Patuakhali University of Science and Technology, Bangladesh
[3] Bangladesh Rice Research Institute, Bangladesh sanjidap05@gmail.com, plcpauliwm@yahoo.com, arashidiwm@yahoo.com
[4] Current address: Sylhet Agricultural University, Bangladesh
[5] Bangladesh Academy of Rural Development, Bangladesh sharifullahak@yahoo.com

Abstract

Rice production in Bangladesh has increased greatly as a result of the expansion of *boro* cultivation – irrigated high yielding varieties of rice grown during the dry/winter season. However, the coastal zone has missed out on this development. In medium salinity regions such as Khulna District, *boro* cultivation is hindered by scarcity of fresh water, as the river water is too saline for irrigation from mid-February to mid-June. In other parts of the coastal zone, such as much of Barisal Division, the cultivation of *boro* rice has been limited by the misperception that the river water is too saline for irrigation in the dry season throughout the coastal zone. Therefore, a series of experiments and demonstrations were conducted to evaluate the feasibility of *boro* cultivation in low and medium salinity regions of the coastal zone. It was hypothesized that early *boro* establishment would reduce the requirements for water stored in irrigation canals (stored water) to finish off the crop in regions where river water salinity becomes too high, and that it would enable intensification to three rice crops per year in regions with year-round availability of fresh water. On the other hand, it was hypothesized that early sowing would predispose the crop to cold damage and result in reduced yields. Replicated experiments and on-farm demonstrations were conducted at medium salinity locations from 2005 to 2007 and 2011 to 2014 in Khulna District, and at low salinity locations from 2011 to 2014 in Patuakhali and Barguna Districts in Barisal Division. Rice variety BRRI dhan28 was sown in seedling nurseries on a range of dates from late October to late December and transplanted when the seedlings had three to four leaves. At both locations in Barisal, irrigation water salinity remained below 1 dS/m throughout the season. Under these conditions, and with effective disease control, yields were highest with sowing from mid-November to mid-December, ranging from 6.0 to 7.5 t/ha. In the more saline environment of Khulna, early sowing (22 October, 1 November) reduced the stored water requirement to finish off the crop (by about 50% for 22 October sowing), but yield was greatly reduced due to cold damage during the reproductive stage. The optimum sowing window for maximum yield was from 7 to 15 November, much narrower than the window in Barisal, and with lower maximum yield (around 5 t/ha in the absence of disease) than in Barisal. The lower yield at Khulna and the decline in yield for sowings after mid-November were probably due to the higher salinity at Khulna. The results demonstrate substantial opportunities for increasing rice production in southern Bangladesh by introducing *boro* cultivation in the south-central coastal zone where the river water remains fresh throughout the year. They also demonstrate the feasibility of achieving yields of 5 t/ha in medium salinity areas by sowing in the second week of November and storing river water in the *khals* inside the polders before rivers become too saline.

Key message: It is possible to achieve high *boro* yields (up to 7.5 t/ha) in the coastal zone districts of Patuakhali and Barguna (and in similar environments) by sowing from mid-November to mid-December and irrigating using the river water, which remains fresh (<1 dS/m) throughout the year.

Keywords: salinity, temperature, cold, Khulna, Barisal, BRRI dhan28

1. Introduction

Bangladesh's economy is dominated by agricultural output; 73% of the population and 48% of the labor force is engaged in agriculture (BBS 2013). Although Bangladesh has achieved self-sufficiency in rice the country faces enormous challenges to maintain food self-sufficiency for its growing population, as there is little scope to further increase cropping system intensity except in the underutilized coastal zone lands. The coastal zone, covering approximately 2.8 Mha (30% of the cultivable land of the country), is the least productive region of Bangladesh but has great potential for increased productivity (Tuong et al. 2014). The Government of Bangladesh constructed a series of polders (about 1.2 Mha) during the 1960s and 1970s to increase agricultural production of the coastal zone, as well as to protect life and property from tidal surges and to prevent saline water intrusion during the dry season. Poldering involved building large embankments around the perimeters of the islands formed between the spaghetti of rivers in the delta. However, despite huge investment, the polders are home to some of the world's poorest and most vulnerable people (BBS 2010; Kabir et al. 2014). While much of Bangladesh enjoyed the benefits of greatly increased rice production due to the expansion of irrigated dry season rice (*boro*), the coastal zone missed out. The expansion of *boro* production was the result of the development of high yielding rice varieties and of groundwater irrigation, and the use of fertilizers.

In the coastal zone the scope for groundwater development is limited because the upper aquifer is saline and there are concerns about salinization of the deep fresh aquifer (Hasan et al. 2013; Dhaka Tribune 2013). However, there is scope for using surface water resources for *boro* production during the dry season. In moderately saline areas of the coastal zone in Khulna District the river water remains suitable for irrigation for the first couple of months of the dry season, until early to mid-February (Fig. 1) (Khan et al., these proceedings). Mondal et al. (2006, 2010) showed that with 'early' (timely) establishment and proper management a *boro* crop could be grown after harvest of the *aman* crop (wet season rice) in this region. This requires replacement of the traditional, photoperiod sensitive and late harvested *aman* landraces with a modern, early maturity *aman* variety, enabling early establishment of the *boro* crop. The production of *boro* in this situation involves two distinct stages of irrigation. The first stage is gravity irrigation while the river water salinity is <4 dS/m (up to mid-February) by letting water into the polder canal networks at high tide through the sluice gates. The second stage involves storage of river water in the canal networks before the river salinity reaches 4 dS/m and pumping water from the canals to finish off the *boro* crop. The extent to which this technology could be adopted in moderately saline regions of the coastal zone depends on several factors: (i) the water requirement of the *boro* crop, (ii) the time when the river water becomes too saline for irrigation, and (iii) the storage capacity of the canal networks inside the polder. Mondal et al. (2010) showed that the *boro* area could be expanded by increasing the storage capacity of the canals and/or by advancing the cropping period. The storage capacity can be increased by digging new canals/ponds and desilting existing ones, but this would require considerable investment. Advancing *boro* establishment reduced the amount of stored water required to finish the crop, and also the cost of pumping, but advancing it too early exposed the crop to low temperature stress during the reproductive stage with large yield loss primarily due to high sterility.

While the rivers become saline during the dry season in much of Khulna Division, Khan et al. (these proceedings) showed most of the rivers in Barisal Division remain non-saline (<1 dS/m) throughout the year. Thus, there is plenty of fresh water available for *boro* production in this region and a dense network of *khals* (small river canals) that can be used to distribute the water across the landscape. In addition to increasing rice production through expanding the *boro* area, earlier planting of *boro* could also create the opportunity for triple rice cropping (Tuong et al. 2014; Saha et al., these proceedings; Bhattacharya et al., these proceedings; Paul et al., these proceedings). Again the question is what is the optimum planting window for *boro*, bearing in mind both yield target and irrigation water requirement.

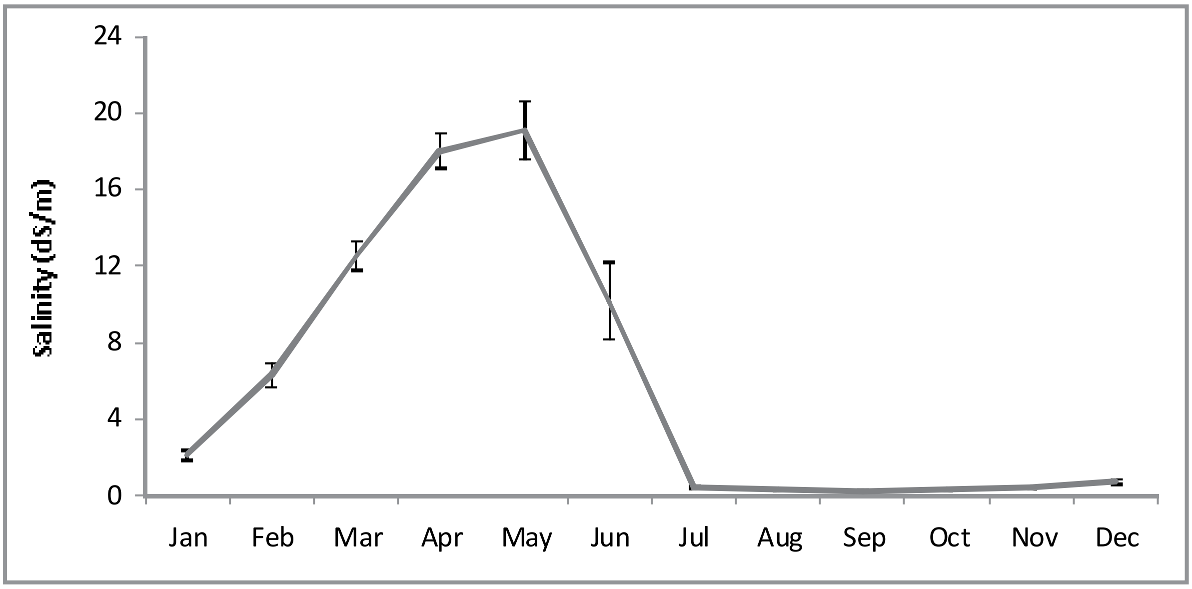


Fig. 1. Long-term monthly average salinity (1990-2008) of Kazibacha River at Batiaghata, Khulna, Bangladesh (vertical capped bars indicate standard error of 19 monthly values).

Given the considerable potential for expanding *boro* production in the fresh and moderately saline regions of the coastal zone a series of experiments was undertaken over the past ten years in low and medium salinity regions of the coastal zone with three key objectives:

- To determine the effect of sowing date on the yield of *boro*
- To determine the irrigation water requirement (and the stored water requirement for irrigation in a medium salinity area) as affected by sowing date
- To determine the optimum sowing date taking into account tradeoffs between yield, irrigation water requirement and stored water requirement

2. Methodology

2.1 Study sites

Two replicated experiments and two non-replicated demonstrations were conducted at three coastal zone locations with low or medium salinity (Table 1). Replicated experiments were conducted at Kismat Fultola village (medium salinity) in Khulna Division during the 2005-06 and 2006-07 dry seasons, and at Patuakhali Science and Technology University (PSTU) farm (low salinity) in Barisal Division during 2012-13 and 2013-14. In addition, non-replicated demonstrations were conducted in farmers' fields at Kismat Fultola and Bazarkhali during 2011-12, 2012-13 and 2013-14. Bazarkhali is also in Barisal Division, and located about 32 km south of PSTU. BRRI dhan28 (a high yielding medium duration (140 d) *boro* variety) was grown at all locations in all years. Details of the replicated experiments are provided in Mondal et al. (2010) and Saha et al. (these proceedings), and details of the demonstrations in Paul et al. (these proceedings). Only information pertinent to the analysis in this paper is briefly summarized here.

2.2 Treatments

The experiments and demonstrations were all designed to compare the effect of sowing date on the performance of *boro* crops (Table 1). Sowing dates at Kismat Fultola ranged from late October to mid-December, while sowing dates at PSTU and Bazarkhali were from mid-November to the end of December.

2.3 Crop management

All experimental fields were ploughed three to four times (wet tillage) using a tiller powered by a two-wheel tractor. Final land leveling was done with a wooden plank drawn by a draft animal. Small bunds (20 cm x 30 cm) were constructed around all fields, and around all the plots in the replicated experiment at Kismat Fultola, and were compacted to minimize seepage between adjacent plots.

Seedlings were raised in nurseries in a separate location. Rice seeds were soaked for 12 h and incubated for 48-72 h. The pre-germinated seed was sown on the seed beds at 28 g/m^2. The seedlings were carefully uprooted and transplanted when they had three to four leaves, with two to four seedlings per hill at a spacing of 20 cm x 20 cm. The age of the seedlings at the time of transplanting varied from 21 to 35 d (usually it was 21-27 d) depending on temperature at the time of seedling growth and thus the time taken for leaves to develop.

Fertilizers were applied based on Bangladesh Rice Research Institute (BRRI 2005) recommendations for *boro* cultivation. In both replicated experiments, urea was applied at 120 kg N/ha in four equal splits: before the last leveling, 25 d after transplanting (DAT), five to seven d before panicle initiation and at heading. In the non-replicated experiments, urea was topdressed in three equal splits on 15, 30 and 55 DAT. Other fertilizers were broadcast at 60 kg P_2O_5, 40 kg K_2O, 60 kg $CaSO_4$ and 10 kg $ZnSO_4$ per ha before the last land leveling.

Pesticides were applied as per BRRI (2005) recommendations and after consultation with the local experts of the Department of Agricultural Extension. In addition, in the replicated experiments, systemic pesticides were applied at the time of each N application to minimize crop damage. Manual weeding was done just prior to urea topdressing. At PSTU, post-emergence weedicide (pyrazosulfuron-ethyl @125 g/ha) was also applied three to five DAT into standing water and the water was held on the plots for two to three d after treatment to control weeds. All experimental sites were surrounded by plastic barriers with traps to prevent damage by rats, and covered by netting as the crops approached maturity to prevent bird damage. Protection from rats and birds was necessary as there were no other crops surrounding the experiments in the dry season.

Table 1. Details of the *boro* sowing date, experimental sites and treatments

Location	Kismat Fultola	Bazarkhali	Patuakhali Science and Technology University
Upazila	Batiaghata	Amtali	Dumki
District	Khulna	Barguna	Patuakhali
Latitude	22° 41' 00''N	22°11'33"N	22°27'51"N
Longitude	89° 30' 00''E	90°15'41"E	90°22'56"E
Height above sea level	2-3 m	2-3 m	2-3 m
Salinity classification	Medium	Low	Low
River water salinity (EC, dS/m))	0.2-25	<1 dS/m	<1 dS/m
Topsoil (0-15 cm) salinity (saturation extract EC, dS/m)	2-16	2-8	2-8
Soil texture	Silty clay loam	Clay loam	Clay loam
Predominant cropping systems	Sesame-Aman-Fallow Expt 1	Fallow-Aman-Grasspea; Aus-Aman-Fallow	Fallow-Aman-Grasspea; Aus-Aman-Fallow
2005-07 experiments	2005-06, 2006-07 4 sowing dates 22 October 1 November 7 November 15 November 4 replicates Sub-plots 6 m x 8 m Mondal et al. (2010)		
2011-14 experiments and demonstrations	Demo 1 2011-12, 2012-13, 2013-14 3 sowing dates 10 November 30 November 20 December Non-replicated Plots 10 m x 20 m	Demo 2 2011-12, 2012-13, 2013-4 3 sowing dates 15 November 7 December 30 December Non-replicated Plots 10 m x 20 m	Expt 2 2012-13, 2013-14 5 sowing dates 15 November 20 November 30 November 05 December 15 December 4 replicates Plots 5 m x 5 m
	Paul et al. (these proceedings)		*Saha et al. (these proceedings)*

2.4 Irrigation water monitoring

All crops were grown under fully irrigated conditions. Irrigation water was pumped from the nearby *khal* at each location using a 4 h.p. centrifugal pump powered by diesel. The crops were irrigated whenever surface water depth fell below 1 cm, and water was added until water depth reached 5 cm. Irrigation was stopped 10 to 15 d before harvest. The salinity of the irrigation water was monitored regularly using a portable EC meter. The amount of irrigation water applied to each plot in the replicated experiments at Kismat Fultola was determined using a 90^{o}V-Notch weir to determine flow rate and the time to irrigate each plot.

2.5 Crop monitoring

Grain yield and yield components were determined in all experiments and demonstrations. In addition, the dates of the main crop development stages were determined in the replicated experiments at both locations.

2.5.1 Phenology

The dates of panicle initiation (PI), flowering (FL), and physiological maturity (PM) were determined in each plot in the replicated experiments at Kismat Fultola and at PSTU. Daily monitoring of six plants was done for 10 d, starting 5 d before the expected onset of PI and FL. For determination of PI, the main tiller of each plant was dissected to determine the date when the panicle was visible to the naked eye (i.e. about 1 mm long). PI was determined as the date when the panicle was visible in 50% of the main tillers examined. Flowering date was determined as the date when 50% of the tillers of 12 randomly selected hills had commenced anthesis. Physiological maturity (PM) was taken as the date when 80% of the grains had turned golden in all experiments and demonstrations.

2.5.2 Grain yield and yield components

In the replicated experiments, grain yield was determined from 4 m x 2 m (Kismat Fultola) and 3 m x 2 m (PSTU) areas in the middle of each plot. Grain yield in the non-replicated trials at Bazarkhali and Kismat Fultola was determined from 5 m^2 areas harvested at five locations (four towards each of the four corners and one in the middle of each plot), except in 2013-14 at Kismat Fultola when an area of 5 m x 2 m was harvested in the middle of each plot. The samples were threshed, cleaned and dried, and moisture content was determined to enable calculation of grain yield at 14% moisture content.

Yield components (number of panicles/m^2, number of florets/panicle, % floret fertility, 1000 grain weight) were determined at PM from 16 hills, 4 hills at each corner of the harvest area at Kismat Fultola and at PSTU; and from 16 randomly selected hills in 8 locations (2 hills per location) at Bazarkhali.

2.6 Weather data

A standard rain gauge was installed in the vicinity of each experimental site. Daily maximum and minimum temperature data were obtained from the Bangladesh Meteorological Department (BMD) for the weather stations at Khepupara in Patuakhali District, and at Khulna city. The Khepupara station is about 24 km and 56 km south of the experimental sites at Bazarkhali and PSTU, respectively; the Khulna station is about 8 km north of Kismat Fultola. Long-term (1998 to 2007) daily maximum and minimum temperatures for Patuakhali (NASA 1 degree grid, http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi) and Khulna (BMD) were used to calculate 10-d long-term means for the period from November to April.

2.7 Data analysis

Crop and irrigation data from the replicated experiments were subjected to analysis of variance (ANOVA). The least significant difference (LSD) was determined at 5% level of probability.

3. Results

3.1 Barisal

3.1.1 Irrigation water salinity

Salinity of the water in the *khals* remained below 1 dS/m throughout the *boro* season (and the entire year) at both Bazarkhali and PSTU (Figs. 2a, b).

(a)

(b)

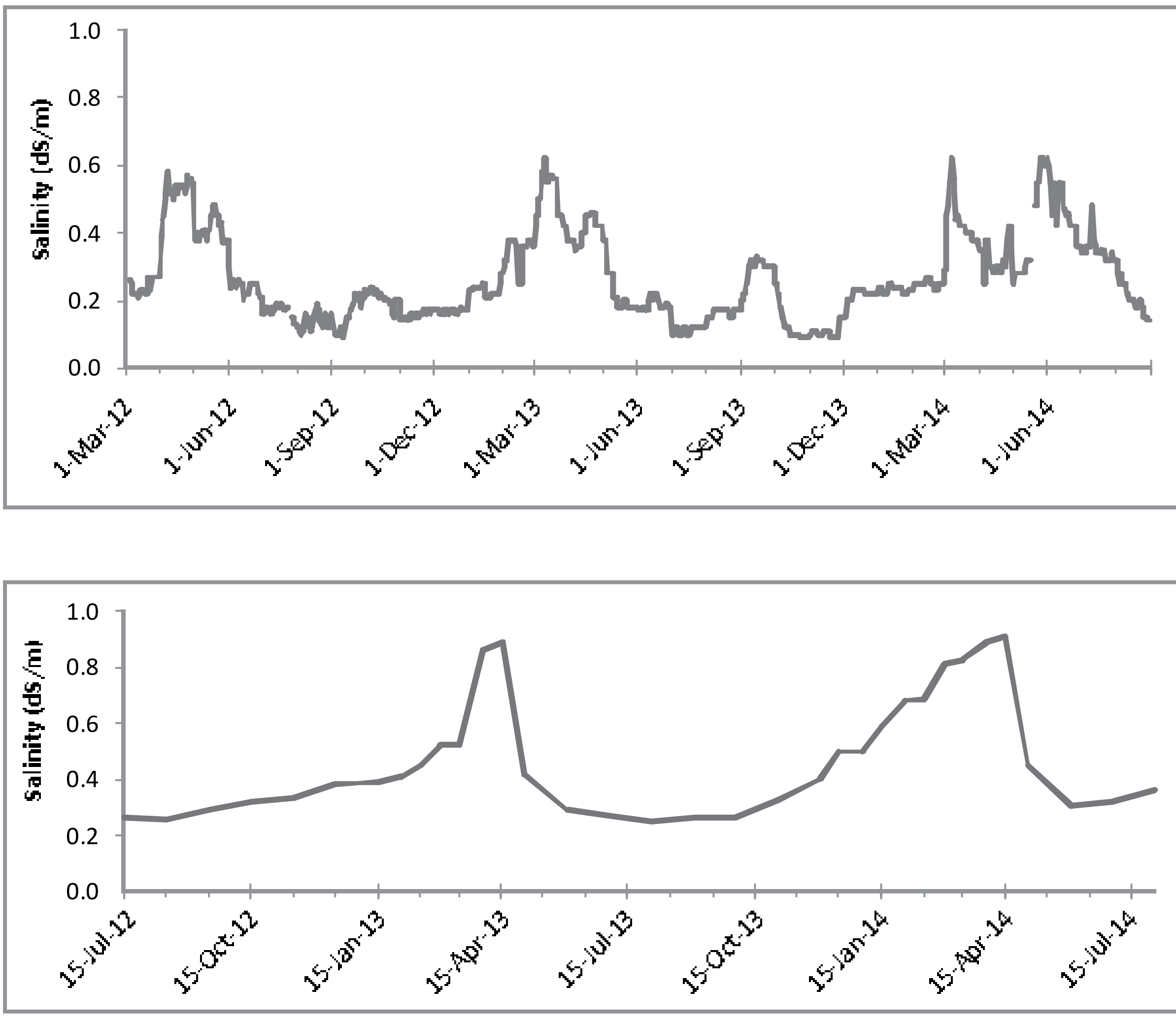


Fig. 2. Irrigation water salinity (water salinity in the *khals*) at Bazarkhali (a) and PSTU (b) from 2012 to 2014.

3.1.2 Temperature

Temperature during the 2011-14 *boro* seasons was generally similar to the long term mean, with a few notable exceptions. Minimum temperature was unusually high from 1 to 10 January and 1 to 10 March 2012, and both minimum and maximum temperatures were unusually low from 21 to 31 December 2012 (Fig. 3). This was followed by low minimum temperatures throughout January 2013. Temperature from early January to early March 2014 was also generally lower than the long-term average, more so in mid- to late February and early March.

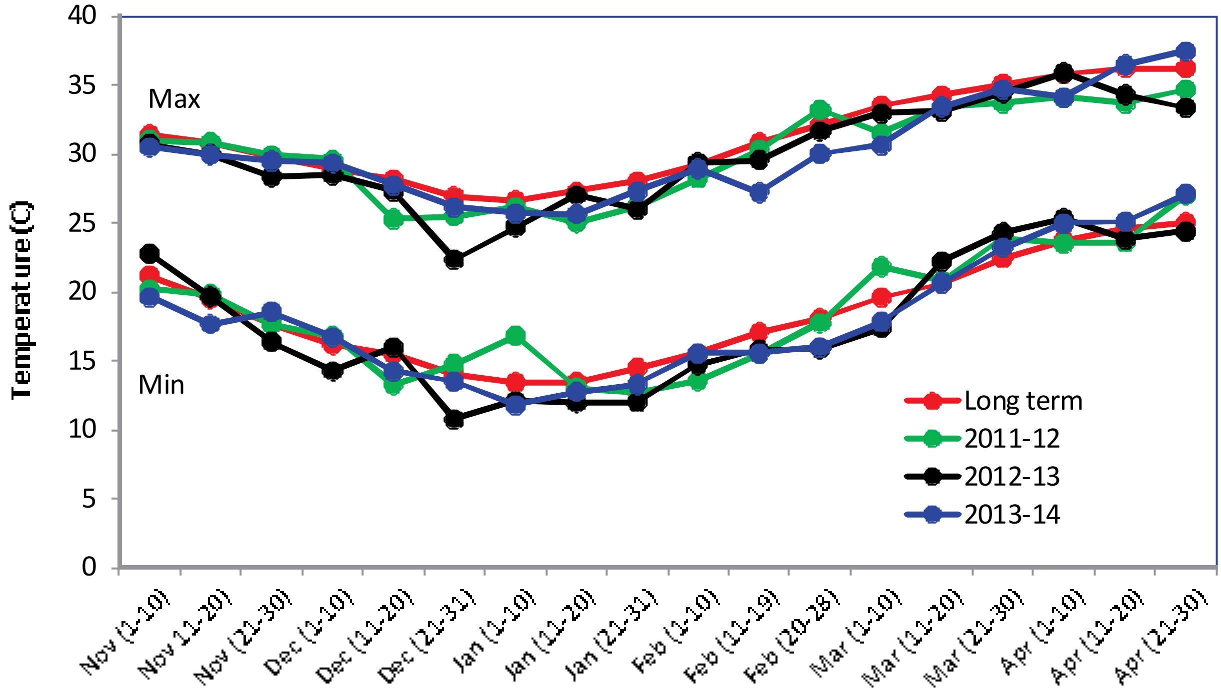


Fig. 3. Maximum and minimum temperature at Patuakhali during the 2011-14 *boro* seasons in comparison with the long-term (1998-2007) mean. Mean values for 10 to 11 d periods.

3.1.3 Crop duration

There was a consistent trend for crop duration to become shorter by about 10 d as sowing was delayed from 15 November to 30 December at Bazarkhali (Table 2) and PSTU (Table 3). The more detailed phenological data at PSTU show that the decrease in duration was due to earlier flowering as sowing date was delayed. The effect of sowing date on time to panicle initiation (PI) and on the duration of grain filling was inconsistent and the variation was small. The earlier flowering with delay in sowing was thus primarily due to reduction in the period from PI to anthesis, due to warmer weather during this period.

Table 2. Duration (days from sowing to physiological maturity) of *boro* crops as affected by sowing date at Bazarkhali in Barisal Division

Year	Sowing date		
	15 Nov	7 Dec	30 Dec
2011-12	148	138	123
2012-13	152	144	126
2013-14	149	139	126

Table 3. Phenological stages (days after sowing, DAS) of *boro* crops as affected by sowing date at PSTU in Barisal Division

Year	Sowing date				
	15 Nov	20 Nov	30 Nov	5 Dec	15 Dec
Panicle initiation (PI)					
2012-13	91	89	86	91	86
2013-14	82	86	83	82	84
Anthesis					
2012-13	117	115	112	112	106
2013-14	116	116	112	110	105
Physiological maturity					
2012-13	140	139	137	136	130
2013-14	140	139	133	131	128
Duration PI-Anthesis					
2012-13	26	26	26	21	20
2013-14	34	30	29	28	21
Duration of grain filling					
2012-13	23	24	25	24	24
2013-14	24	23	21	21	23

3.1.4 Grain yield

Grain yield of the *boro* crops in Barisal ranged from 4.4 to 7.9 t/ha across locations, sowing dates and years (Table 4). The effect of sowing date on yield was inconsistent across years and across locations within year. At Bazarkhali, grain yield declined with delay in sowing from mid-November to late December in 2011-12. The very low yield of the 30 December sowing in that year may have been partly due to leaf blight attack in the seed bed; growth and tillering after transplanting were poor. In 2012-13, yields of the mid-November and early December sowings were similar, but again decreased with the late December sowing. In 2013-14, the first sown (15 Nov) crop was severely affected by stem borer (estimated as 20% yield loss) and maximum yield occurred with early December sowing. At PSTU, yield increased with delay in sowing from mid-November to early December in both years. Yields at PSTU in 2012-13 were much lower than at Bazarkhali in the same year, probably due to heavy infestation with brown spot disease at PSTU, with the first two sowings being the most severely affected. This was associated with a large reduction in panicle density, more so for earlier sowings (data not presented). In 2013-14, yield also increased with delay in sowing to 7 December, and yields at PSTU were higher than at Bazarkhali, where there was stem borer infestation, more so in the first sowing.

Table 4. Grain yield (t/ha, 14% moisture) of *boro* crops as affected by sowing date at Bazarkhali and PSTU in Barisal Division

Year	Sowing date					
	15 Nov	20 Nov	30 Nov	5/7 Dec[1]	15 Dec	30 Dec
Bazarkhali (mean ± standard error)						
2011-12	7.9 ±0.1	-	-	6.7 ±0.2	-	4.4±0.2
2012-13	6.7±0.2	-	-	7.0±0.2	-	5.9±0.2
2013-14	5.8±0.2	-	-	6.6±0.3	-	6.1±0.2
PSTU						
2012-13	4.9	5.0	5.6	5.9	6.1	-
2013-14	6.2	7.0	7.3	7.4	7.1	-
	Significant interaction between year and sowing date, lsd for the interaction = 0.3					

[1] 5 Dec sowing at PSTU, 7 Dec sowing at Bazarkhali

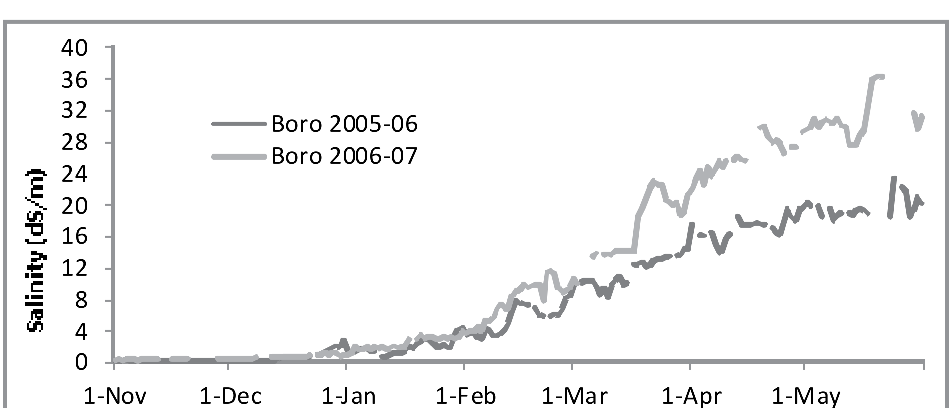
3.2 Kismat Fultola

3.2.1 Irrigation water salinity

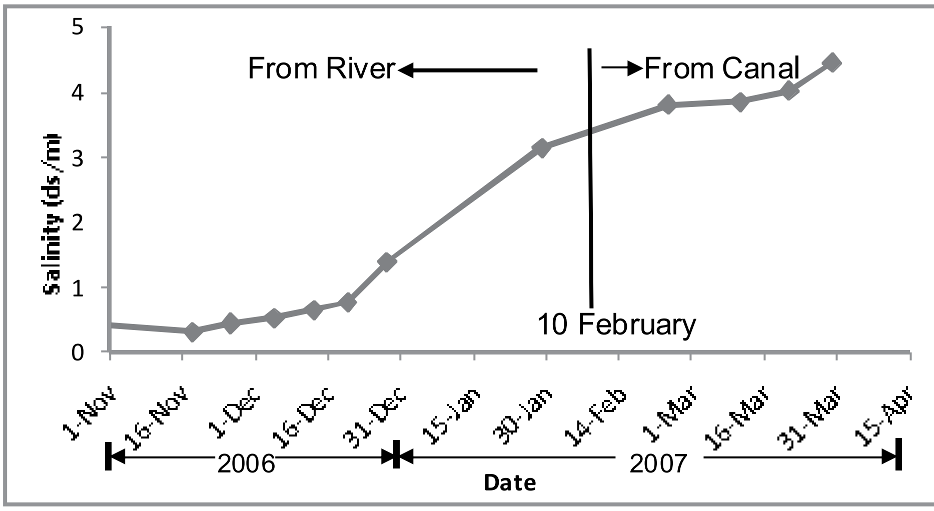
From 2005 to 2007 the *boro* crops at Kismat Fultola were irrigated from river water until the river became too saline (early February, Fig. 4a). Thereafter, they were irrigated using water stored in the adjacent *khal* that was filled in the first week of February just prior to the river becoming too saline, after which the sluice gate was closed. The results from 2006-07 show that the salinity of the irrigation water gradually increased as the season progressed reaching 4.5 dS/m at the time of maturity of the last sown crop (Fig. 4b) (salinity was not monitored in 2005-06, but it can be assumed that it was similar to that in 2006-07; there were no signs of salinity damage in any crop at any stage). Salinity of the saturation extract also gradually increased, with values similar to that of the irrigation water (data not presented).

In 2011-12, the salinity of the water in the *khal* remained below 4 dS/m throughout the *boro* season. However, in 2012-13 and 2013-14 the community water management group decided to leave the sluice gate partly open during the dry season to try and prevent siltation in the gate intake canal. As a result the salinity of the irrigation water increased as the dry season progressed to about 15 dS/m around the time of maturity of the last sown crop in 2012-13. Salinity data were not collected during 2013-14, however, there was clear evidence of salinity damage, including seedling death in early February in the most recently (late) transplanted crop.

(a)



(b)



(c)

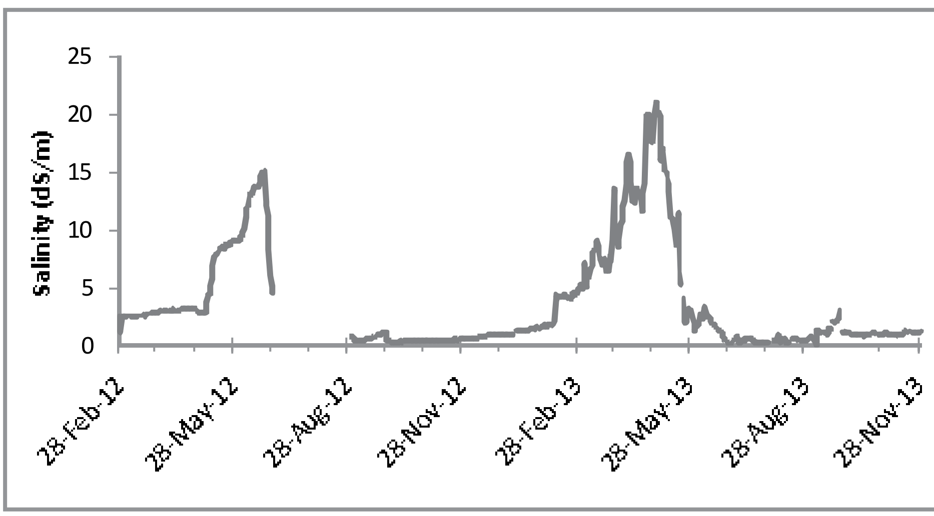
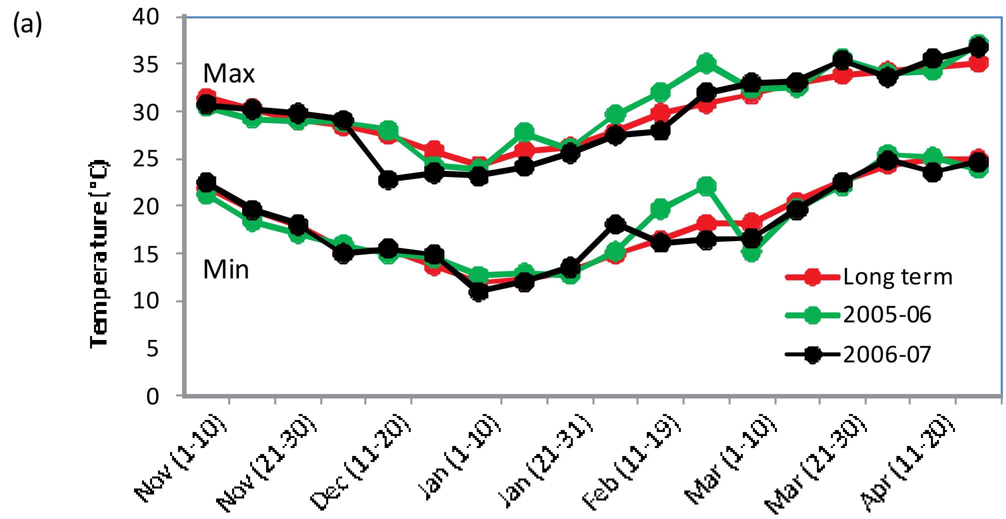


Fig. 4. Salinity of the river water at Kismat Fultola in 2005-06 and 2006-07 (a), and salinity of the irrigation water in 2006-07 (b) and 2012-13 (c).

3.2.2 Temperature

Maximum temperature at Khulna was considerably lower in 2006-07 than in 2005-06 from mid-December to mid-February, and also lower than the long-term average (Fig. 5a). Maximum temperature in February 2006 was higher than the long-term mean.

Mean minimum temperature during the first 10 d of January and 1-10 March 2012 was much higher than the long-term average (Fig. 5b), as also observed at Patukhali (Fig. 3). Also as at Patuakhali, 2012-13 was colder than normal in late December and January. Minimum and maximum temperatures during the last part of December at Khulna were much lower than the long-term average and minimum temperatures during January also remained lower than normal (Fig. 5b).



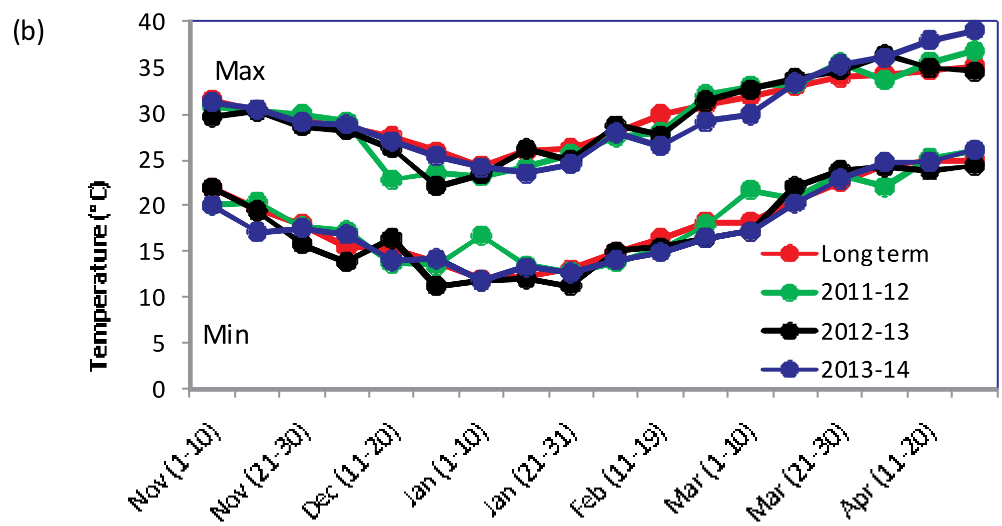


Fig. 5. Maximum and minimum temperature at Khulna during the 2005-07 (a) and 2011-14 (b) *boro* seasons in comparison with the long term (1998-2007) mean. Mean values for 10-11 d periods.

3.2.3 Crop phenology

The time taken to reach PI increased with delay in sowing from around 75 d with sowing on 22 October to around 90 d with sowing on 7 and 15 November in 2005-06 and 2006-07 (Table 5). This was due to lower temperatures during the vegetative phase as sowing was delayed (Fig. 5a). The duration of PI to anthesis (~41 d) was much longer (by 7 to 14 d) with 22 October sowing than with later sowing dates as PI occurred in early January, at the start of the period when temperature was lowest (during the first three weeks of January). The net result was that the effects of time of sowing on the date of anthesis were small and inconsistent. The duration of grain filling was also about 10 d longer with 22 October sowing than all later sowings due to the production of numerous late tillers. In 2006-07 it was also probably partly due to 10 d earlier anthesis and thus cooler weather during early grain filling. The net result was that the duration of 22 October sowings was longer than that of 15 November sowings each year (by 7 to 10 d), with the duration of the 1 and 7 November sowings somewhere in between, but with no consistent trends.

The time to maturity of the crop for the 10 November sowing in 2011-12 and 2013-14 was similar to that of the 15 November sowings in 2005-07 (around 145 d) (Table 6). However, in 2012-13 the duration was about 20 d longer, presumably due to unusually cold weather in late December 2012 and low minimum temperature in January 2013 (Fig. 5b). In 2012-13, seedlings from the 30 November sowing died after transplanting due to cold damage as transplanting took place in early January. In 2013-14, seedlings from both the 30 November and 20 December sowings died after transplanting due to salinity, possibly exacerbated by low temperature in the case of the 30 November sowing.

Table 5. Phenological stages of *boro* crops as affected by sowing date at Kismat Fultola from 2005-07 (adapted from Mondal et al. 2010)

Year	Sowing date			
	22 Oct	1 Nov	7 Nov	15 Nov
Panicle initiation(PI)				
2005-06	74	84	93	93
2006-07	77	94	93	90
Anthesis				
2005-06	116	112	121	121
2006-07	117	127	125	118
Physiological maturity				
2005-06	155	140	149	147
2006-07	154	154	152	145
Duration PI-Anthesis				
2005-06	42	28	28	28
2006-07	40	33	32	28
Duration of grain filling				
2005-06	39	28	28	26
2006-07	37	27	27	27

Table 6. Duration of phenological stages of *boro* crops as affected by sowing date at Kismat Fultola from 2011-14

Year	Sowing date		
	10 Nov	30 Nov	20 Dec
Panicle initiation			
2011-12	95	89	79
2012-13	97	Crop died	Crop died
2013-14	92	87	Crop died
Anthesis			
2011-12	122	120	112
2012-13	131	Crop died	Crop died
2013-14	129	116	Crop died
Physiological maturity			
2011-12	143	143	135
2012-13	166	Crop died	Crop died
2013-14	150	144	Crop died

3.2.4 Grain yield

Grain yield increased with delay in sowing to 7 November in both 2005-06 and 2006-07, and declined with further delay to 15 November in 2006-07 only (Table 7). The low yields of the first sowing in 2005-06 and the first two sowings in 2006-07 were due to high sterility (more so for the 22 October sowing) and fewer florets per panicle, as a result of low temperature during the reproductive phase (Mondal et al. 2010). Yields of the 7 and 15 November 2005-06 sowings were reduced due to stem borer attack, and predicted yield of these two sowings was 5-5.6 t/ha in the absence of stem borer attack (adjusted yield was calculated using the proportion of white heads [panicles with no filled grains] to total number of panicles within the harvest area). In the 2011-14 *boro* crops, delaying sowing beyond 10 November greatly reduced grain yield in two out of three years (Table 8).

Table 7. Grain yield, water input and stored-water (from canal networks) productivity of *boro* crops during 2005-07 as affected by sowing data at Kismat Fultola, Khulna Division (adapted from Mondal et al. 2010)

Sowing date	Grain yield[1] (t/ha)	Adjusted grain yield[2] (t/ha)	Irrigation amount (mm)			Land preparation water[4] (mm)	Rainfall (mm)	Total water input (mm)	Canal water productivity (kg grain/m³ canal water)
			River	Canal	Total				
2005-06									
22 Oct	2.7	2.7	349	147	496	31	16	543	1.9
01 Nov	4.6	4.9	269	202	471	80	16	567	2.3
07 Nov	3.6	5.0	238	220	458	130	16	604	1.7
15 Nov	4.3	5.6	179	269	448	172	16	636	1.6
LSD (p=0.05)	1.0	1.2	91.4	26	NS[3]				0.4
2006-07									
22 Oct	0.7		351	143	494	31	96	621	0.5
01 Nov	2.4		323	223	546	80	96	722	1.1
07 Nov	5.0		266	268	534	130	96	760	1.9
15 Nov	4.5		215	278	493	172	96	761	1.6
LSD (p=0.05)	0.8		54	37	NS				0.4

[1] Actual yield

[2] Adjusted to remove the effect of stem borer damage (Mondal et al. 2010)

[3] NS not significant

[4] Land preparation water was same in both years

Table 8. Grain yield of *boro* crops during 2011-14 as affected by sowing data at Kismat Fultola (mean ± s.e.)

Year	Sowing date		
	10 Nov	30 Nov	20 Dec
2011-12	4.6±0.3	5.9±0.2	6.3±0.6
2012-13	4.9±0.2	0.0	0.0
2013-14	4.6	1.7	0.0

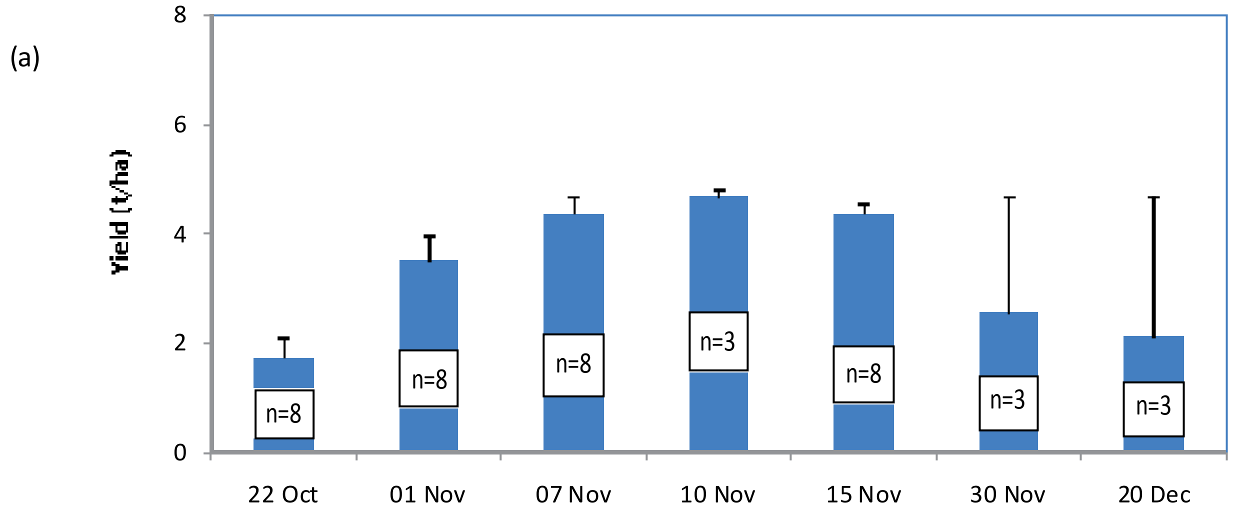
3.2.5 Irrigation input and water productivity

At Kismat Fultola, irrigation input from the river decreased with delay in sowing from 22 October to 15 November in both years while input from water stored in the canal increased with delay in sowing (Table 7). The net result was that there was no significant effect of time of sowing between 22 October and 15 November on total irrigation input.

4. Discussion

Combining the yield data for both experiments (five different years x sowing dates from 22 Oct to 30 Dec) at Kismat Fultola shows that maximum average yield occurred when sowing was during the period 7 to 14 November (Fig. 6a). In the absence of stem borer damage, this trend would have been even more pronounced. Furthermore, yield variability was least for these sowing dates, suggesting that sowing in the second week of November is optimum for higher yields. The simulations of Sharifullah et al. (2009) also showed that yield increased with delay in sowing to 10 November, and with no further yield increase beyond that to 20 November (20 November was the latest sowing date tested). The simulations also showed that the requirement of stored water for irrigation increased steadily as sowing is delayed from 15 October to 20 November, consistent with the findings of the field experiments. In the field experiments, productivity of the stored water (kg grain/m^3) was highest and similar for 1 to 15 November sowings in 2005-06, and for 7 and 15 November sowings in 2006-07 (Table 7). Thus there were tradeoffs between yield, stored water irrigation requirement and productivity of the stored water, for sowings between 15 October and 20 November. Maximum yield and stored water productivity were observed for sowings in the second week of November, while stored water requirement was least for the earliest sowings (15 and 22 October in the modeling and field studies, respectively).

The results from the two locations in Barisal Division showed little effect of sowing date from mid-November to mid-December on both grain yield and variability of grain yield (Fig. 6b). During this period, yields were always above 6 t/ha, except for the first two sowings at PSTU, which were affected by stem borer and brown spot. Yields at Kismat Fultola (Khulna District) were always much lower than yields at both sites at Barisal for similar sowing dates. The 10 d mean minimum temperature at Khulna and Patuakhali was similar during each *boro* season from 2011-12 to 2013-14 (Fig. 7). However, maximum temperature during the coldest part of the year was a couple of degrees lower in Khulna in 2011-12 and 2013-14, but not in 2012-13, the coldest of the three years. The lower temperature at Khulna may partly explain the lower yields at Khulna in 2011-12 and 2013-14, but not in 2012-13. A more likely explanation is the higher salinity at Khulna. While the salinity of the irrigation water in 2005-07 and 2011-12 could be considered acceptable (<4 dS/m), it was much higher than at both sites in Barisal. The threshold for salinity injury in rice (yield and growth) is about 3 dS/m for Indicas and 1.9 dS/m for Japonicas. BRRI dhan65 is an Indica, suggesting that yield at Khulna was constrained by salinity, even. Salinity stress at these thresholds does not necessarily manifest as visual symptoms, but does reduce yield and growth if salinity exceeds these limits (Ismail et al. 2007). Whether the combination of marginally high salinity and marginally low temperature for rice would have an antagonistic effect on the plants is not known. The long term data show that both minimum and maximum temperature are lower at Khulna than Patuakhali from late December to mid-February, suggesting that Khulna is a more risky environment for early planted *boro* rice than Barisal.



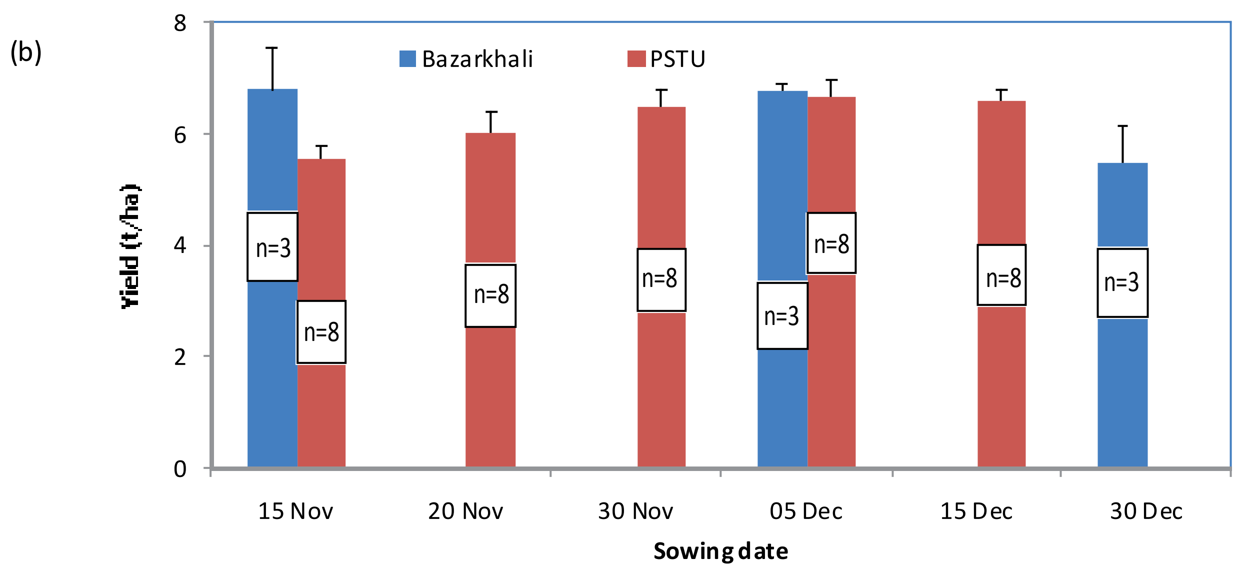


Fig. 6. Effect of sowing date of BRRI dhan28 on grain yield in moderately saline (Kismat Fultola, Khulna district) (a) and low salinity (Dumki, Patuakhali district and Bazarkhali, Barguna district) (b) areas of the coastal zone of Bangladesh. Vertical bars are standard error. Actual 2005-06 yield data for Kismat Fultola were used.

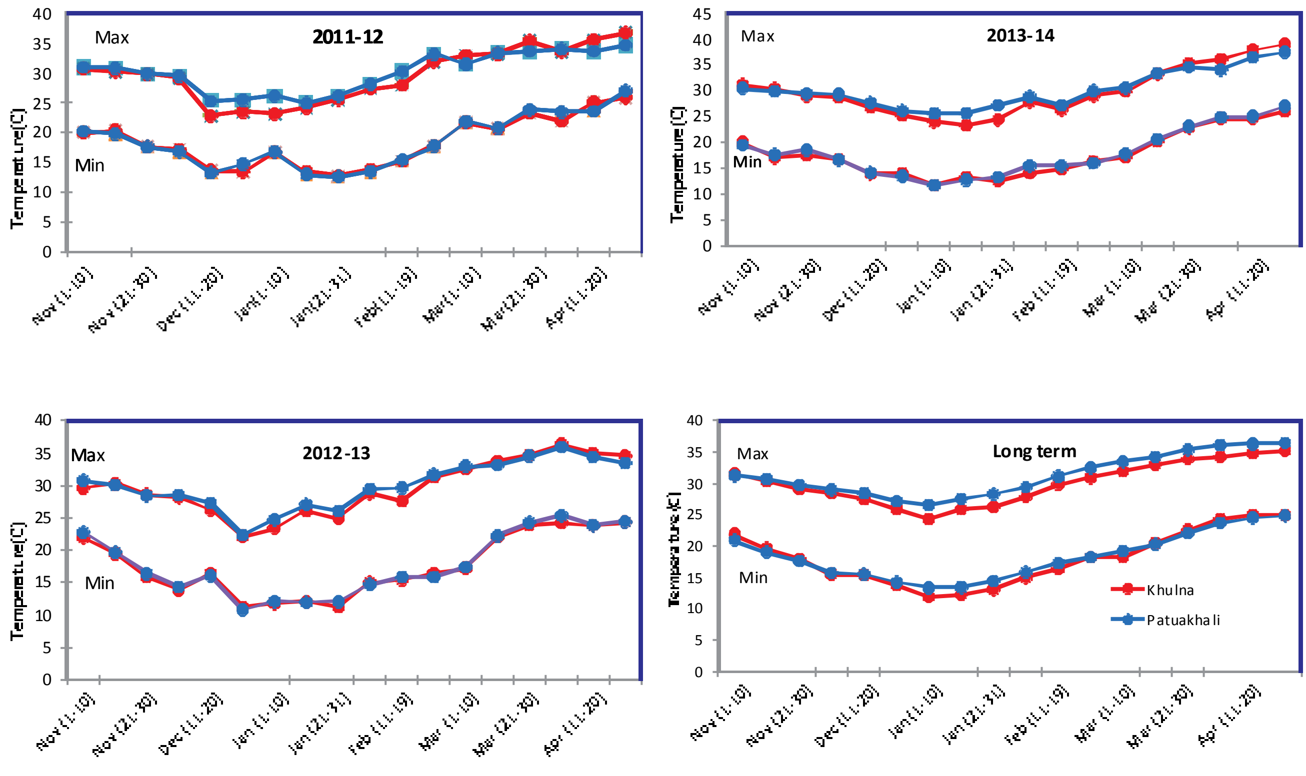


Fig. 7. Comparison of 10 d mean maximum and minimum temperatures at Khulna and Patuakhali during the 2011-12, 2012-13, 2013-14 *boro* seasons, and the long-term mean (1998-2007).

5. Conclusions and recommendations

The study provides strong evidence of the feasibility of high yielding *boro* cultivation in the south-central (Barisal Division) coastal zone of Bangladesh, where river water salinity remained <1 dS/m throughout the year. Yields of 6 to 7.5 t/ha were achieved with sowing from mid-November to mid-December in the absence of significant disease incidence. In the medium salinity site in Khulna District maximum yields of around 5 t/ha were achieved with sowing in the second week of November. Here, yields appeared to be constrained by the generally higher salinity at this location, even when salinity of the irrigation water remained below 4 dS/m throughout the season. Low temperature reduced floret fertility and yield of earlier sown crops and increased vulnerability to disease (and possibly salinity). Therefore, the development of *boro* varieties with greater cold tolerance during the vegetative and reproductive stages is needed, especially considering the narrow sowing window and risk of lower temperatures in some years that occurred during the experiment period. At all sites, infestation with stem borers was a problem in some years. Our *boro* crops were the only crops in the field and were surrounded by fallow land, and were thus more vulnerable to attack by pests and diseases. In other parts of Bangladesh where *boro* crops are widespread, farmers are able to achieve good control of pests and diseases.

Acknowledgements

This paper presents findings from PN10 'Managing Water and Land Resources for Sustainable Livelihoods at the Interface Between Fresh and Saline Water Environments in Vietnam and Bangladesh' and G2 'Productive, profitable, and resilient agriculture and aquaculture systems', projects of the CGIAR Challenge Program on Water and Food. The authors are grateful for the high quality technical assistance provided by Swapan Bhadra, Akbar Ali, Jahid Hasan, Elias Hossain, Amal Ray, Samir Sarkar, Shakti Mondal, Lincoln Ray, Tanmoy Ray and Mithun Ray.

References

Bangladesh Bureau of Statistics (BBS) 2010. *Census of agriculture 2008.* Ministry of Planning, Dhaka, Bangladesh.

Bangladesh Bureau of Statistics (BBS) 2013. *Statistical year book of Bangladesh 2012.* Ministry of Planning, Dhaka, Bangladesh.

Bangladesh Rice Research Institute (BRRI). 2005. *Adhunik dhaner chas* (Modern rice cultivation - in Bangla). BRRI, Gazipur,Bangladesh.

Bhattacharya, J., Mondal, M.K, Humphreys, E., Saha, N.K., Rashid, M.H., Paul, P.C. and Ritu, S.P. 2014. Rice-rice-*rabi* cropping systems for increasing the productivity of low salinity regions of the coastal zone of Bangladesh. These proceedings

Dhaka Tribune 2013. Salinity in coastal aquifers alarming. http://www.dhakatribune.com/bangladesh/2013/oct/20/salinity-coastal-aquifers-alarming

Hasan, M.R., Shamsuddin, M. and Hossain, A.F.M.A. 2013. Salinity status in groundwater: A study of selected upazilas of southwestern regions in Bangladesh. *J. Global Sci.Technol.* (1):112-122.

Ismail, A.M., Heuer, S., Thomson, M.J. and Wissuwa, M. 2007. Genetic and genomic approaches to develop rice germplasm for problem soils. *Plant Mol. Biol.* 65:547–570

Kabir, K. A., Karim, M., Shahrier, M.B., Saha, S.B., Chakraborty, S., Jharendu, P. and Phillips, M. J. 2014. Homestead farming systems in southwest Bangladesh: A survey. Water Land and Ecosystems Technical Paper (in press).

Khan, Z.H. and Kamal, F.A. The Ganges coastal zone – current conditions, future projections. These proceedings.

Mondal, M. K., Tuong, T.P., Sharifullah, A.K.M. and Sattar, M.A. 2010. Water supply and demand for dry-season rice in the coastal polders of Bangladesh. In C. T. Hoanh, B. W. Szuster, K. Suan-Pheng, A. M. Ismail and A. D. Noble (Eds.) *Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land-Water Interface*. Comprehensive Assessment of Water Management in Agriculture Series, no. 9. CABI Publishing pp. 264-278.

Mondal, M. K., T. P. Tuong, S. P. Ritu, M. H. K. Choudhury, A. M. Chasi, P. K. Majumder, M. M. Islam and S. K. Adhikary 2006. Coastal water resource use for higher productivity: Participatory research for increasing cropping intensity in Bangladesh. In C. T. Hoanh, T. P. Tuong, J. W. Gowing and B. Hardy (Eds). *Environmental and livelihoods in tropical coastal zones: Managing agriculture-fishery-aquaculture conflicts.* Comprehensive Assessment of Water Management in Agriculture Series, no. 2. CABI Publishing pp. 72-85.

Mondal, M.K, Paul, P.L.C., Humphreys, E., Tuong, T.P., Ritu, S.P. and Rashid, M.A. 2014. Opportunities for cropping system intensification in the coastal zone of Bangladesh. These proceedings

Saha, N.K., Mondal, M.K., Humphreys, E., Bhattacharya, J., Rashid, M.H., Paul, P.L.C. and Ritu, S.P. 2014. Triple rice in a year: Is it a feasible option for the low salinity areas of the coastal zone of Bangladesh? These proceedings

Sharifullah, A., Tuong, T.P., Mondal, M.K. and D.T. Franco. 2009. Assessing water supply and demand for dry season rice in coastal polders of Bangladesh. In: Humphreys, E. and R.S. Bayot (eds). *Increasing the productivity and sustainability of rainfed cropping systems of poor smallholder farmers.* Proceedings of the CGIAR Challenge Program on Water and Food International Workshop on Rainfed Cropping Systems, Tamale, Ghana, 22-25 September 2008. The CGIAR Challenge Program on Water and Food, Colombo, Sri Lanka. Available at: http://r4d.dfid.gov.uk/PDF/Outputs/WaterfoodCP/CPWF_Proceedings_Rainfed_Workshop%5B1%5D.pdf (last accessed 31 December 2014)

Tuong, T. P., Humphreys, E., Khan, Z.H., Nelson, A., Mondal, M.K., Buisson, M.C. and George, P. 2014. *Messages from the Ganges basin development challenge: Unlocking the production potential of the polders of the coastal zone of Bangladesh through water management investment and reform.* CPWF Research for Development Series 9. Available at: https://cgspace.cgiar.org/bitstream/handle/10568/41708/CPWF%20Ganges%20basin%20messages%20Sept%2014.pdf?sequence=5 (last accessed 30 Dec 2014).

An *aus-aman* system for increasing the productivity of a moderately saline region of the coastal zone of Bangladesh

S.P. Ritu[1,2], M.K. Mondal[3], T.P. Tuong[3], S.U. Talukdar[2] and E. Humphreys[3]

[1] Formerly: Bangladesh Rice Research Institute, Bangladesh, sanjidap05@gmail.com
[2] Sylhet Agricultural University, Bangladesh, talukder_iwm@yahoo.com
[3] International Rice Research Institute, Bangladesh and Philippines, m.mondal@irri.org, t.tuong@irri.org, e.humphreys@irri.org

Abstract

Due to lack of readily available fresh water and salinity intrusion in the dry season, most agricultural land in the coastal zone of Bangladesh grows a single rice crop (*aman*) during the rainy season, mainly using local varieties with low yield potential. This study aimed to develop a double rice cropping system with an *aus* crop grown at the onset of the rainy season followed by an *aman* crop. A field experiment (Experiment 1) was conducted in 2006-2008 in Batiaghata, Khulna District, to test the hypothesis that high and stable system productivity can be achieved in moderately saline areas by: (i) dry seeding a short-duration *aus* variety (BRRI dhan65) to advance crop establishment, (ii) supplemental irrigation during establishment, and (iii) transplanting a high-yielding *aman* variety after harvest of the *aus* crop. Experimental treatments in the *aus* season included three water regimes (rainfed, I1; supplemental irrigation, I2; full irrigation, I3) and three sowing dates (D1 = early April; D2 = mid-April; D3 = late April). In the *aman* season, two high yielding varieties BR11 and BRRI dhan53 were established by puddling and transplanting about three weeks after *aus* harvest. The findings of Experiment 1 led to a supplemental experiment (Experiment 2) in 2009, with the hypotheses that late transplanting will secure good *aus* establishment and that high yield of late planted *aman* can be maintained using a suitable photoperiod insensitive variety. The *aus* rice was established by dry seeding (M1) and transplanting (M2) with two sowing dates - 30 April (D1) and 10 May (D2). A photoperiod sensitive variety BRRI dhan46 and photoperiod insensitive variety BRRI dhan49 were transplanted in the *aman* season. The effects of irrigation and sowing date treatments on yield of *aus* varied between years, due to variation in rainfall distribution. Yields with full and supplemental irrigation were comparable (4 t/ha) and were greater than those of fully rainfed *aus* (2 t/ha) when there were dry spells after sowing. Supplemental irrigation required much less irrigation water (100-200 mm) than full irrigation (660-1042 mm) but had similar yield. The average incremental irrigation water productivity varied from 0 (in a year of adequate rainfall) to 1.3 kg grain/ha/mm. Delaying *aus* sowing to late-April delayed the planting of *aman*, decreasing the growth duration of BRRI dhan53 and reducing yield compared to yield of *aman* following earlier *aus* seeding. The duration of BR11 was less strongly affected by sowing date and had similar yield level (> 4 t/ha) to that of BRRI dhan53 with early April sowing. In Experiment 2, dry seeded *aus* had similar yield for both late April and early May sowings (>4.6 t/ha), but yield of late sown and transplanted *aus* had lower yield (3.5 t/ha) due to submergence between flowering and the start of grain filling, while yield of late sown dry seeded *aus* was not affected as the crop was more advanced at the time of flooding. For *aman*, BRRI dhan49 had higher yield (>4.6 t/ha) than BRRI dhan46 (average 4.3 t/ha) for both establishment dates. In favorable conditions, *aus-aman* cropping system yield ranged from 8.0 to 9.6 t/ha/yr. Thus, with timely establishment of *aus* (sowing near the end of April) using a modern, short duration *aus* variety, followed by a medium duration *aman* variety, it is possible to produce 8 **to** 9 t/ha/yr in the moderately saline coastal zone.

Key message: It is possible to produce 8 **to** 9 t/ha of rice per year in medium salinity areas of the coastal zone of Bangladesh by growing a modern, short duration, salt tolerant *aus* variety, followed by a modern *aman* variety.

Keywords: cropping system, direct seeding, dry seeding, Khulna, irrigation

1. Introduction

The major constraints to productivity of the agricultural lands in the polders of the coastal zone of Bangladesh are soil and water salinity during the dry season, waterlogging during the monsoon season, and lack of knowledge of modern agricultural interventions (Karim et al. 1990). Poor soil physical properties (bulk density, low permeability) and chemical properties (high pH, low total N, exchangeable cations, low available P and micronutrients) also constrain productivity of rice and non-rice crops. The salinity constraints are more acute and widespread in the south-west coastal zone (SWCZ) in Khulna Division than in the central coastal zone (Barisal Division) (Khan et al. these proceedings). Farmers in the SWCZ usually cultivate low-yielding (2.5 t/ha) traditional *aman* varieties in the monsoon season. Some farmers also cultivate sesame in the dry season, but this is often damaged by the pre-monsoon rains due to late establishment and thus late maturity.

Several attempts have been made over the past 20 years to increase the productivity of agricultural cropping systems of the SWCZ, either by improving existing systems or developing new ones. Mondal et al. (2004) showed that yield of the *aman* crop could be more than doubled by the introduction of modern high yielding varieties (HYV), which also reduced growth duration and advanced the harvest. The earlier *aman* harvest allowed 'early' (timely) establishment of *boro* rice (transplanting in mid-December), meaning that the crop could be irrigated directly using river water for the first two months after transplanting. This also meant a lower stored water requirement to finish off the crop once the rivers become too saline (mid-February). Mondal et al. (2006) showed that annual rice yield could be increased to 6.0 to 8.5 t/ha with this HYV *aman-boro* system at Batiaghata, Khulna. However, the expansion of this cropping system is constrained by the limited amount of water that can be stored in the canal networks to finish off the *boro* crop, and the risk of salinity if the sluice gates are not properly closed once the river water becomes saline (Mondal et al. 2015). Another option for increasing the productivity of the SWCZ could be to intensify to an *aus-aman* system. This system is practiced in many parts of Bangladesh (SRDI 2004), but not in the SWCZ. The *aus* crop needs to be established early enough so that the *aman* crop can be planted on time for maximum yield. However, early *aus* establishment usually requires irrigation. In the SWCZ, the river water is too saline for irrigation for early (April-May) *aus* establishment. However, delaying establishment of the *aus* crop until after the onset of the monsoon rains could lead to late harvest, delayed establishment of the *aman* crop and reduced *aman* yield. Dry seeding (direct seeding into dry tilled soil) instead of transplanting into puddled soil may enable early *aus* establishment. In water scarce areas of other parts of Asia, the use of dry seeding has enabled double cropping of rice during the rainy season, thereby increasing farm productivity (Tuong and Bouman 2003; Tuong 1999). Dry seeding enables early crop establishment on the pre-monsoon rains, rather than waiting until there has been enough rain to puddle the soil for wet seeding or transplanting.

Therefore, the present study was undertaken with the hypothesis that with the use of a short-duration, dry-seeded HYV *aus* variety followed by HYV *aman*, it is possible to intensify to a highly productive *aus-aman* system in the SWCZ. Successful implementation would require knowledge of the optimum time for establishment of dry seeded *aus*. Sowing too early could lead to poor establishment due to water deficit stress. In such situations, the use of non-saline groundwater could be used to help establish the crop. But the availability of non-saline groundwater in the coastal zone is limited, and pumping is costly, therefore sowing and management practices that minimize irrigation water requirement would be needed. On the other hand, sowing too late could delay harvest and establishment of the *aman* crop beyond the optimum time, which may in turn reduce *aman* yield. Most commonly available *aman* varieties in Bangladesh are photoperiod-sensitive (flowering is delayed until October); late establishment of photoperiod-sensitive varieties would limit biomass accumulation prior to anthesis, thus reducing grain yield. One possible solution is the use of photoperiod-insensitive *aman* varieties.

Experiments were carried out to test the feasibility of an *aus-aman* cropping system in the SWCZ, and to develop a technology package that would lead to stable and high yield with minimum irrigation water requirement to establish the *aus* crop. The specific objectives were: (i) to evaluate the effects of date and method of *aus* establishment and *aus* irrigation management on the growth and yield of both crops in an *aus–aman* system, (ii) to evaluate *aman* varieties for the *aus-aman* system, and (iii) to determine the effects of sowing date and water management on irrigation water requirement of dry seeded *aus*.

2. Materials and Methods

2.1. Experimental site

Two experiments were conducted at two sites (one experiment per site) about 4 km apart in Batiaghata *Upazila*, Khulna District. Experiment 1 (2006-2008) was established in Basurabad village (site 1), and experiment 2 (2009) was in Fultola village (site 2). Both sites had a cropping system history of a transplanted local *aman* variety (yield about 2-3 t/ha), followed by a late planted, low yielding sesame crop.

The soil at site 1 was silty clay and fairly uniform to the sampling depth (90 cm), with 45-53% clay and 44-54% silt (Table 1). The texture of the topsoil at site 2 was similar to that at site 1. The topsoil (0-15 cm) at both sites was slightly alkaline, with 2.0-2.6% organic matter (Table 2). Total N content of the topsoil was low at 0.1%, while available P and exchangeable K content were adequate. Micronutrient content (S, B, Cu, Fe, Mn and Zn) of the topsoil at both sites was sub-optimal. The soil properties were typical of soils of the coastal zone; Haque (2006) found that most saline soils of the coastal zone have low to very low organic matter, N, P and micronutrient (Zn, Cu) contents.

Table 1. Bulk density, particle size analysis and texture of the soil profile at site 1

Depth (cm)	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	Texture
0-15	1.4	1.2	47.8	51.1	Silty clay
15-30	1.6	5.2	49.8	45.1	Silty clay
30-45	1.5	3.2	53.8	43.1	Silty clay
45-60	1.3	3.2	47.8	49.1	Silty clay
60-75	1.4	3.2	46.8	50.1	Silty clay
75-90	1.4	3.2	43.8	53.1	Silty clay

Table 2. Chemical properties of the topsoil (0-15 cm) at the experimental sites

	pH	Total N (%)	Organic matter (%)	Exchangeable (meq 100 g^{-1} soil)			Avail. P	S	B	Cu	Fe	Mn	Zn
				K	Ca	Mg	(µg g^{-1})						
Experiment 1													
Mean	8.0	0.1	2.0	0.4	24.4	3.6	**13.8**	125	0.7	3.6	20.7	10.3	0.7
SE[1]	0.1	0.0	0.1	0.0	1.3	0.1	**2.0**	12.8	0.1	0.2	1.5	0.9	0.1
Experiment 2													
Mean	7.9	0.1	2.6	0.5	17.0	5.3	**6.7**	71.6	0.8	4.8	95.8	12.4	0.8
SE	0.1	0.0	0.1	0.0	0.8	0.2	**1.2**	7.2	0.0	0.7	15.3	0.7	0.0

[1]SE = standard error of the mean

2.2 Experimental design

2.2.1 Experiment 1 (2006-2008)

Experiment 1 was designed to evaluate the effects of *aus* sowing date, *aus* irrigation management and *aman* variety on the performance of the *aus-aman* cropping system. For the *aus* crop, a short duration, salt tolerant variety OM1490 (released in October 2014 as BRRI dhan65) was established by dry seeding, while the *aman* crops were transplanted about 7 d after harvest of the *aus* crops.

Aus treatments

Main plots: Water regime (I)

I1 = rainfed (RF)

I2 = supplementary irrigation (SI) to ensure adequate soil moisture during crop establishment up to three weeks after emergence

I3 = full irrigation (FI) throughout the growing season

Sub plots: Date of sowing (D)

D1 = early April (5-10 April)

D2 = mid-April (10-15April)

D3 = late April (25-30 April)

Aman treatments

Main plots: Variety (V)

V1 = BR11 (planted in the *aus* I3 plots)

V2 = PVST2 (BR 5778-156-1-3-HR14) (planted in the *aus* I2 plots)

Sub plots: Date of transplanting (D)

D1 = 10 August

D2 = 15 August

D3 = 30 August

BR11 was selected as it is one of the highest yielding *aman* rice varieties and only slightly photoperiod sensitive, with a nominal growth duration of 145 d. The line PVST2 (released as BRRI dhan 53 in 2010) was also selected as it has the same yield potential as BR11, but with 5 d less growth duration. This variety also has moderate salinity tolerance.

The *aman* varieties were randomly assigned to the I2 and I3 main plots, and transplanting dates were randomized within each *aman* variety main plot. The I1 plots were also planted with *aman* crops to avoid border effects. The size of each experimental unit (sub plot) in both seasons was 8 m x 6 m. The main plots and internal bunds were 50 cm x 20 cm and 20 cm x 20 cm, respectively, and were compacted to prevent seepage between adjacent plots.

2.2.2 Experiment 2 (2009)

Based on the findings of experiment 1, it was hypothesized that transplanting *aus* rice is more suitable than dry seeding if crop establishment is delayed until rainfall becomes more frequent. Furthermore, it was hypothesized that the use of late planted photoperiod sensitive varieties in the *aman* season would reduce yield due to reduced growth duration in comparison with a suitable photoperiod insensitive variety. Therefore a cropping system experiment was conducted to compare the effects of two *aus* establishment methods (dry seeded, transplanted), two *aus* seeding dates (30 April, 11 May) and two *aman* varieties (sensitive and insensitive to photoperiod) on cropping system productivity (Table 3). It was planned to have a 10 d interval between the sowing (and thus transplanting) dates of the *aman* sowing date treatments. But the seedlings transplanted on 1 September 2009 (sown on 1 August) were destroyed by heavy rain in the first week of

September. Therefore, seedlings from a backup seedbed (sown on 5 August) were used and both sowing date treatments were transplanted on 11 September (35 and 30 d after sowing, DAS).

Table 3. Details of treatments in experiment 2

Aus			*Aman*		
Main plot	Sub plot		Main plot	Sub plot	
Establ. method	Date of seeding	Harvest date	Variety	Date of seeding (transplanting)	Harvest date
Dry seeding	30 Apr	15 Aug	BR 46	5 Aug (11 Sep)	9 Dec
	11 May	19 Aug		10 Aug (11 Sep)	11 Dec
Transplanting	30 Apr	17 Aug	BR 49	5 Aug (11 Sep)	9 Dec
	11 May	27 Aug		10 Aug (11 Sep)	11 Dec

The *aus* crop was established in a strip-plot design with crop establishment method as the main plot in a single long strip, and date of seeding was in subplots with four replicates (two diagonally opposite subplots per replicate). The two *aman* varieties were planted in two strips within each *aus* establishment method plot. The size of each *aus* sowing date x *aman* variety unit (sub-subplot) was 4 m x 3 m. The main plot and internal bunds were 50 cm x 20 cm and 20 cm x 20 cm, respectively. All bunds were compacted to prevent seepage between adjacent plots.

2.3. Crop management

The land was plowed under dry conditions for the dry seeded *aus*, and was puddled for the transplanted *aus (*2009) and all *aman* crops. No irrigation was required for puddling as a result of rainfall. The dry seeded *aus* was sown with 20 cm row spacing and three to four seeds were sown at a spacing of 20 cm within each row (hill density 25 m^{-2}).

The seedbeds for the transplanted rice (2009 *aus* and 2006-09 *aman* crops) were prepared in separate places outside the experimental fields. The rice seeds were soaked for 12 h, incubated for 48 to 72 h, and sown by broadcasting at 100 and 50 g m^{-2} for the transplanted *aman* and *aus*, respectively. The seedlings were raised using rainwater and groundwater during the *aman* and *aus* seasons, respectively. Insecticide and urea were applied to protect the seedlings and to ensure good seedling growth (BRRI 2004). Thirty-day-old seedlings were transplanted after final land leveling at a spacing of 20 cm x 20 cm in the *aman* season (BRRI 2009b). Seedlings of 20-day-old varieties were used in the 2009 transplanted *aus* at a spacing of 20 cm x 20 cm.

Basal fertilizers at 60, 40, 10 and 60 kg P_2O_5, K_2O, $ZnSO_4$ and $CaSO_4$ per ha, respectively, were incorporated into the soil during the last harrowing of both crops. Urea was applied to both crops at 120 kg N ha^{-1} in four equal splits 15 d after emergence (DAE), mid-tillering (30 DAE), 5 d before panicle initiation (DBPI, 45 DAE), and at heading in the *aus* season, and at basal, mid-tillering (35 d after transplanting, DAT), 5 DBPI (45 DAT), and heading in the *aman* season.

Good weed control was achieved in the dry seeded rice by applying the pre-emergence herbicide Longstar 25 EC @ 0.2 kg *ai* ha^{-1} to the moist soil 1 DAS, followed by the post-emergence herbicides Ronstar 25 EC and Longstar 25 EC @ 0.2 kg a.i. ha^{-1} two weeks after emergence, plus hand weeding as needed. In the *aman* crops, hand weeding was done just before each urea top dressing.

Attacks of insects, pests, and diseases were closely monitored. Granular systemic pesticides diazinon 10G (1.68 kg a.i. ha^{-1}) and carbofuran 5G (0.5 kg a.i. ha^{-1}) were applied at 15-d intervals to protect the crops from stem borer infestation. Diazinon 10EC (0.1 kg a.i. ha^{-1}) was sprayed during the mid-tillering stage at 15-d intervals to prevent infestation of leaf roller and yellow stem borer each season. Carbendazim 50WP (0.25 kg ai ha^{-1}) and carbosalfan 20EC (0.15 kg ai ha^{-1}), along with copper oxychloride 50 WP (@ 0.1725 kg ai ha^{-1}), were sprayed to control brown spot and leaf blight. Gypsum and a mixture of potassium and sulfur (1:1 ratio), basally applied at 60 kg ha^{-1}, helped to prevent fungal disease infestation and aided crop recovery along with fungicides. Malathion 57EC was applied at 0.57 kg ai ha^{-1} during the grain-filling stage to prevent grain spot. Despite these measures, yield loss due to pests and diseases occurred in some treatments in some years (section 3.3.2).

2.4 Water management

Groundwater (EC<2 dS/m) was used for irrigation in both experiments. In experiment 1, the *aus* crop was irrigated according to treatment using groundwater. At each irrigation water was added until the topsoil was saturated. In 2009, both the dry seeded and transplanted *aus* were irrigated as needed throughout the season. The *aman* rice crops were mainly rainfed. During excessive rainfall, water was pumped from the experimental field as needed to maintain a suitable water depth for modern, high yielding rice varieties.

2.5 Monitoring

2.5.1 Soil salinity

Salinity of the topsoil (0-15 cm) was determined before each *aus* seeding and at 15-d intervals during the period of *aus* establishment (April-June), and monthly at other times. Electrical conductivity of the saturation extract was determined using the American Society of Agronomy and Soil Science Society of America (1982) method at the Soil Research and Development Institute laboratory at Khulna.

2.5.2 Crop performance

Establishment of dry seeded aus. After seeding of the dry seeded *aus*, the number of hills in which plants had emerged was counted daily from four rows per plot, two rows from two sides of each plot, until 50% of the hills had emerged plants (mean of four replicates). This was taken as the date of 50% emergence.

Crop development. In both seasons, the dates of anthesis and physiological maturity were determined. The date of 50% anthesis was estimated by visual observation of 10 rows per plot in each replication. Physiological maturity was taken as the date when 80% of the grains in the whole field had become golden, following the procedures of Cassman (1994) and IRRI (1994).

Yield components. Yield components (panicles density, total spikelets per panicle, % filled spikelets, 1000-grain weight on oven dry weight basis) were determined from 16 hills following the procedures of Cassman (1994) and IRRI (1994).

Grain yield. Grain yield was determined in 4 m x 2 m and 2 m x 1 m areas in the middle of each sub plot during 2006-2008 and 2009, respectively. Grain yield was calculated at 14% moisture content (Gomez 1972).

2.5.3 Irrigation amount

The discharge rate of the tubewell was determined using the volumetric method (Michael 1978): Q = V x T
where Q = discharge rate, m^3/s

V = volume of the bucket, m^3

T = time required to fill the bucket, s

The time required to irrigate each plot was recorded, and the depth of applied water was calculated from the product of discharge rate and time divided by the plot area (m^2). Total irrigation during the growth of rice was determined by summing the amount of water applied during each irrigation.

2.5.4 Incremental water productivity

Incremental water productivity was calculated during the *aus* 2006-08 seasons. Incremental water productivity is the yield increase of the irrigated treatment over yield of the rainfed treatment divided by the amount of irrigation water applied.

2.5.5 Weather data

A rain gauge and a USWB Class A evaporation pan were installed near the experimental field and monitored daily at 8 AM. Monthly totals of rainfall and evaporation were calculated. Other weather data including maximum temperature (Max T) and minimum temperature (Min T) were collected from Khulna meteorological station, about 8 km north of the experimental sites.

2.6 Statistical analysis

In experiment 1, the crop and irrigation input data were analyzed using a standard split plot analysis of variance (ANOVA) for each crop. In experiment 2, the *aus* and *aman* crop data were analyzed using a strip plot ANOVA. Total system yield was determined by summing the yields of the aus and aman crops. Statistical analysis of total system yield (*aus* plus *aman*) in 2006-2008 was done for the systems in which the *aus* was fully irrigated (I3), by two factor ANOVA in a split plot design with *aman* variety as the main plot and *aus* sowing data as the sub plot. Total system yield in 2009 was done by three factor strip plot ANOVA with aus establishment method in the strips, and with *aus* sowing date and *aman* variety fully randomized sub plots. The least significant difference (LSD) test at 5% probability was used to compare treatment means.

3. Results

3.1 Weather

The wet season started in May in all years except 2007, when it started in June, and usually ended between late September and mid-October (Figs 1a, 2). Annual rainfall varied from 1600 mm in 2008 to 2000 mm in 2006, about 80% of which occurred from June to October, compared with the long term (1999 to 2006) average of 1685 mm. Rainfall was unusually high in July 2006, August 2009 and September in all years, and unusually low in April in all years except 2007. Evaporation was usually similar to the long term values, except for unusually high evaporation during the relatively dry rainy season (May-August) in 2008. Monthly evaporation ranged from 55 to 65 mm in January and December each year to around 180 mm in May to August of 2008.

Temperature was favourable for rice throughout the cropping period (Fig. 1b). Mean monthly minimum and maximum temperatures during the *aus-aman* period were similar to the long term average each year. Mean maximum temperature tended to be highest during the period of establishment of *aus (*April/May*,* around 36°C), and fluctuated around 32°C, during the remainder of the *aus-aman* period each year. Mean monthly minimum temperature was around 20 to 25°C throughout the *aus-aman* period each year.

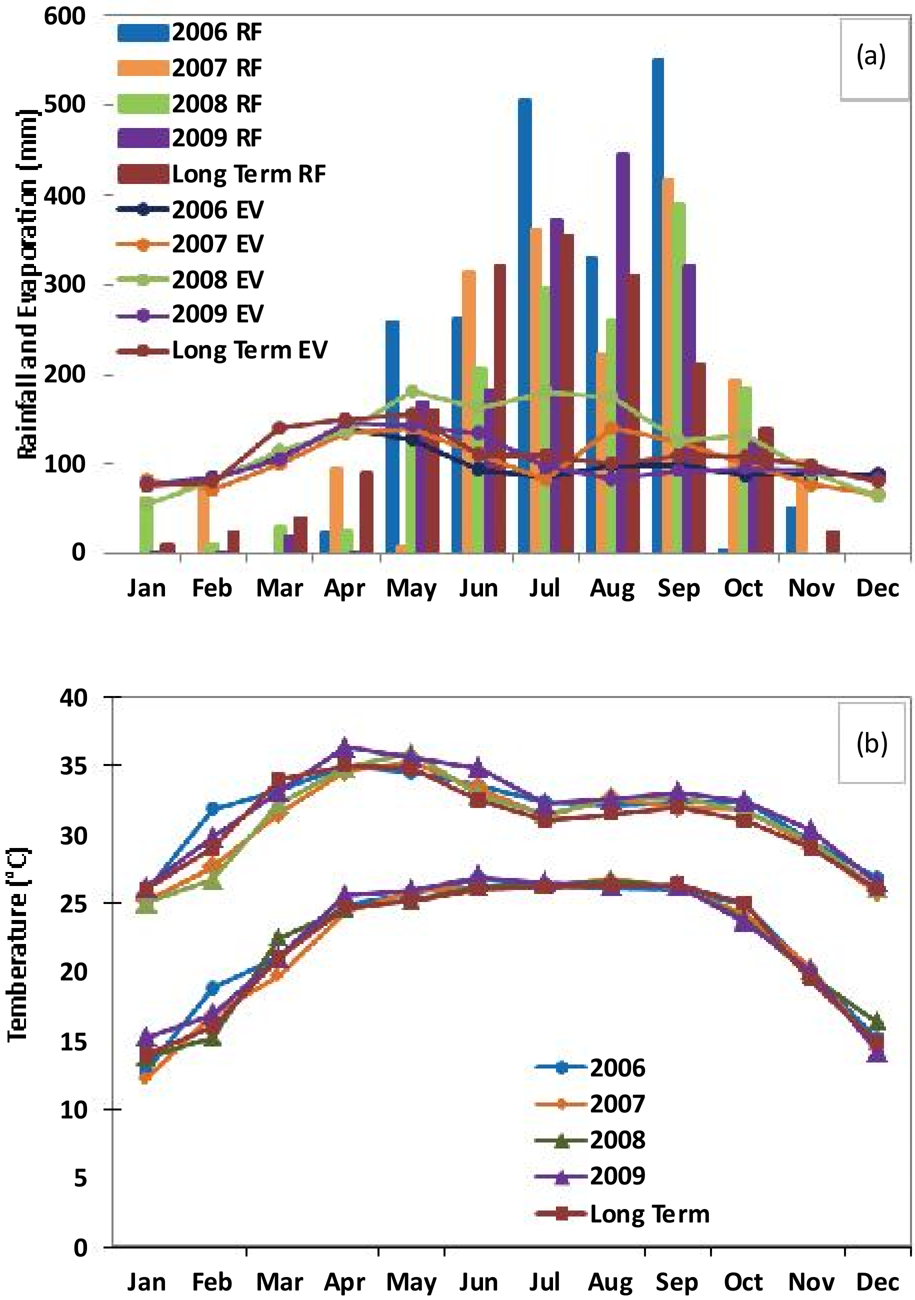


Fig. 1. a) Monthly total rainfall (RF) and evaporation (EV) and b) monthly average maximum and minimum temperatures during 2006-2009 in comparison to the long term (1999-2006) data for Khulna City.

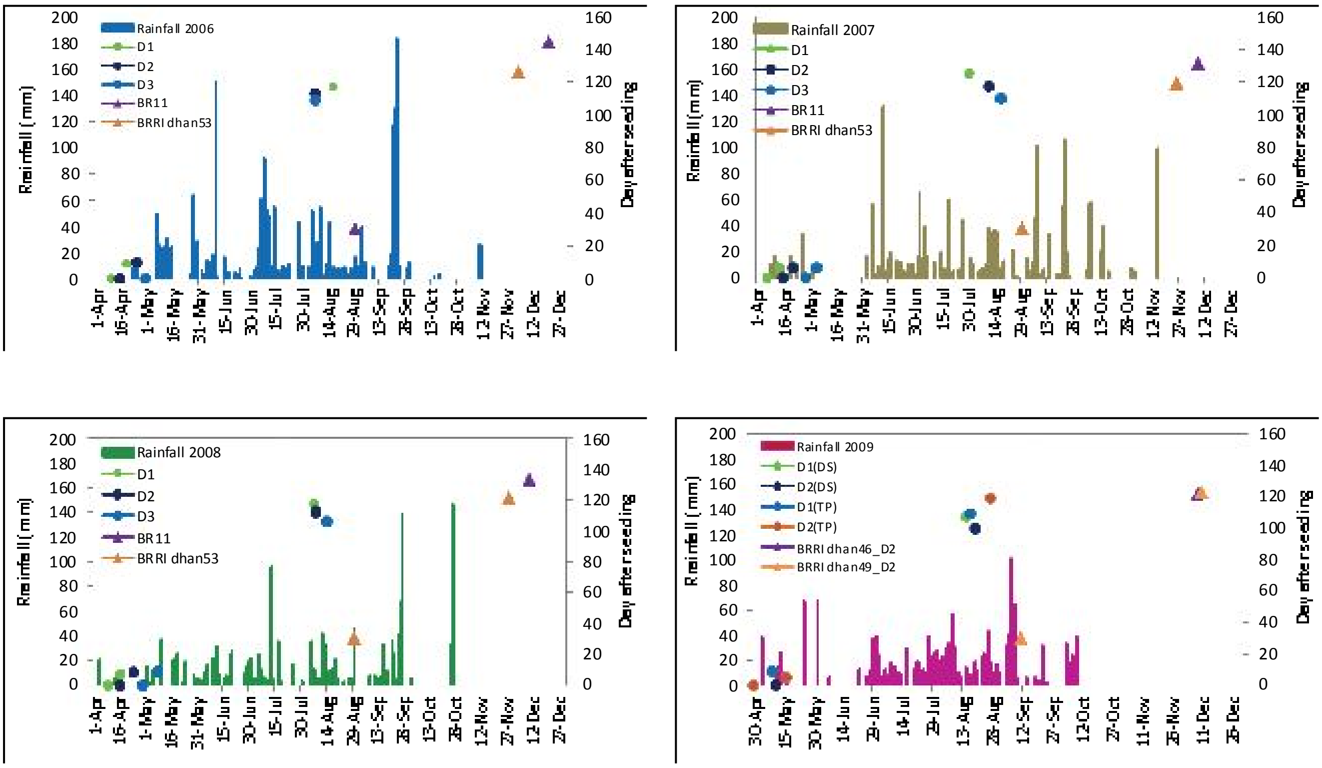


Fig. 2. Daily rainfall during the *aus* and *aman* seasons of 2006 to 2009. The dates of seeding, emergence and physiological maturity of fully irrigated (I3) *aus* (2006-2008), and of dry seeded (DS) and transplanted (TP) *aus* (2009) are indicated by colored dots. The dates of transplanting and maturity of the *aman* varieties are indicated by colored triangles

3.2 Soil salinity

Topsoil salinity of the saturation paste extract (ECe) generally varied from about 4 to 6 dS/m, with higher values in April and June 2007 as a result of the late onset of the monsoon rains (Fig. 3). Salinity decreased to 2-3 dS/m during the rainy season in some but not all years.

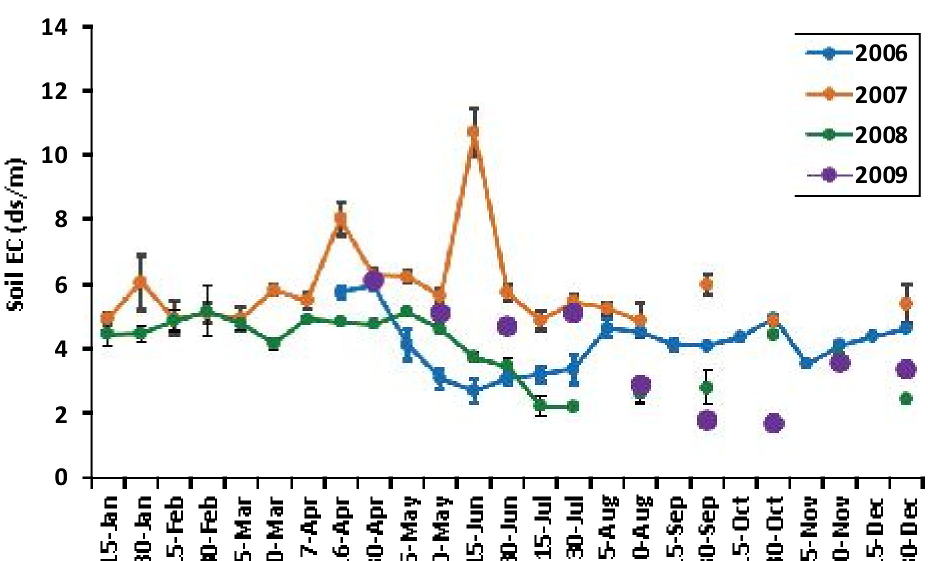


Fig. 3. Topsoil (0-15 cm) ECe (dS m^{-1}) of the study area during the study period (2006-2009). Vertical capped bars are standard errors of the means.

3.3 Effect of sowing date and irrigation method and establishment method on aus crop performance

3.3.1 Insect, pest and disease infestation

Pest and disease infestation were common during both the *aus* and *aman* cropping seasons each year. In both seasons leaf rollers attacked during the early vegetative stage, stem borers from the vegetative to flowering stages, and rice bugs in the grain filling stage; however, these infestations were well-controlled and did not affect yield. The main diseases were leaf blight in 2006, and brown spot and grain spot in 2007-2009. These diseases were also well-controlled and not yield-reducing (section 2.3).

For irrigated dry seeded *aus*, soil moisture fluctuated between saturated and field capacity most of the time during the early establishment period. This created a environment conducive for soil pests (cutworms and ants). Whenever the soil surface became dry, insects were visible in the field. Cutworms cut the roots of the young plants and the problem only became visible when the hills became yellowish, and ants removed the sown seed. Severe cutworm damage occurred in the irrigated treatments of the early sown (D1) 2007 *aus*. Severe infestation also occurred in all sowing date treatments in the 2008 cropping season, mainly affecting I3. Repeated application of systemic insecticides at double the usual rate did not stop the attack in 2008, probably due to adulteration of the insecticide. In *aus* 2006, cutworms were not a problem, probably due to the higher rainfall in May. Cutworms and ants caused little damage in 2009, because of the combination of irrigation and insecticide provided good control.

3.3.2 Aus establishment and population dynamics

Fifty percent emergence of dry seeded *aus* in the irrigated treatments occurred from 6 to 20 DAS depending on the incidence of rainfall and on the irrigation treatment. Emergence of dry seeded rice was faster with irrigation than under rainfed conditions, except for the early April 2007 sowing when there was optimal rain (10 and 28 mm 1 d before and 2 to 3 d after the first sowing date, respectively)(Fig. 4). In most situations, final hill density under rainfed conditions (5-10 hills m^{-2}) was much lower than under irrigated conditions (14-24 hills m^{-2}). The irrigated treatments did not suffer from water stress during establishment, yet hill density was sometimes less than the theoretical maximum. This was due to insect pest damage as described above. De Datta (1981) reported that cutworm is a problem in upland (dry seeded) rice. In the dry seeded plots of experiment 2 in 2009, hill density was the theoretical maximum (25 hills m^{-2}) for both seeding dates because full irrigation enhanced crop establishment and there was no pest damage.

3.3.3 Water depth during the aus crops

The experimental field was occasionally flooded by water from surrounding (higher) lands that overtopped the bund surrounding the experimental field following heavy rainfall. In June 2006, the entire crop was submerged for 4 d, when the irrigated crops of D1 and D2 were at the panicle initiation stage and all the rainfed crops and the irrigated crops of D3 were at mid tillering (Table 4). High rainfall in July 2006 again submerged the irrigated rice of D1 and D2 at the flowering stage. In 2009, the late sown transplanted *aus (*M2 D2) was submerged for several days between flowering and grain filling.

Table 4. Rainfall and water levels inside and outside the experimental field that caused partial or complete submergence of the crops, and the dates and stages at which submergence occurred during the *aus* season

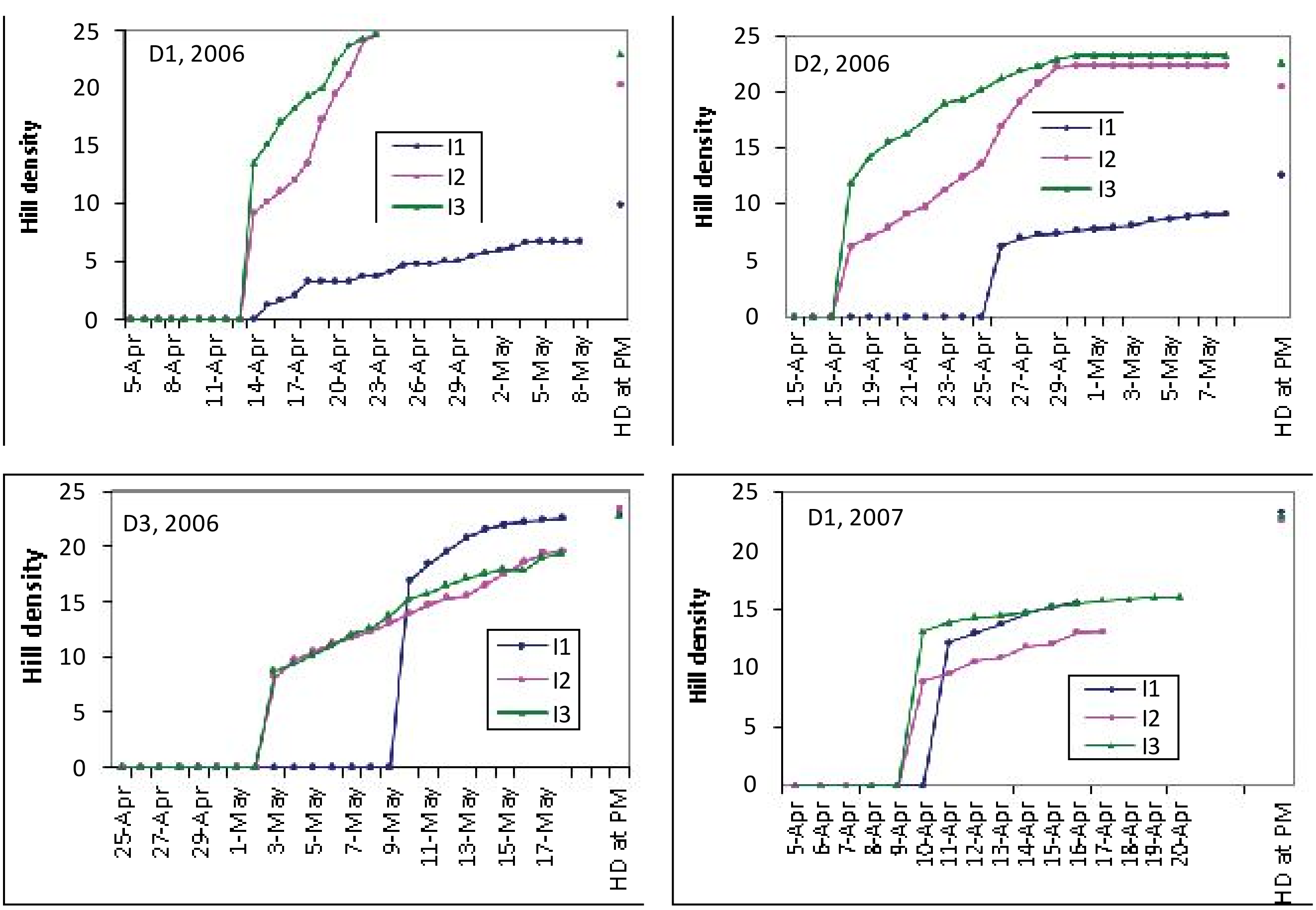
Raifall period	Total rainfall (cm)	Average field water level (cm)	Water level outside expt field (cm)	Submergence period	Crop phenology[1] (treatments)[2] affected
2006					
24 May-10 Jun	32	32	32	10 -14 Jun	MT[1] (I_1D_1, **I_1D_2***, I_1D_3 ; I_2D_3 I_3D_3) *aus* **PI[2]** (I_2D_1, **I_2D_2*** , I_3D_1, **I_3D_2***) *aus*
1–14 Jul	40	40	50	7-14 Jul	**FL[3]** (I_2D_1, **I_2D_2*** , I_3D_1, **I_3D_2***) *aus*, seedbed *aman* (D_1)
2009					
20 Jul-9 Aug	60	80	80	6 -12 Aug	**FL-GF[4] (transplanted D_2* *aus*)**

[1]MT = maximum tillering, [2]PI = panicle initiation, [3]FL = flowering, [4]GF = grain filling

[5]I =Water regimes in the aus season; I1 = rainfed, I2 = supplementary irrigation, and I3 = full irrigation

[6]D = date of sowing; D1 = 5-10 Apr, D2 = 15-20Apr, D3 = 25-30 Apr (2006-08); D1= 30 Apr and D2 = 10 May (2009)

*Bold fonts indicate severely affected crops



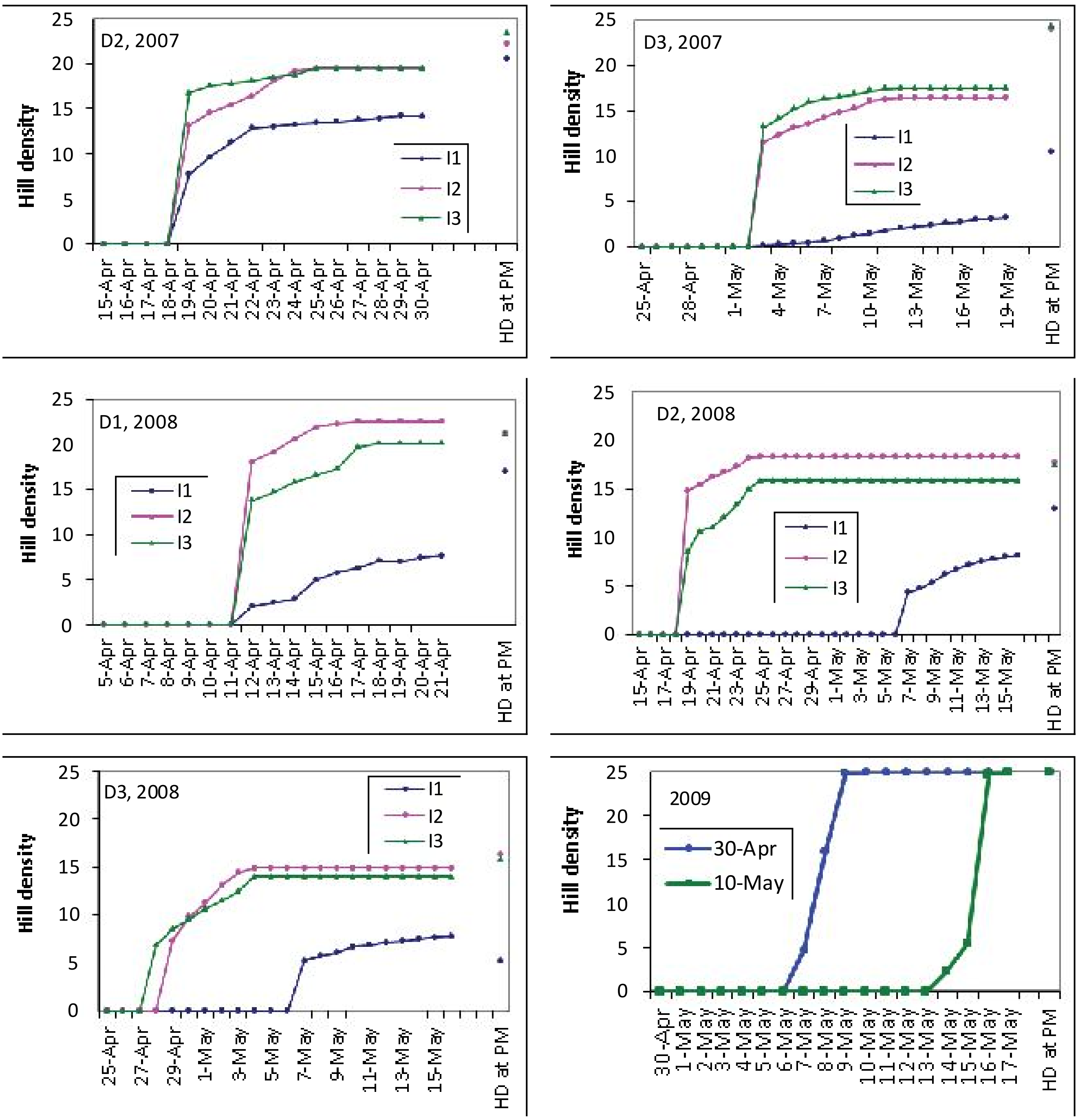


Figure 4. Hill density of dry seeded *aus* from seeding to physiological maturity (PM) as affected by water regime (I1= rainfed, I2= supplementary irrigation and I3 = full irrigation) and sowing date (D1, D2 and D3) during 2006-2008 cropping seasons, and irrigated dry seeded *aus* as affected by sowing date (D1 and D2) in 2009.

3.3.4 Aus phenology

2006-2008. Crop duration varied from around 110 to 130 d across sowing dates and irrigation treatments each year (Table 5). There was a consistent trend for around 10 d shorter duration as sowing was delayed from early to late April in both rainfed and irrigated treatments. The decrease in duration was due to a shorter time from sowing to flowering as sowing was delayed, which was probably due to increasing temperature during April/early May (Fig. 5) (Yoshida 1981). There was little effect of time of sowing on duration of the grain filling period.

Flowering and PM were delayed in the rainfed treatments when establishment was delayed as a result of inadequate rain, as for the first sowing each year, and the second sowings in 2006 and 2007. Physiological maturity was delayed in the irrigated treatments of the second sowing in 2006 as a result of water stagnation during flowering (Table 4).

Table 5. Time (days after sowing, DAS) of flowering and physiological maturity of *aus* crops as affected by irrigation treatment and date of sowing (2006-2008) and by establishment method and date of seeding (2009)

	Flowering			Physiological maturity			Grain filling		
	I1	I2	I3	I1	I2	I3	I1	I2	I3
2006 – dry seeded									
10 Apr	107	88[1]	97	129	117	117	22	29	20
15 Apr	102	97	95	124	113	113	22	16	18
30 Apr	88	95	87	110	109	109	22	14	22
2007 – dry seeded									
7 Apr	98	98	98	123	121	125	25	23	27
16 Apr	104[2]	92	92	130[2]	120	117	26	28	25
29 Apr	97	90	88	120	110	110	23	20	22
2008									
9 Apr	106	99	94	129	117	117	23	18	23
16 Apr	95	92	86	119	112	112	24	20	26
29 Apr	95	92	85	116	107	106	21	15	21
2008 – dry seeded									
9 Apr	106	99	94	129	117	117	23	18	23
16 Apr	95	92	86	119	112	112	24	20	26
29 Apr	95	92	85	116	107	106	21	15	21
2009 – dry seeded									
30 Apr	-	-	75	-	-	107	-	-	32
11 May	-	-	70	-	-	100	-	-	30
2009 – transplanted									
30 Apr	-	-	78	-	-	109	-	-	31
11 May	-	-	78	-	-	119[3]	-	-	41

[1]Delayed and poor establishment (Fig. 3b)

[2]Water stagnation during flowering

[3]Water stagnation during flowering and early grain filling

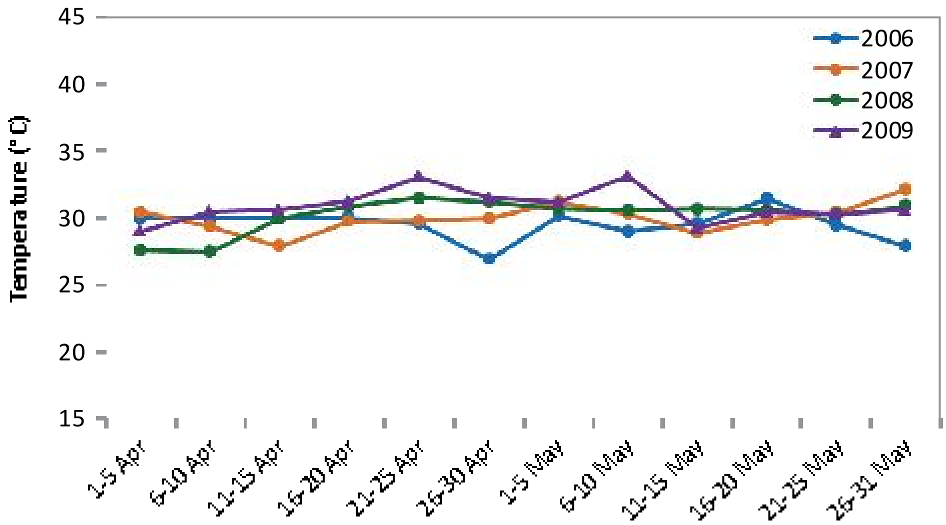


Fig. 5. Mean daily temperature (5-d means) at Khulna in April to May during 2006 to 2009.

2009. Duration of the 30 April dry seeded and transplanted *aus* crops was similar to that of the late April sown irrigated crops in the previous three years. Delaying sowing to 11 May further reduced duration of the dry seeded crop to 100 d, however, duration of the transplanted crop increased to 119 d (Table 5). The longer duration of the late sown transplanted crop was due to both later flowering and a longer grain filling period. The longer grain filling period was due to the fact that the crop was flooded (80 cm water depth for about 7 d during flowering and early grain filling) (Table 4).

3.3.5. Yield and yield components

Experiment 1. Grain yield of the sowing date by irrigation management treatment combinations ranged from 0.7 to 4.5 t/ha (Figs 6a-c). Yields in 2008 were generally lower than in the other two years due to pest infestation and less rainfall.

The interaction between water regime and sowing date on all yield components and grain yield was not significant (P=0.05) in 2006 and 2008, but was significant in 2007. In 2006 and 2008, grain yield was significantly affected by sowing date, but not by irrigation treatment.

The response to irrigation treatment and sowing date was variable depending on the incidence and amount of rainfall each year, and of flooding. Under favourable conditions (adequate water, no submergence or water stagnation, no severe disease or pest infestation), yield was similar for all sowing dates and around 4 t/ha.

There was a consistent trend for the irrigated treatments to have higher yields than rainfed treatments in years when the rice was seeded during dry spells, with significant differences in 2007. This was due to poor establishment (Figure 4) and low panicle density (Table 6) of the rainfed treatments in the absence of adequate rainfall. Better establishment (higher plant density) resulted in higher yield, except when submergence occurred at critical stages (in I2 D2 and I3 D2 of 2006) (Table 4) and when pest damage occurred (all irrigation treatments of D1 2007 and D1 2008)(section 3.3.1)(Ritu 2012). Submergence of the second sowing of both irrigated treatments in 2006 tended to reduce panicle density and/or the number of spikelets per panicle.

Experiment 2. In *aus* 2009, yields ranged from 3.5 to 4.7 t/ha (Fig. 7). The interaction between establishment method and sowing date on grain yield was significant at p<0.064. The interaction was due to a large decline in yield of transplanted rice for the second sowing due to submergence between flowering and the start of grain filling (Table 4). The panicles were fully submerged, whereas the other treatments were more advanced and the panicles were above the water. The submergence of the later sown transplanted rice resulted in a 23% reduction in the number of spikelets per panicle, whereas the number of spikelets per panicle in the dry seeded rice increased with the second sowing (Table 7). This is consistent with the findings of Reddy and Mittra (1985) that submergence of rice at flowering is very detrimental to grain yield. Delaying sowing reduced panicle density of both the dry seeded and transplanted rice, but in the case of the dry seeded rice, this was compensated for by more spikelets per panicle. Within sowing date, panicle density of dry seeded rice was much higher than for transplanted rice, as commonly found (e.g. Sudhir-Yadav et al. 2011).

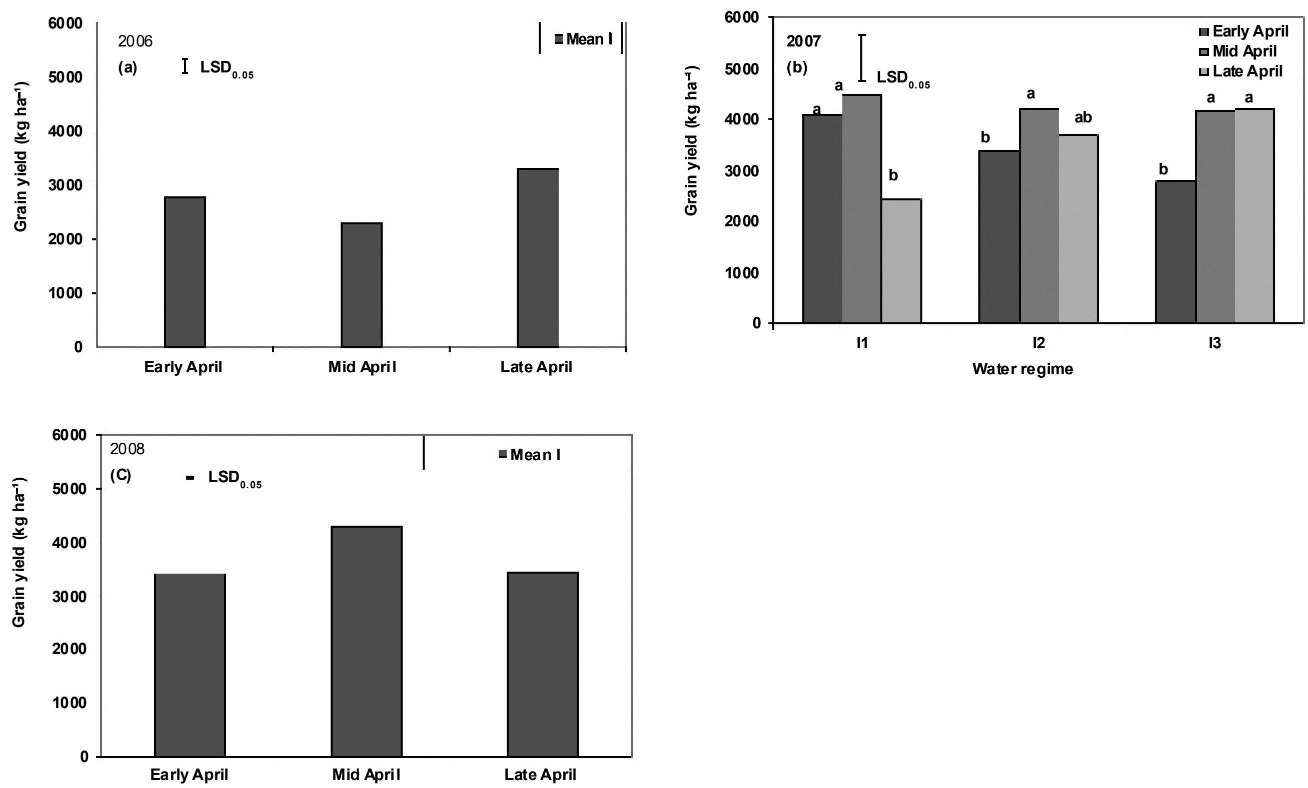


Fig. 6. Grain yield of *aus* rice in (a) 2006, (b) 2007 and (c) 2008 as affected by sowing dates (D_1 = early April, D_2 = mid April and D_3 = late April) and water regimes (I_1 = rainfed, I_2 = supplementary irrigation, I_3 = full irrigation). Vertical bars are the LSD (P=0.05) for seeding dates in 2006 and 2008, and for the interaction between seeding date and irrigation treatment in 2007.

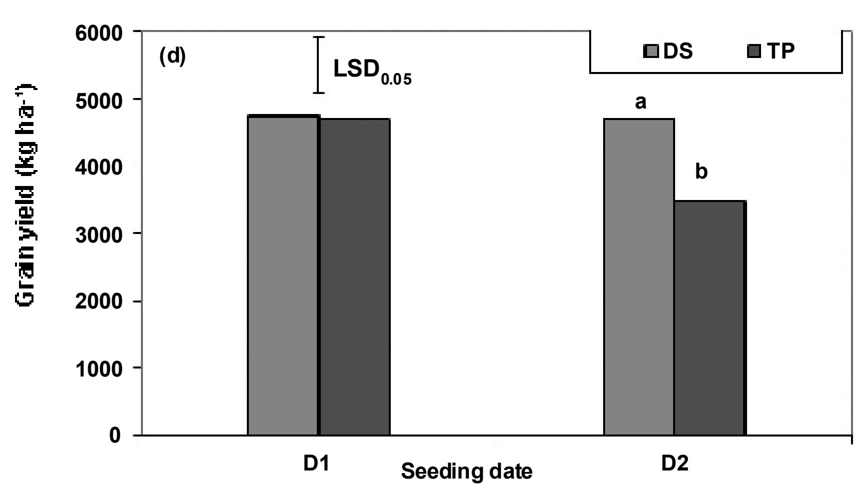


Fig. 7. Grain yield of *aus* rice as affected by establishment method and sowing date in 2009. DS = dry seeding, TP = transplanting, D_1 = sowing on 30 April, D_2 = sowing on 11 May. Vertical bars are the LSD (P=0.05) for the interaction between sowing date and establishment method.

Table 6. Effect of sowing date and water regime on panicle density, number of spikelets per panicle, percent filled grain and thousand grain of *aus* rice (2006-2008)

	2006 cropping season					2007 cropping season				2008 cropping season			
	I1[3]	I2	I3	Mean D		I1	I2	I3		I1	I2	I3	Mean D
Productive panicles (m^{-2})													
D1[1]	138 b[4]	212 b	224 a		D1	357 a	323 ab	274 b	D1	165	205	184	
D2	140 b	180 ab	198 a		D2	318 a	308 a	309 a	D2	112	129	147	
D3	279 a	248 b	253 b		D3	131 b	212 a	233 a	D3	46b	126a	146a	
$LSD_{.05}$[2]	48.3					$LSD_{.05}$ = 48.7				$LSD_{.05}$ = 56.0			
Spikelets per panicle (no)													
D1	78 a	76 a	64 b		D1	55 ab	60 a	52 b	D1	62 a	52 b	57 ab	
D2	65 ab	73 a	53 b		D2	73 a	62 b	59 b	D2	59 b	69 a	60 b	
D3	63 a	66 a	71 a		D3	79 a	70 b	65 b	D3	59 b	71 a	67 ab	
	$LSD_{.05}$ = 12.0					$LSD_{.05}$ = 6.8				$LSD_{.05}$ = 9.7			
Percent filled spikelet (%)													
D1	76	73	69	73 y	D1	79 a	77 ab	64 b	D1	82	87	87	85 x
D2	72	73	77	74 y	D2	83 a	86 a	85 a	D2	87	88	87	87 x
D3	84	81	84	72 x	D3	84 b	88 a	89 a	D3	79	86	84	83 y
Mean I	78	76	77			$LSD_{.05}$ = 5.4				Mean I	82	87	86
Thousand grain weight (gm)													
D1	21.6 a	21.2 a	20.9 b		D1	21.5 a	21.0 ab	20.8 b	D1	20.9	20.8	21.2	20.9 x
D2	21.2 a	21.5 a	21.0 a		D2	21.6 a	21.4 a	21.3 a	D2	20.6	21.3	21.3	21.1 x
D3	21.5 a	21.6 a	21.4 a		D3	21.2 b	21.9 a	21.8 a	D3	20.9	21.5	21.7	21.4 x
$LSD_{.05}$ = 0.42						$LSD_{.05}$ = 5.5				Mean I	20.8 a	21.2 a	21.4 a

[1]D1 = Sowing on 5-10 April, D2 = Sowing on 15-20April, D3 = Sowing on 25-30 April;

[2]$LSD_{.05}$ = LSD values for comparing three seeding dates under the same water regimes at 5% level of significance;

[3]I1 = Rainfed, I2 = supplementary irrigation, I3 = full irrigation; in each season and in each row mean values followed by the same letter are not significantly different at 5% level by LSD. Mean values are averaged over four replications;

[4] In each season and in each column mean values followed by the same letter are not significantly different at 5% level by LSD. Mean values are averaged over four replications.

Table 7. Effect of sowing date and establishment method on yield components of *aus* in 2009

	Establishment method[1] (M)						
Seeding date[2]	DS	TP	Mean D		DS	TP	Mean D
Panicle density (no. m^{-2})					Spikelets per panicle (no.)		
D1	534	406	470a	D1	63 b	75 a	
D2	403	318	361b	D2	72 a	58 b	
Mean M	468a	362b					
					LSD.05= 11.42		
Filled spikelets (%)					Thousand-grain weight (g)		
D1	80	80	80 y	D1	21.7	21.8	21.7 x
D2	84	84	84 x	D2	21.7	21.3	21.5 x
Mean M	82 a	82 a		Mean M	21.7 a	21.5 a	

[1]DS = dry seeded, TP = transplanted;

[2]D1 = sowing on 30 April 2009, D2 = sowing on 11 May 2009;

[3] In each row, mean values followed by the same letter (a, b) are not significantly different at the 5% level by LSD. Mean values are averaged over four replications;

[4]In each column, mean values followed by the same letter (x, y) are not significantly different at the 5% level by LSD. Mean values are averaged over four replications;

[5] $LSD_{.05}$ = LSD for comparing establishment methods under the same seeding date;

[6]$LSD_{.05}$ = LSD for comparing seeding date for same establishment method.

3.4 Effect of transplanting date and variety on performance of aman rice

3.4.1 Insect and pest infestation

In all four *aman* seasons, there was little damage from insects or diseases. The main insect pests were leaf roller and stem borer during the mid tillering stage, which were controlled by cypermethrin and carbofuran and/or diazinon. Rice bug attacked during the grain filling stage and this was controlled by propiconazol.

3.4.2 Water depth during the aus growing period

Farmers usually use the river water to prepare the land for *aman* transplanting from late July. This results in a water depth of about 30 cm in lowland areas such as the experimental site, including the seedling nursery. This high water level together with high rainfall in July/August caused seedbed submergence during 2006, 2008, and 2009. Seedlings of D1 in 2006, D1 and D3 in 2007, all sowing dates in 2008, and D1 in 2009 were fully submerged for 6 d (Table 8). Water in the seedling nurseries was rapidly removed by pumping and there was serious damage to the seedlings due to continuous rainfall and water stagnation.

The *aman* crop was affected by submergence during the mid tillering stage of all three seedings of 2006, and during the mid tillering stage of D1 in 2007. Submergence during panicle initiation occurred in D1 in 2007 and D2 in 2008. Basal fertilizer applied during transplanting, and top dressed urea at the MT (maximum tillering) and PI (panicle initiation) stages was also lost from the target plots as a result of pumping out excess water or inundation of the whole experimental area by flood water entering the experimental site from outside by overtopping the bunds.

Table 8. Rainfall and water levels inside and outside the experimental field that caused partial or complete submergence of the crops, and the dates and stages at which submergence occurred, during the *aman* season

Raifall period	Total rainfall (cm)	Average field water level (cm)	Water level outside expt field (cm)	Submergence period	Crop phenology[1] (treatments)[2] affected
2006					
1–14 Jul	40	40	50	7-14 Jul	seedbed (D1)
19–24 Sep	47	62	70	21-30 Sep	MT[1] (D1, D2 and D3)
2007					
11–16 Aug	14	19	30	12-17 Aug	Seedling D1
26 Aug – 8 Sep	21	30	35	7- 17 Sep	**Seedling of D3** and MT D1
23–25 Sep	18	30	33	24 -30 Sep	**PI[2] (D1)**
2008					
10 - 19 Jul	18	28	35	14-18 Jul	Seedbed
5– 20 Aug	20	30	40	11-17 Aug	seedbed and main field seedling
25–27 Sep	25	37	45	28-30 Sep	**PI (D2)**
2009					
4-9 Sep	27	40	60	4-9 Sep	D1 planting delayed

[1]MT = maximum tillering;

[2]PI = panicle initiation;

[3]D = date of transplanting D1 =10 Aug, D2 =20 Aug, D3 =30 Aug (2006-08); D1=11 Sept (2009) (30 days old seedling). *Bold fonts indicate severely affected crops and seedlings.

3.4.3 Phenology

Growth duration over the three sowing dates and three years from 2006 to 2008 ranged from 131 to 145 d for BR11, and from 121 to 136 d for BRRI dhan53. In 2009, duration of BRRI dhan46 ranged from 121 to 126 d, and for BRRI dhan49 the range was 123 to 138 d.

BR11, BRRI dhan49 and BRRI dhan53 all exhibited photoperiod sensitivity, with greater sensitivity in BRRI dhan53 and BRRI dhan49. The duration of BR11 was decreased by 1 to 10 d with delay in sowing from 10 to 30 August during 2006 to 2008 (Table 9). The duration of BRRI dhan53 decreased by 8 to 14 d with delay in sowing in the same years, while the duration of BRRI dhan49 decreased by 15 d in 2009 with a delay in sowing of only 5 d. In the case of BR11 and BRRI dhan53, the decrease in duration with delay in sowing was due to a decrease in the time to flowering. The effect of sowing date on duration of the grain filling period was small and inconsistent. However, in the case of BRRI dhan49, there was a large decrease (by 13 d) in the duration of the period from flowering to PM with delayed sowing.

Table 9. Effect of sowing date and variety on time (days after sowing, DAS) of flowering and physiological maturity of *aman* crops in 2006 to 2009

		Flowering (DAS)		Physiological maturity (DAS)		Duration of grain filling (d)	
Year	Transpl. date[1]	BR11	BRRI dhan53	BR11	BRRI dhan53	BR11	BRRI dhan53
2006	10 Aug	109	106	145	134	36	28
	20 Aug	108	100	141	136	33	36
	30 Aug	106	93	144	126	38	33
2007	10 Aug	111	103	141	133	30	30
	20 Aug	106	95	133	125	27	30
	30 Aug	101	92	131	119	30	27
2008	10 Aug	106	100	136	133	30	33
	20 Aug	98	92	132	124	34	30
	30 Aug	102	89	133	121	31	32
		BRRI dhan46	BRRI dhan49	BRRI dhan46	BRRI dhan49	BRRI dhan46	BRRI dhan49
2009	11 Sept	93	96	126	138	33	44
	11Sept	90	92	121	123	31	31

[1]Seedlings were transplanted 30 DAS, except for the first sowing in 2009 when the seedlings were transplanted 35 DAS (sown on 5 Aug)

3.4.4 Yield

Yields of BR11 ranged from 3.5 to 4.9 t/ha, and of BRRI dhan53 from 2.8 to 4.5 t/ha, across the three sowing dates and three years 2006 to 2008 (Figs 8a-c). There was a significant interaction between variety and sowing date on grain yield of *aman* in 2006 and almost ($p<0.06$) in 2008, but not in 2007 (Figure 8). Yield of BR11 was significantly higher than yield of BRRI dhan53 in 2007. Yield of BR11 was not affected by sowing date, indicating that the reduced duration as sowing was delayed from 10 to 30 August did not affect yield significantly. These results are in contrast with other findings that a growth duration of 145 d is needed for maximum yield (6.5 t/ha) of BR11 (BRRI 2009a). However there was a consistent trend for yield of BRRI dhan53 to decline with delay in sowing in all three years, with significant differences in 2006 and 2008, probably reflecting the greater reduction in duration of this variety. The reduction in yield with delayed sowing of BRRI dhan53 was associated with a trend for lower panicle density and grain weight in 2006 (significant) and 2008, and also significantly fewer spikelets per panicle in 2006 (Table 10). Both varieties produced higher yield (>4 t/ha) in 2006 (first two seeding dates) and 2008 (first seeding date) than in 2007 (<4 t/ha) as the aman crop was submerged three times in 2007. In addition to the direct effects of submergence on crop processes, submergence prevented proper topdressing of N fertilizer during critical stages including panicle initiation. Widawsky and O'Toole (1990) reported that submergence can cause up to 70% yield loss in rainfed lowland rice.

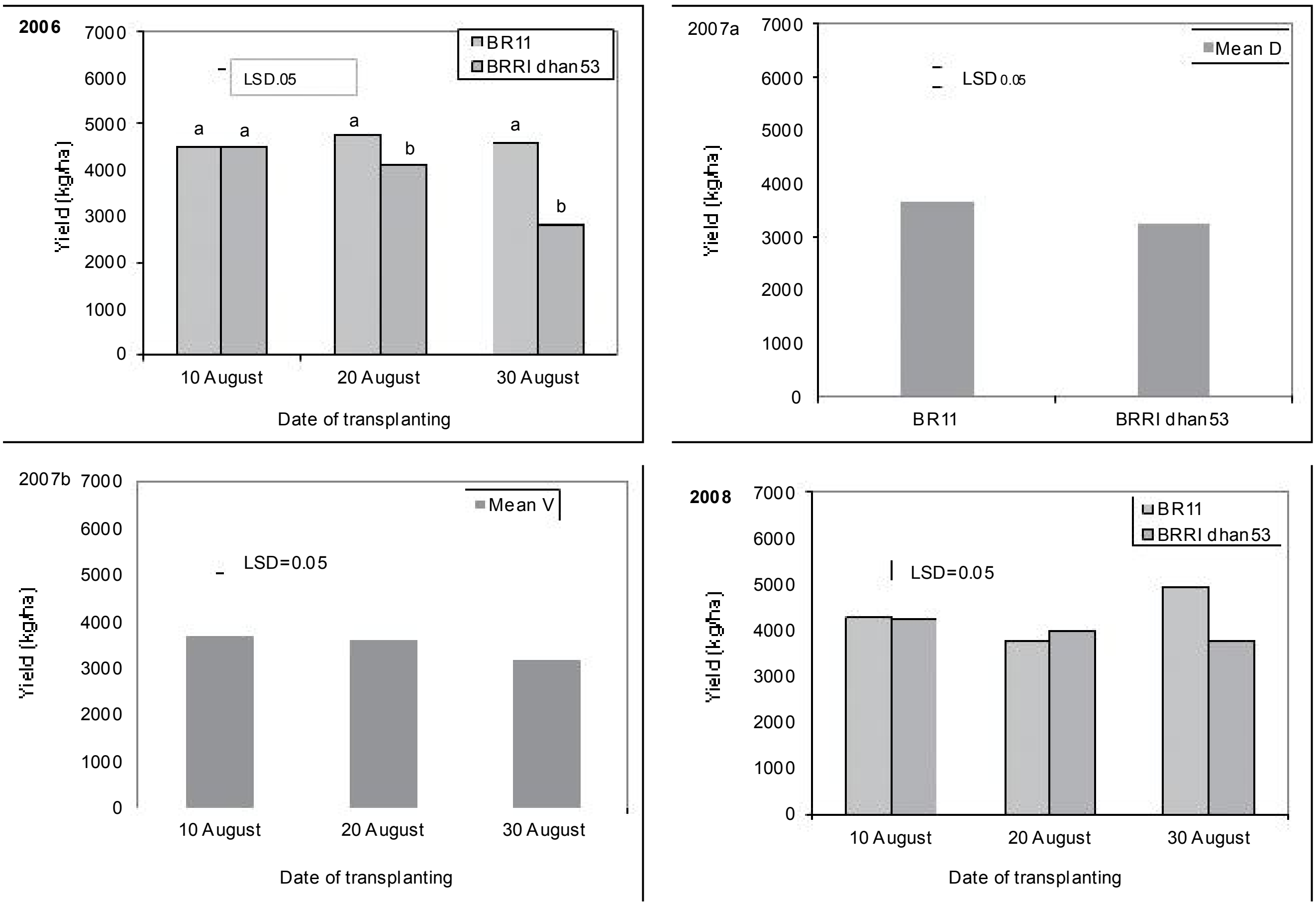


Fig. 8. Grain yield of *aman* as affected by sowing date and variety. Vertical bars are LSD (P=0.05) for the interaction between seeding date and variety in 2006 and 2008, and for the effects of variety and sowing date in 2007.

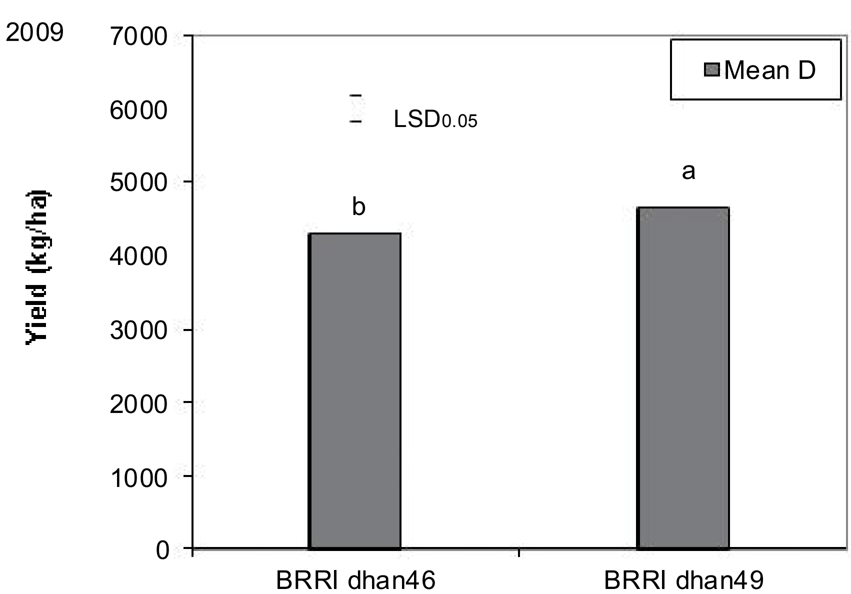


Fig. 9. Grain yield of *aman* varieties during the 2009 aman cropping season.

In 2009, the interaction between sowing date and variety on grain yield was not significant. Grain yield of BRRI dhan49 (4.7 t/ha) was significantly higher than of BRRI dhan46 (4.3 t/ha). There was no effect of seeding date on grain yield. The higher yield of BRRI dhan49 was associated with significantly more spikelets per panicle and significantly higher spikelet fertility, although this was partly compensated for by lower grain weight (Table 11). The results suggest that BRRI dhan49 can still give acceptable yields, even if sowing is delayed until 10 August, despite its photoperiod sensitivity. This is consistent with a recent BRRI finding that BRRI dhan49 gave yields of 4.5 t/ha when 35 d-old seedlings were transplanted on 15 September (BRRI 2009a).

Table 10. Effect of variety on panicle density, number of spikelets per panicle, percent filled grain, and thousand-grain-weight during different establishment dates of *aman* rice in 2006 to 2008

Transplanting date[1]	2006 cropping season			2007 cropping season			2008 cropping season		
	Variety[2]			Variety			Variety		
	V1	V2	Mean D	V1	V2	Mean D	V1	V2	Mean D
				Panicle density (no. m^{-2})					
D1	210	210	210	202	171	186	239	218	229
D2	217	199	208	167	174	171	223	201	212
D3	234	198	216	194	180	187	244	188	216
Mean V	220	202		188	175		235 a	202b	
$LSD_{.05}$[3]							$LSD_{.05}$ for v=17.8		
Interaction	N/S			N/S			N/S		
				Spikelets per panicle (no.)					
D1	115	117 a	116 a[4]	131	107	119 x[5]	92 a	106 a	
D2	107	97 b	102 b	115	103	109 y	93 a	102 a	
D3	102	91 b	97 c	122	113	117 x	98 b	112 a	
Mean V	108	102		123a	108b				
$LSD_{.05}$ for D	7.42						14.9		
Interaction		N/S					N/S		
				Filled spikelets (%)					
D1	67	66	67 y[5]	71b	79a		76 a	74 a	
D2	77	72	74 x	73a	70a		75 a	75 a	
D3	76	69	73 x	68a	65a		75 a	81 b	
Mean V	73	69							
	$LSD_{.05}$ for D =7.26			LSD.05 = 5.6			LSD.05 = 3.6		
Interaction						N/S			
				Thousand-grain weight (g)					
D1	22.0 a	22.1 a		22.3	23.0	22.6 a	20.8	21.7	21.2 x
D2	22.2 a	21.8 a		22.3	22.3	22.3 a	21.0	21.5	21.3 x
D3	22.2 a	20.2 b		20.7	20.7	20.7b	20.4	20.3	20.4 y
Mean V				21.8	22.0		20.7a		21.2b
$LSD_{.05}$	0.42						1.06		
Interaction							N/S		

[1] D = transplanting date, D1 = 10 August, D2 = 20 August, D3 = 30 August;
[2] V= rice Varieties, V1 = BR11, V2 = BRRI dhan53;
[3] LSD.05 = LSD values for comparing three seeding dates under the same variety at 5% level of significance;
[4] In each season and in each row, mean values followed by the same letter (a, b) are not significantly different at the 5% level by LSD. Mean values are averaged over four replications;
[5] In each season and in each column, mean values followed by the same letter (x, y) are not significantly different at the 5% level by LSD. Mean values are averaged over four replications.

Table 11. Effect of variety and seeding date on yield components of *aman* rice in 2009

Transplanting date[2]	Varieties[1]			Varieties		
	V_1	V_2	Mean D	V_1	V_2	Mean D
	Panicle density (no. m^{-2})			Spikelets per panicle (no.)		
D_1	251	293	272	83	110	96
D_2	274	250	262	83	102	93
Mean V	263	271		83 b	106 a	
Interaction	N/S			N/S		
$LSD_{.05}$[3]						
Filled spikelets (%)				Thousand-grain weight (g)		
D_1	72	81	76	23.1	17.6	20.4
D_2	68	82	75	22.6	17.9	20.2
Mean V	70 b[4]	82 a		22.9 a	17.7 b	
Interaction	N/S			N/S		
$LSD_{.05}$						

[1]V1 = BRRI dhan 46 (photoperiod-sensitive), V2 = BRRI dhan49 (photoperiod-insensitive);

[2]D1 = sowing on 5 Aug and transplanting on 11 Sep (35-day-old seedlings), D2 = sowing on 10 Aug and transplanting on 11 Sep (30-day-old seedlings);

[3]LSD.05 = LSD values for comparing seeding dates for the same variety at the 5% level of significance;

[4]In each row, mean values followed by the same letter are not significantly different at the 5% level by LSD. Mean values are averaged over 4 replications.

3.5 Annual yield of the aus–aman cropping system

Total system yield ranged from 5.5 t/ha to 8.0 t/ha over the three years from 2006 to 2008, and was much higher (8.0 to 9.6 t/ha) in 2009. The effects of *aus* sowing date and *aman* variety on annual system yield were inconsistent over the three years 2006 to 2008. The interaction between *aman* variety and *aus* seeding date was significant ($P<0.05$) in 2006 and 2008, but not in 2007. With BR11, there was no consistent effect of seeding date, but with BRRI dhan53, total system yield declined with delay in sowing in both 2006 and 2008 (Figs 10a, d). In 2007, system yield was significantly lower with the earliest sowing (Figure 10c). The BRRI dhan65-BR11 *aus-aman* system produced annual yields of 7 to 8 t/ha for all sowing dates under favourable conditions (no significant damage from drought, waterlogging or pests). Yields of this system were lower (6 to 7 t/ha) in 2008 because of lower *aus* yield caused by drought and insect infestation.

Total yield of the *aus-aman* system in 2009 varied from 7.9 to 9.6 t/ha, and was significantly affected by the interaction between aus sowing date, *aus* establishment method and *aman* variety (Fig. 11). With dry seeded *aus* in the system, total yield (8.8 to 9.6 t/ha) was not affected by *aus* sowing date x *aman* variety. However, with late sowing of transplanted *aus*, system yield was lower with the photoperiod sensitive variety (BRRI dhan49) (7.9 to 8.3 t/ha) than with the non-photoperiod sensitive variety (BRRI dhan46) (8.7 to 9.2 t/ha).

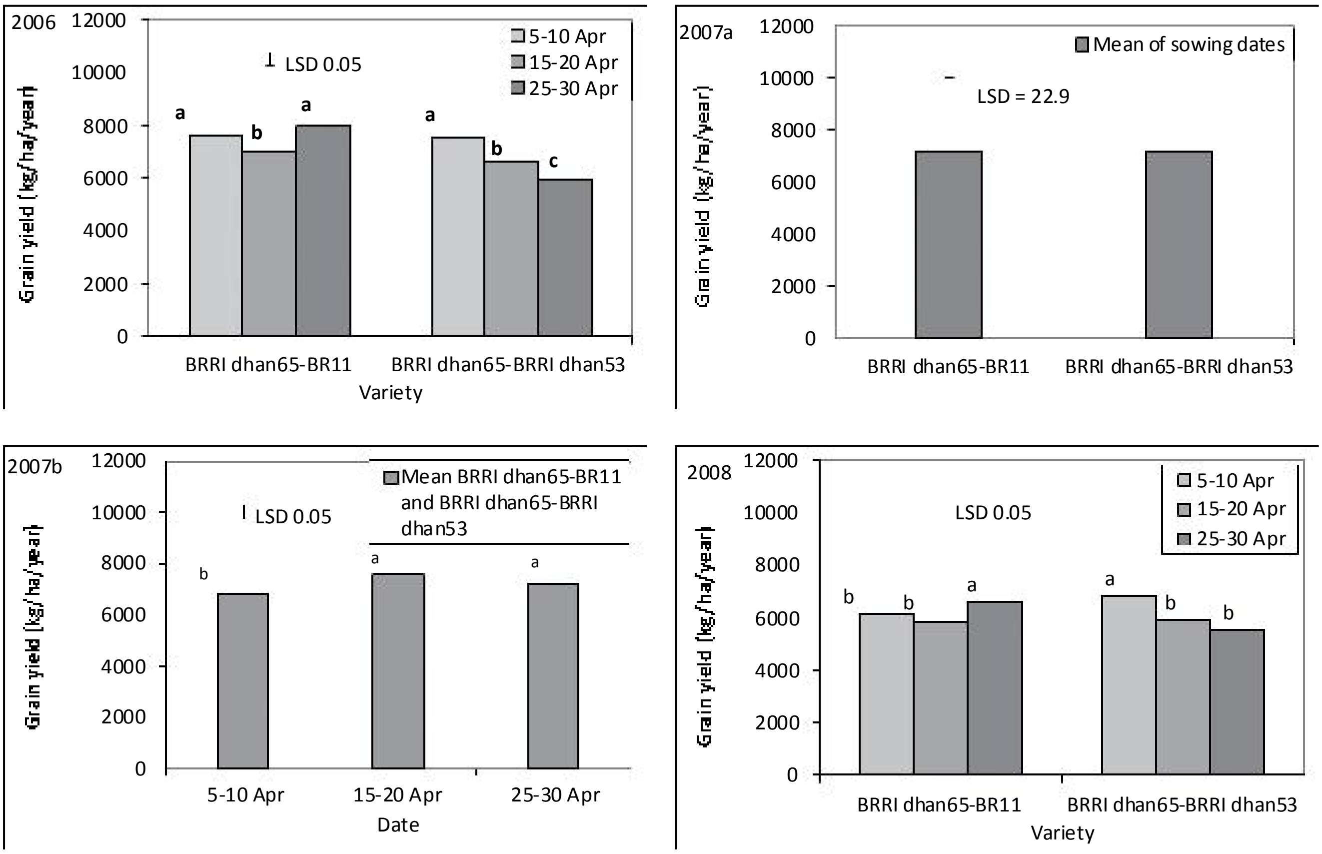


Fig. 10. Total grain yield of the *aus-aman* cropping system as affected by *aus* seeding date and *aman* variety and *aman* variety during (a) 2006, (b-c) 2007 and (d) 2008. Vertical bars are the LSD (P=0.05) for comparing all treatment combinations in 2006 and 2008, and for comparing seeding date and variety means in 2007.

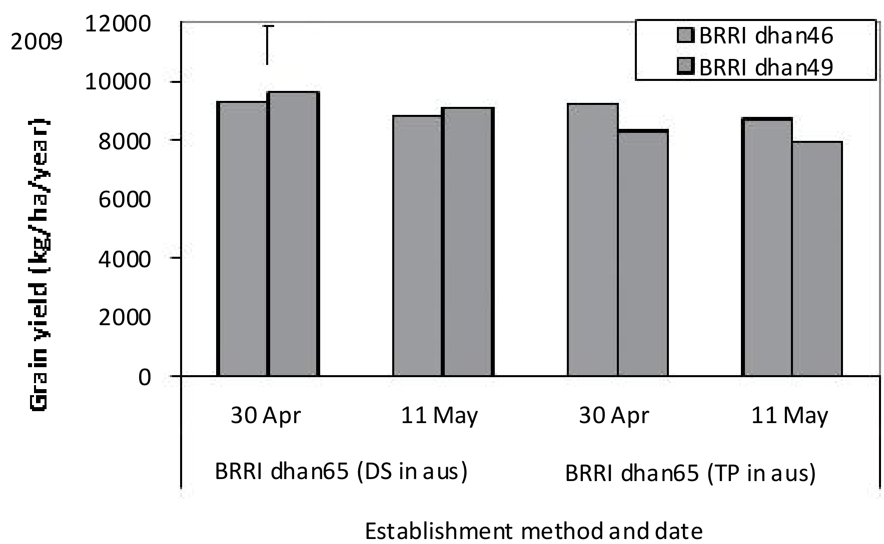


Fig. 11. Total grain yield of the *aus-aman* cropping system as affected by *aus* establishment method and sowing date and *aman* variety in 2009. Vertical bar is the LSD (P=0.05) for the interaction between between *aus* establishment method and *aman* variety x sowing date.

3.6 Effect of seeding date and irrigation management on irrigation input to aus

During the three *aus* seasons of 2006 to 2008, rainfall intercepted by each treatment combination varied from 664 to 1043 mm (Table 12). Irrigation input to I_2 ranged from 94 to 188 mm, and to I_3 from 87 to 300 mm. There was a significant interaction between sowing date and irrigation treatment (supplementary vs. full) on irrigation input to the *aus* crops in all three years (2006-2008). Each year, irrigation input to the fully irrigated treatment declined as sowing was delayed, while the effect of sowing date on irrigation input to the supplementary-irrigated treatment was variable. Total water input (rainfall plus irrigation) to *aus* ranged from about 900 mm in 2008 to about 1300 mm in 2006.

In 2009, the *aus* crops received around 725 mm rain, and irrigation input ranged from 562 to 1040 mm depending on sowing date and establishment method (Table 13). The interaction between seeding date and establishment method on irrigation input was not significant. Irrigation input was significantly higher with early sowing than late sowing, and with dry seeding than with transplanting, reflecting the dry weather in May (Fig. 1).

Table 12. Total water input from rainfall and irrigation in *aus* growing season (2006-2008), Basurabad village, Batiaghata, Khulna, Bangladesh

	2006			2007			2008		
	I_1	I_2	I_3	I_1	I_2	I_3	I_1	I_2	I_3
Rainfall (mm)									
D_1	1068	996	996	800	897	922	664	773	767
D_2	1068	996	996	851	913	957	664	715	738
D_3	1043	1043	1043	842	875	923	659	745	747
Irrigation (mm)									
D_1	0	116	300	0	108	251	0	188	183
D_2	0	101	279	0	100	195	0	140	159
D_3	0	161	262	0	94	142	0	86	87
LSD		87			63			56	
Total water applied (mm)									
D_1	1068	1113	1297	800	1005	1173	664	961	950
D_2	1068	1098	1276	851	1014	1152	664	855	897
D_3	1043	1204	1305	842	968	1065	659	831	834
LSD		76			95			86	

Table 13. Total water input from rainfall and irrigation to *aus* in 2009

		Rainfall (mm)	Irrigation (mm)	Total water applied (mm)
Dry seeding	30 Apr-15 Aug	723	1040	1763
	11 May – 19 Aug	728	723	1451
Transplanting	26 May- 17 Aug	728	849	1577
	6 June-27 Aug	728	562	1290
Establishment method means				
	Dry seeding	725	882	1607
	Transplanting	728	629	1365
	LSD (p=0.05)	n/a	36	n/a
Sowing date means				
	30 April	725	868	1593
	11 May	728	642	1370
	LSD (p=0.05)	n/a	36	n/a

3.7 Incremental water productivity

Under favourable conditions (no submergence, water stagnation or severe pest or disease infestation), there was a general trend for higher incremental input water productivity with supplementary irrigation than full irrigation within seeding date, with bigger differences for earlier seeding, except for D3 of 2008 (Table 14). Incremental water productivity of both irrigation treatments was higher when the crop faced drought that hampered rainfed rice establishment (e.g. D3 of 2007). On the other hand, there were times when rainfed rice had a higher yield than irrigated rice because the latter suffered from pest infestation or submergence. The computation of incremental water productivity is not meaningful for the third sowing date in 2006 and for the first two sowing dates in 2007 as irrigated yield was lower than or equal to rainfed yield. Rainfed D1 and D2 of the 2008 cropping season had low yield due to drought during crop establishment, which caused high incremental water productivity of I2 and I3 in D1 and D2 of 2008. But incremental water productivity was low in D2 of 2006 compared with that in D1 under both irrigated water regimes because of low yield in D2 due to crop submergence.

Table 14. Incremental water productivity (kg rice m^{-3} water) in the *aus* seasons of 2006 to 2008 as affected by sowing date and irrigation treatment

	2006		2007		2008	
	I_2[2]	I_3	I_2	I_3	I_2	I_3
D_1	0.77	0.31	Na	Na	0.43	0.04
D_2	0.27	0.008	Na	Na	0.63	0.54
D_3	na[3]	0.009	1.34	1.26	1.03	1.16

[1]D1 = seeding on 5-10 April, D2 = seeding on 15-20 April, D3 = seeding on 25-30 April;

[2]I2 = supplementary irrigation, I3 = full irrigation;

[3]na = not applicable; when yield without irrigation is equal to or higher than that with irrigation, indicating no increment in yield with irrigation compared to without irrigation.

4. Conclusions and recommendations

This study aimed to develop technical packages for an *aus–aman* cropping system with stable and high yields in areas of the coastal zone with moderate salinity during the dry season. The interaction between *aus* seeding date and water management varied from year to year due to variation in rainfall at the beginning of the rainy season. With a short duration modern *aus* variety (BRRI dhan65, ~110 d) and supplementary irrigation of less than 100 mm, yields of 3.7 to 4.2 t/ha of dry seeded *aus* for sowing dates ranging from mid-April to late April were achieved under favourable conditions (no submergence, water stagnation or severe pest or disease infestation). Combining this with a modern, high yielding aman variety resulted in total system yields approaching 9 t/ha/yr, much higher than the 2.5 t/ha/yr of rice commonly obtained by farmers who grow a single rice crop (*aman*) using local varieties.

For systems with late sown (early May) *aus*, the use of a photoperiod sensitive aman variety reduced *aman* and total system yield, therefore the use of non-photoperiod sensitive varieties is recommended. For good establishment and yield stability of a solely rainfed *aus* crop, seeding should be delayed until the end of April.

The research also highlighted the problem of poor water management in the polders, leading to submergence and water stagnation at times in both the *aus* and *aman* crops. This points to the need for better water management at a regional scale, including the separation of lands of higher and lower elevation with small levees to prevent accumulation of water in lower lying lands, and for the ability to drain. It also points to the need for better submergence and water stagnation tolerance in modern *aus* and *aman* varieties. In areas without suitable water for supplementary irrigation, seeding of *aus* can be delayed until 10 May followed by transplanting during the first week of June. In most years, this would allow field preparation taking advantage of rainfall or tidal flooding. Late crop establishment, however, would expose the newly established *aus* crop to higher risk of submergence from high rainfall or flooding from surrounding areas.

The combinations of BRRI dhan65 (*aus*) + BR11 (*aman*) and BRRI dhan65 (*aus*) + BRRI dhan46 (*aman*) gave the best yields under favourable conditions. The use of photoperiod-insensitive varieties (such as BRRI dhan49) in the *aman* season would give greater flexibility to the *aus–aman* cropping calendar than would a photoperiod-sensitive variety such as BRRI dhan49.

Acknowledgements

The paper presents findings from CGIAR Challenge Program on Water and Food (CPWF), CPWF phase 1 project, PN10 entitled “Coastal Resources Management for Improving Livelihoods". Therefore, the authors are grateful to CGIAR Challenge Program on Water and Food (CPWF) for financial support to carry out research work and a fellowship for the PhD of the first author. We are thankful to our field assistant Mr. Amal Krisna Roy for his continuous support during the work and the farmers for provision of land for field experiments

References

American Society of Agronomy (AAS) and Soil Science Society of America (SSSA). 1982. Methods of soil analysis, part 2. AAS and SSSA, Madison, Wisconsin, USA. p 225-260.

American Society for Testing and Materials (ASTM). 1964. Standard method for grain-size analysis of soil (D422-63) (adopted 1963). In: Nomenclature and definitions, standard methods, suggested methods. 4th ed. ASTM, Philadelphia, Pa. p 95-106.

Bangladesh Rice Research Institute (BRRI). 2009a. Annual internal research review report. BRRI, Gazipur, Bangladesh.

Bangladesh Rice Research Institute (BRRI). 2009b. Adhunik dhaner chas [in Bengali]. BRRI, Gazipur, Bangladesh

Cassman, K.G. (ed.). 1994. Breaking the yield barrier: proceedings of a workshop on rice yield potential in favorable environments, IRRI, 29 November-4 December 1993. International Rice Research Institute, Manila, Philippines.

De Datta, S.K. 1981. Principles and practices of rice production. John Wiley & Sons, USA. 618 p.

Food and Agriculture Organization (FAO). 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy. 300 p.

Gomez, K.A. 1972. Techniques for field experiment with rice. IRRI, Los Banos, Philippines. 46 p.

Haque, A.K. 2006. Salinity problems and crop production in coastal regions of Bangladesh. Pakistan Journal of Botany 38(5): 1359-1365.

International Rice Research Institute (IRRI). 1994. Soil and plant sampling and measurements. IRRI, Los Banos, Laguna, Philippines. 13 p.

Karim, Z., S.G. Hussain, and M. Ahmed. 1990. Salinity problems and crop intensification in the coastal regions of Bangladesh. Soils Publication no. 33. Soils Irrigation Division, BARC, Dhaka, Bangladesh. p 1-22.

Michael, A.M. 1997. Irrigation: theory and practice. Vikas Publishing House Private Ltd., New Delhi, India. 801 p.

Mondal, M.K., Saha, N.K., Ritu, S.P., Paul, P.L.C, Sharifullah, A.K.M., Humphreys, E., Tuong, T.P. and Rashid, M.A. 2015. Optimum sowing window for *boro* cultivation in the coastal zone of Bangladesh. These proceedings.

Mondal, M.K, T.P. Tuong, S.P. Ritu, M.H.K. Choudhury, A.M. Chasi, P.K. Majumder, M.M. Islam, and S.K. Adhikary, 2006. Coastal water resource use for higher productivity: participatory research for increasing cropping intensity in Bangladesh. In: C.T. Hoanh, T.P. Tuong, J.W. Gowing, and B. Hardy (eds.). Environment and livelihood in tropical coastal zones: managing agriculture-fishery-aquaculture conflicts. Comprehensive Assessment of Water Management in Agriculture Series. CABI International, UK. p 72-85.

Mondal, M.K, S.P. Ritu, M.H.K. Choudhury, A.M. Chasi, M.A. Mannan, P.K. Majumder, M.M. Islam, and S.K. Adhikary. 2004. Introduction to soil and water salinity dynamics of the south-west coastal region of Bangladesh. In: Proceedings of the workshop on coastal water management and uptake technologies, Khulna, Bangladesh, 26 June 2004. p 1-7

Nishat, A. 1988. Review of present activities and state of the art of the coastal areas of Bangladesh. In: Coastal area resource development and management ,part II. Coastal Area Resource Development and Management Association (CARDMA), Dhaka, Bangladesh. p 23 – 35.

Reddy, M.D. and B.N. Mitra. 1985. Response of rice to different forms of urea and phosphorus fertilization under intermediate deepwater condition. Plant and Soil 84(3): 431-435.

Ritu, S. P. 2012.Crop and water management for increasing rice cropping intensity and productivity of the coastal region of Bangladesh. Unpublished PhD thesis. Submitted to Bangladesh Agricultural University. November 2010.

Soil Resource Development Institute (SRDI). 2004. Land use map of Bangladesh. SRDI, Ministry of Agriculture, Dhaka, Bangladesh

Sudhir-Yadav, Gurjeet Gill , E.Humphreys, S.S.Kukul, and U.S.Walia(2011). Effectof water management on dry seeded and puddled transplanted rice Part 1: Crop performance. Field Crops Research 120, 112-122.

Tuong, T.P. 1999. Productive water use in rice production: opportunities and limitations. Journal of Crop Production 2(2): 241-264.

Tuong, T.P. and B.A.M. Bouman. 2003. Rice production in water-scarce environments. In: Kline J.W., Barker R., and Molden D. (eds.). Water productivity in agriculture: limits and opportunities for improvement. CABI International, Wallingford, UK. p 53-67.

Widawsky, D.A. and J.C. O'Toole. 1990. Prioritizing the rice biotechnology research agenda for Eastern India. The Rockfeller Foundation.

Rice-sunflower: An alternative cropping system for sustained livelihoods in the coastal zone of Bangladesh

M. Afsar[1] and T.H. Miah[2]

[1] Exim Bank Agricultural University Bangladesh, Bangladesh, mahnazafsar@yahoo.com
[2] Bangladesh Agricultural University, Bangladesh, tofazzal_miah@yahoo.com

Abstract

Although a large number of crops and vegetables are grown in Bangladesh the country is not yet self-sufficient in food grain production. Despite the country's efforts to increase agricultural production, feeding a huge population of 150.7 million (Hossain 2014) from cultivable land that is continuously decreasing in size due to infrastructural development and environmental challenges is the most critical issue in Bangladesh. Promoting agricultural growth is a critical element of the government's strategy aimed at food security and improving the household incomes of rural people. This study assesses the profitability of a modern rice-sunflower cropping pattern over a traditional rice-sesame pattern and the causes of favoring the new cropping pattern in Batiaghata *Upazila* in the Khulna District of Bangladesh. Profitability is considered in terms of income and food security. The analysis is anchored on a sample of 200 farmers; 100 farmers from each of the patterns were selected. Activity budgets, a logit model, and a food security index were employed to achieve the main objectives. It is evident from the study that the socio-demographic characteristics of rice-sesame and rice-sunflower farmers differ from each other. The farmers who adopted sunflower in their existing pattern were more experienced as well as older than the rice-sesame farmers. Educational status of the two groups was more or less similar and agriculture was the main occupation of both categories of the farmers; but the participation of the sunflower farmers in off-farm activities was higher than that of sesame farmers. The adopters of the modern rice-sunflower cropping pattern earned much higher profits than traditional rice-sesame growers. In addition, the average daily per capita calorie intake was relatively higher for the rice-sunflower adopters than the rice-sesame growers. Finally, this study identified some crucial problems in the expansion of sunflower cultivation in coastal Bangladesh and suggests probable solutions. It is concluded that a modern rice-sunflower pattern can play a significant role in achieving food security and improving the household income of coastal farmers in the Khulna District of Bangladesh.

Key message: The study confirmed that sunflower is a profitable enterprise for farmers in coastal zone of Bangladesh. The farmers in the coastal zone can therefore produce sunflower for better financial return and improved livelihoods and food security.

Keywords: activity budgets, net return, food security, sunflower, coastal Bangladesh

1. Introduction

Improved seeds and new cropping patterns that make use of high yielding varieties of crops are essential for ensuring the food security of the people of Bangladesh. The economy of Bangladesh largely depends on agriculture. Agriculture has direct linkages to food security through the potential to supply food grains for consumption. New cropping patterns with higher yields than existing cropping pattern have the potential to greatly impact food security, as they enhance production and thereby provide greater access to food via both production and trade.

Bangladesh has achieved near self-sufficiency in the production of rice, a staple food in the country. However, self-sufficiency in other food items has yet to be achieved. The potential of minor crops in Bangladesh has not been fully exploited for contribution to the goal of sustainable food security. Their production and utilization is still very low. Under these circumstances, oilseed crops may be considered as minor crops but are nevertheless important from a nutritional point of view. Oilseed crop cultivation can also help to achieve important substitution by reducing imports of edible oils from abroad. Sunflower has proved to be a relatively good oilseed crop. The cultivation of sunflower began in Bangladesh in 1975 as a garden plant and has gradually gained popularity as a field crop in the coastal area of Bangladesh (Miah 2014).

Fluctuation in economic well-being caused by periodic shocks is a common phenomenon, but its effects are especially pernicious in the coastal zone of Bangladesh (Osmani and Ahmed 2013). In the coastal zone, most lands remain fallow in the *rabi* season due to a shortage of irrigation water and/or soil salinity constraints. Tropical coastal deltas present one of the most challenging planning and management settings given their diverse character and location at the land-water interface. The most prominent issue in the recent evolution of tropical delta systems has been the widespread expansion of shrimp aquaculture, first in Thailand and then throughout the coastal areas of East Asia, Southeast Asia and South Asia (Chuenpagdee and Pauly 2004). This shrimp farming has led to the dramatic transformation of coastal land use and subsequent environmental impacts that include: loss of mangrove habitats, water pollution, land salinization and declining fisheries (Primevera 1997; and Talaue-McManus 2006). In Bangladesh, shrimp farming is profitable from the viewpoint of individual farmers but it is undesirable from the viewpoint of society (Fatema 2012). The cropping pattern followed in this area is mainly sesame-*T. Aman* rice. Sesame is a summer crop and is highly susceptible to water logging. The CSISA-CIMMYT Khulna hub has taken an initiative to promote sunflower production in this area in collaboration with BARI (Bangladesh Agricultural Research Institute) and Khulna University. BRAC (Bangladesh Rural Advancement Committee) and some other Non-Government Organizations have also tried to introduce a rice-sunflower pattern. However, the impact of sunflower cultivation on household income and food security is not known due to a lack of available data. Surprisingly only limited literature related to sunflower is available in Bangladesh. No research has yet been conducted to identify the role of rice-sunflower cropping patterns in improving the household income and food security of farmers in the polder area.

This study was therefore designed to provide detailed information regarding sunflower production. Specifically, the study was designed to achieve the following objectives:

- to identify the socioeconomic backgrounds of rice-sesame and rice-sunflower farmers
- to estimate the profitability of a rice-sunflower cropping pattern in terms of household income and food security
- to assess the causes of favoring the new cropping pattern
- to identify some problems in the expansion of sunflower cultivation and probable solutions

2. Research methods

2.1 Sample and data sources

This study is based on primary data collected from selected respondents of five villages, namely Amtola, Baruiabad, Titukhali, Debitola, and Boyervanga in Batiaghata *Upazila* of Khulna District, Bangladesh. A simple random sampling technique was followed for selecting traditional rice-sesame farmers while purposive sampling was employed for selecting farmers of the new rice-sunflower cropping pattern. In total 200 farmers, 100 from each of the selected cropping patterns, were selected for the study.

Table 1. Distribution of sampled farmers

Selected villages	Number of rice-sesame farmers	Number of rice-sunflower farmers	Total sample size
Amtola	20	20	40
Baruiabad	20	20	40
Titukhali	20	20	40
Debitola	20	20	40
Boyervanga	20	20	40
Total	100	100	200

Source: adapted from Afsar (2013)

The required data were collected in August and September 2012 using a structured interview schedule. Secondary data were also collected from the government and research reports, online materials and periodicals. Descriptive statistics were employed to examine the objectives (i), (iii) and (iv) whereas an activity budget, food security index (Babatunde *et al.* 2007) and logit model (Babatunde *et al.* 2007) were used for analyzing objective (ii). These specific methods are explained in the following sub-sections.

2.2 Activity budget

Activity budgets were calculated for each of the concerned crops. The algebraic equations employed to prepare activity budgets is as follows:

$$\pi = TR - TC$$

Or, $\pi = TR - (VC + FC)$

In these equations, π stands for net return, TR is the total return from the sale of produce, TC is the total cost required for the production of the concerned crop. This total cost is also the sum of the variable costs (VC) and the fix costs (FC). All these variables are calculated in Bangladesh Taka (BDT) per hectare.

2.3 Food security index and logit model

Hoddinott (1995) outlines four ways of measuring food security outcomes, namely individual intake, household caloric acquisition, dietary diversity and indices of household coping strategies. Logistic regression was used by Kidane et al. (2005) and Feleke et al. (2005) to assess the causes of household food insecurity. Babatunde et al. (2007) examined the factors influencing the food security status of rural farming households in Kwara State of Nigeria. Using the calorie intake approach this study revealed that 36 and 64% of the households were food secure and food insecure, respectively. Nasrin (2011) and Mannaf (2012) checked household food security against a recommended minimum calorie requirement (i.e., 2122 kilocalories per person per day). In the present case, we follow a similar approach where we first measure household food security and then identify the causes.

In order to measure food security for each household in the sample, we derived a food security index from the daily per capita caloric intake of each household compared to the recommended per capita daily caloric intake. When the caloric intake for the household is greater than or equal to the recommended intake, the household is considered to be food secure and the household food security status Z_i takes the value 1. If the intake is lower than the recommended requirement, then the household is considered to be food insecure and Z_i is equal to 0.

The food security index calculated for each sampled household is then used as the dependent variable of a logit model. The logit model estimated aims to identify the determinants of food security and thus, to assess the role of the new rice-sunflower cropping pattern in improving household food security of farmers in the coastal zone.

The implicit form of the model estimated was as follows:

$Z_i = \beta X_i + U_i$

Where Z_i is the food security status of ith household as previously defined

X_i is a vector of explanatory variables and U_i is the error term

β is the vector of the estimated parameters of interest.

The explanatory variables considered in the vector X_i include the size of the household, the age of the household head, the size of the farm (in hectares), the production per capita (in BDT), the household income (in BDT), the food expenditures (in BDT) and a dummy equal to 1 if the household is involved in off-farm activities.

3. Results and discussion

3.1 Socioeconomic characteristics of the farmers

First, it is essential to know the socio-demographic profile of the sample farmers to get a complete picture of rice-sunflower production and its impact on income and food security.

3.1.1 Farmer age

Table 2 indicates that the highest percentage of selected rice-sesame farmers (32.00%) belonged to the age group of 30 to 40 years while the highest percentage of rice-sunflower farmers (35.00%) belonged to the age group of 50 to 60 years.

Table 2. Age distribution of selected farmers

Age group (Years)	Rice-sesame farmer		Rice-sunflower farmer	
	Number of respondents	% of total	Number of respondents	% of total
20.00 - 30.00	9	9.00	6	6.00
30.01- 40.00	32	32.00	20	20.00
40.01-50.00	29	29.00	29	29.00
50.01- 60.00	20	20.00	35	35.00
Above 60.00	10	10.00	10	10.00
Total	**100**	**100.00**	**100**	**100.00**
Average age (Years)	45.92		49.2	

Source: adapted from Afsar (2013)

So it can be stated that the farmers who have adopted sunflower into their cropping patterns are slightly older and more experienced in farming than rice-sesame farmers.

3.1.2 Farmer occupation

The farmers were engaged in various occupations. Agriculture was the main occupation of both categories of farmers. Some were also engaged in small business, service and even labor selling (Table 3).

Table 3. Distribution of sample farmers according to their main occupations

Types of occupation	Rice-sesame farmers		Rice-sunflower farmers	
	Number of respondents	% of total	Number of respondents	% of total
Agriculture	81	81.0	80	80.0
Business	5	5.0	10	10.0
Labor selling	8	8.0	4	4.0
Service	6	6.0	6	6.0
Total	100	100	100	100

Source: adapted from Afsar (2013)

The participation of the sunflower farmers in other income generating, off-farm activities, especially business, was relatively higher than that of sesame farmers.

3.1.3. Farmer land use patterns

Table 4 indicates that the average land holdings of rice-sesame and rice-sunflower farmers were 1.061 and 1.360 hectares, respectively. From these areas, crops (including rice, vegetables, sesame, sunflower and *Golda/Bagda*) accounted for 0.918 and 1.181 hectares, respectively, for each group. The areas under sesame production were 0.793 hectares by the rice-sesame farmers and 1.006 by the rice-sunflower farmers. The area under sunflower production by the rice-sunflower farmers was 0.131 hectare, which was 8.98% of total cultivated land (Table 4).

Table 4. Land ownership patterns of the selected farmers

Land type	Rice-sesame farmers		Rice-sunflower farmers	
	Area (ha)	% of total	Area (ha)	% of total
Homestead area	0.082	7.74	0.095	7.01
Area under crops	0.918	86.50	1.181	86.82
Area under ponds	0.061	5.75	0.083	6.16
Total owned area	1.061	100	1.360	100
Area under sesame production (ha)	0.793 (73.99)		1.006 (69.17)	
Area under sunflower production (ha)	-		0.131 (8.98)	

Note: Figures within the parenthesis indicate percentages of land under sesame and sunflower cultivation out of total cultivable land.

Source: adapted from Afsar (2013)

The average size of rice-sunflower farmers' land holdings (1.36 hectares) was much larger than that of rice-sesame farmers (1.06 hectares). This implies relatively larger-scale farmers (in terms of cultivable land area) adopt sunflower.

3.1.4 Farmer sources of household income

The highest contribution to household income comes from rice farming. It contributed to 21.05% of the total income for rice-sesame farmers. However, for rice-sunflower farmers, 33.55% of income comes from sunflower cultivation and 12.93% from rice.

Table 5. Household annual income of selected farmers

Sources of household income	Rice-sesame farmer		Rice-sunflower farmer	
	Amount (Tk/year)	% of total	Amount (Tk/year)	% of total
Rice	20,968.00	21.05	20,968.00	12.93
Sunflower	-	-	54,417.00	33.55
Sesame farming	18,866.00	18.95	17,595.00	10.84
Vegetables production	10,163.00	10.21	9000.00	5.54
Livestock farming	7666.00	7.70	6830.00	4.21
Shrimp culture	18,940.00	19.02	19535.00	12.04
White fish culture	9346.00	9.38	16346.00	10.08
Small business	3247.00	3.26	8500.00	5.24
Service	5850.00	5.88	6700.00	4.13
Labor selling	4520.00	4.54	2300.00	1.42
Total	99,566.00	100.00	162,191.00	100.00

Source: adapted from Afsar (2013)

It can therefore be concluded that sunflower and rice farming were the most significant contributors to the household income of rice-sunflower farmers. The average annual income of rice-sunflower farmers was much higher than rice-sesame farmers.

From the above-mentioned discussions it can be cautiously concluded that the major socioeconomic characteristics of rice-sesame and rice-sunflower farmers differ from each other. The farmers who adopted sunflower were in relatively better economic condition than rice-sesame farmers. As a result they can more easily purchase seed and bear the production costs of sunflower. This also means that not all farmers can afford the high cost of production associated with sunflower.

Table 6. Activity budgets per hectare *T. Aman* rice, sunflower and sesame production

Items of returns/costs	*T. Aman* rice				Surflower				Sesame			
	Total quantity/ha	Per unit price (Tk)	Returns /costs (Tk/ha)	% of total	Total quantity /ha	Per unit price (Tk)	Returns /costs (Tk/ha)	% of total	Total quantity/ha	Per unit price (Tk)	Returns /costs (Tk/ha)	% of total
A. Gross Returns												
Main product	3046 kg	17.00	51,782.00	92.07	1957 kg	51.00	99,807.00	96.43	952 kg	44.00	41,888.00	100
By-product	n.a	-	4455.00	7.92	n.a	-	3694.00	3.57				
Total returns	-	-	56,238.00	100	-	-	103,501.00	100			41,888.00	100
B. Gross Costs												
C. Variable Costs												
Seedlings/seed	n.a	-	3627.00	10.28	10 kg	1060.00/kg	10,600.00	21.60	11 kg	54/kg	594.00	2.53
Power tiller	3 times	8/decimal	5928.00	15.81	3 times	8/decimal	5928.00	12.08	3 times	8/decimal	5928.00	25.22
Human labor	69 Man-day	300/Man-day	20,700.00	58.69	75 Man-day	300/ Man-day	22500.00	45.84	55 Man-day	300/ Man- day	16500.00	70.21
Urea	92 kg	20.00/kg	1840.00	5.22	124 kg	20.00/kg	2480.00	5.05			23,022.00	97.96
TSP	57 kg	22.00/kg	1254.00	3.56	106 kg	22.00/kg	2332.00	4.75				
MOP	16 kg	16.00/kg	255.00	0.73	56 kg	15.00/kg	840.00	1.71				
Fertilizers cost	-	-	**3350.00**	**9.50**	-	-	**5652.00**	**11.51**				
Irrigation						-	2465.00	5.02				
Insecticides	n.a	-	1087.00	3.08		-	1134.00	2.31				
Total	-	-	34,692.00	98.36	n.a	-	48,279.00	98.36	-	-	23,022.00	97.96
D. Fixed Costs												
Interest on OC	n.a		1087.00	3.08		@10%	805.00	1.64		@10%	480.00	2.04
Total	-	-	34,692.00	98.36	-	-	805.00	1.64	-	-	480.00	2.04
E. Total costs	-	-	35,270.00	100.00	-	-	49,084.00	100.00	-	-	23,502.00	100.00
F. Gross Margin (A-C)		-	21,546.00	-		-	55,222.00	-		-	18,856.00	-
G. Net Return/profit (A E)		-	20,968.00	-		-	54,417.00			-	18,386.00	-

Source: adapted from Afsar (2013)

3.2 Farmer profit

3.2.1 Economics of rice, sesame and sunflower farming

For any agricultural production, the profit of the concerned crops plays a significant role in the production decisions of farmers. To assess the role of a rice-sunflower cropping pattern in improving household income and food security it is essential to know the relative profitability of rice, sesame and sunflower.

The average cost of *T. Aman* rice seedlings was Tk 3627.00 per hectare, which accounted for 10.28% of total cost (Table 6). The costs of seed per hectare of sesame and sunflower were Tk 594.00 and Tk 10,600.00, respectively, accounting for 2.53% and 21.60% of total costs, respectively (Table 6). The cost of sunflower seeds was much higher than those for seasame or rice.

In the study area, power tillers were used three times on average for land preparation at a rate of Tk 8.00/decimal for each tillage operation. Per hectare costs of power tiller use for land preparation of *T. Aman* rice, sesame and sunflower were estimated at Tk 5928.00 (Table 6).

In the study area, average wage rate was Tk 300.00 per man-day during the study period. It can be seen from Table 6 that *Aman* rice growers used 69 man-days per hectare, accounting for 58.69% of the total gross costs of *T. Aman* production. Table 6 indicates that sesame and sunflower growers used 55 and 75 man-days per hectare for human labor, respectively. Sunflower should be planted in rows with row-to-row distance of 50 cm, giving 30cm plant-to-plant distance in a row; this requirement may explain why sunflower cultivation is labor intensive.

Since sunflower farmers have to apply fertilizers in their fields and the sowing method of sunflower is different from that of sesame, human labor costs for sunflower cultivation are much higher than sesame. An optimum dose of fertilizer is a major requirement for production but in the study area most farmers did not use any type of fertilizer during sesame cultivation, which is followed by rice cultivation. The sample farmers used three kinds of fertilizers, namely, Urea, Triple Super Phosphate (TSP) and Muriate of Potash (MOP) for *T. Aman* rice and sunflower. Total fertilizer costs of *T. Aman* and sunflower accounted for 9.50 and 11.51% of total costs, respectively (Table 6).

The selected farmers did not use any insecticide for sesame cultivation while rice-sunflower farmers used it to protect their crops from pest attack. Per hectare insecticide cost was Tk 1134.00 for sunflower, or 2.31% of total gross costs and Tk 1087.00 for *T. Aman* rice, or 3.08 % of total gross costs.

Finally, irrigation is considered one of the most important inputs of sunflower production. Rice and sesame does not require irrigation. Per hectare cost of irrigation for sunflower production was Tk 2465.00, which constituted 5.02% of total costs (Table 6).

The cost of the operating capital was estimated at Tk 578.00 per hectare, or 1.64% of total cost of *T. Aman* rice production, and Tk 480.00 and Tk 805.00 for sesame and sunflower farming, respectively (Table 6).

3.2.2 Selected cropping pattern profitability

In total, per hectare costs of *T. Aman* rice, sesame and sunflower production were estimated at Tk 35,270.00, Tk 23,502.00 and Tk 49,084.00, respectively (Table 6). Per hectare yield of *T. Aman* rice was found to be 3,046.00 kg with a per unit price of Tk 17.00 per kg. The gross return of T. *Aman* was Tk 56,238.00 per hectare (Table 6).

Table 6 shows that gross returns per hectare for sesame and sunflower farming were Tk 41,888.00 and Tk 103,501.00, respectively. Per hectare net returns of *T. Aman* rice, sesame and sunflower were Tk 20,968.00, Tk 18,386.00 and Tk 54,417.00, respectively (Table 6).

These results indicate that production of *T. Aman* rice, sesame and sunflower were profitable for individual farmers, but with some large differences in profitability among the selected crops.

The additional income from sunflower production contributed significantly to the total household income of sunflower growers. Sesame and sunflower are both profitable crops, but sunflower is more profitable than sesame.

Table 7. Comparison of profitability following different cropping patterns

Cropping pattern	Net return (Tk/ha/yr)
Rice - sesame	39354.00
Rice - sunflower	75385.00
Difference	36031.00

Source: adapted from Afsar (2013)

Table 7 shows that there is a significant difference in profitability between the two categories of farmers; the rice-sunflower farmers earned much higher profits than the rice-sesame farmers. The main reason was, as mentioned earlier, that per hectare yield of sunflower was much higher in the polder area than traditional sesame crops. In fact, rice-sunflower farmers received Tk 36,031.00/ha more profit than rice-sesame farmers. If farmers replace sesame with sunflower they can obtain an additional Tk 36,031.00 from the same hectare of land. The role of sunflower cultivation for improving farm household income is highly encouraging and likely significant.

3.3 Farmer food security

3.3.1 Household nutritional status

Food security can be viewed from several perspectives, such as availability of food, access to safe and nutritious food, and utilization of food. Household calorie availability was estimated using a food nutrient composition, which is presented in appendix 2. Table 8 shows the per capita daily calorie intake from different food items by the households.

Table 8. Calorie intake from different food items by family members of households under two cropping patterns

Food items	Rice – sesame (Kcal/day/capita)	Rice – sunflower (Kcal/day/capita)
Rice	1622.43	1728.12
Fish	40.54	48.26
Egg	13.26	13.81
Pulses	66.50	81.67
Vegetables	98.55	103.16
Meat	3.72	32.50
Milk	1.08	6.93
Dry fish	2.12	2.21
Soybean oil	163.65	59.72
Sunflower oil	-	161.52
Spices and other	34.94	35.47
Total	2046.80	2273.37
Difference in per capita daily calorie intake	226.57	

Source: adapted from Afsar (2013)

Average per capita calorie intake by households practicing a rice-sesame cropping pattern was estimated at 2046.80 kcal as shown in table 8, which is relatively lower than the recommended daily calorie intake of 2122 kcal per day. Thus, these households lived below the food poverty line and were food insecure from a nutritional availability viewpoint. On the other hand, average per capita calorie intake was relatively higher for households practicing a rice-sunflower cropping pattern, at 2273.37 kcal. This was above the recommended daily calorie intake. Thus, these farmers were, on an average, food secure.

3.3.2 Logit model and food security

In order to assess the role of a rice-sunflower cropping pattern and other determinants on farm household food security, a logit model was estimated. As mentioned earlier, seven explanatory variables were identified to be major determinants of food security in this study. The estimated parameters of the logit regression model are presented in Table 9.

Table 9. Estimation of the logistic regression of determinants of the food security status of farming households

Variable	Coefficient	Standard Error	Level of Significance	Exponential of coefficient or odds ratio
Constant	-3.837	1.533	0.012	0.022
Household size	-0.726	0.320	0.023*	0.484
Age of household head	0.011	0.019	0.544	1.011
Farm size	0.586	0.851	0.492	1.796
Per capita production	0.003	0.001	0.052**	1.003
Income	0.002	0.001	0.005*	1.002
Involvement in off-farm activities	0.920	0.509	0.070***	2.510
Food expenditures	0.002	0.001	0.003*	1.002

Note: * indicates significant at 1% level, ** indicates significant at 5% level, *** indicates significant at 10% level

Source: adapted from Afsar (2013)

Household size has a negative coefficient, which was significant at 1% level. The household size coefficient of -0.726 means there is a negative relationship between household size and food security. An odds ratio of 0.484 means a unit increase in household size will reduce the probability of a household to be food secure by 0.484. Per capita aggregate production was positive and significant at 5% level. A unit increase in per capita production will consequently increase the probability of household to be food secure by 1.003.

Household income was positive and significant at 1% level. This indicates that the higher the household income, the higher the probability that the household will be food secure. A unit increase in the level of income will increase the probability of a household to be food secure by 1.002. The household income of rice-sunflower farmers was much higher and 46.60% of total income came from rice and sunflower cultivation, which was much higher than the percentage share of other sources of income (Table 5).

Table 9 shows that involvement in off-farm activities is positive and significant at 10%. This indicates that households that were engaged in non-farm activities were nearly 2.51 times more likely to be food secure than those households that were not engaged in off-farm activities, other things remaining the same.

Finally, food expenditures have a low but positive coefficient that was significant at 1% level. A unit increase in food expenditures increase the probability of household to be food secure by 1.002.

3.3.3 Food security index

On average, the food security index for rice-sesame farmers was 1.05 when they were food secure whereas the value of this index for food insecure households from this group was 0.85. Average caloric intake of food insecure households was 1806.15 kcal, lower than the national average calorie intake (Table 10). On the other hand, Table 10 shows that farmers who cultivated sunflower in the study area could be classified as food secure since their average food security index was 1 and on average they were able to meet the recommended daily per capita calorie requirement of 2,122 kcal.

From the above-mentioned discussion, it can be concluded that food security was much more common in the sunflower farmers' households than among the sesame farmers' households.

Table 10. Food security indicators for farm households under two cropping patterns

Food security indices	Rice-sesame			Rice-sunflower		
	Food secure households	Food insecure households	All	Food secure households	Food insecure households	All
Food security index	1.05	0.85	0.95	1.07	0.90	1.00
Per capita daily calorie avail-ability (kcal)	2236.97	1806.15	2046.80	2271.52	1919.18	2273.37

Source: adapted from Afsar (2013)

3.4 Causes for favoring rice-sunflower cropping pattern

After realizing the profitability of sunflower farming many farmers are willing to choose the rice-sunflower cropping pattern. Indeed, the current adoption rate of sunflower is, perhaps, far better than ever before. Appendix Table 1 shows that about 25.00% and 35.00% of farmers were in favor of sunflower and in favor of both sesame and sunflower, respectively. Table 11 shows the ranking of reasons for adopting a rice-sunflower cropping pattern. About 95.00% of the farmers stated that sunflower cultivation was profitable for them. About 80.00, 50.00, and 40.00% of the sunflower farmers argued that they would grow sunflower for their own consumption of edible oil, utilization of cultivable land and utilization of family labor, respectively. Fifteen percent of all farmers expressed that they would produce sunflower because it might be harvested earlier and they could consequently move to rice cultivation after sunflower harvest.

Table 11. Reasons for choosing sunflower cultivation

Reasons	Number of respondents	% of total
For earning more profit	114	95.00
For household consumption of edible oil	96	80.00
For better utilization of cultivable land	60	50.00
For proper utilization of family labor	48	40.00
Early harvesting of sunflower provides an opportunity for growing next crop and hence earning more profits	18	15.00

Source: adapted from Afsar (2013)

Some farmers do not cultivate sunflower due to the high price of its seeds and other inputs like hired labor and fertilizers, the scarcity of financial capital and lack of awareness about the cultivation process and the potential benefits from sunflower cultivation. These were perhaps some of the important reasons for not adopting a rice-sunflower cropping pattern in the study area.

3.5 Problems associated with sunflower farming and probable solutions

Sunflower farmers in the study area have been facing some crucial problems that may explain the low rate of adoption despite the potential of sunflower. These issues are briefly discussed below.

3.5.1 Economic and technical problems

Lack of knowledge about cultural practices. As sunflower was a newly introduced crop in the study area, 55.00% of farmers (Table 12) reported that due to lack of knowledge about cultivation practices they failed to take proper care of the crop and thus they did not gain the expected per hectare yield.

Inadequate extension services. Although the selected farmers were producing the sunflower crop that was supplied by BRAC, it was alleged that their extension service was not sufficient for serving the purpose of individual farmers in the study area. Forty-three percent of sunflower growers reported that they were not getting adequate extension services (Table 12).

Lack of institutional credit facilities. As confirmed by this study, the cost of sunflower cultivation is relatively higher than the cultivation costs of other crops. Consequently, sunflower requires substantial amount of cash to purchase recommended doses of inputs such as seeds, fertilizers and irrigation water. Many farmers lacked the money to purchase the relevant inputs and it can be seen from Table 12 that 37.00% of sunflower growers mentioned that they lacked access to credit during crop cultivation when they would have needed it.

Inadequate supply of quality seeds. Availability of improved and quality seeds was another limiting factor in sunflower production, as reported by 84.00% of sunflower growers (Table 12).

Higher price of fertilizer, insecticides and water. About 76.00% of the sunflower growers sampled reported that they had to purchase fertilizer and insecticides from the market that they claimed were a higher price than the normal price (Table 12).

Parrot and squirrel attacks. Parrots and squirrels eat the seeds of sunflowers and cause great damage to yield. Seventy percent of sunflower growers reported this problem (Table 12).

Attack by pest and disease. Few incidences of pest and disease attacks were noted in the production of sunflower crop. Only 10.00% of the farmers referenced this problem (Table 12).

Flower plucking. Sunflower is not only recognized as an oilseed crop but is also well known as an ornamental crop to both children and adults. People are fascinated by its lovely color and often pluck the flower. It can be seen from Table 12 that 51.00% of the sunflower farmers sampled reported this problem.

Table 12. Problems associated with sunflower farming

Problems and Constraints	Number of respondents	% of total
(a) Economic and technical problems		
i. Lack of knowledge about cultural practices	55	55.00
ii. Inadequate extension services	43	43.00
iii. Lack of institutional credit facilities	37	37.00
iv. Inadequate supply of quality seeds	84	84.00
v. Higher price of fertilizers, insecticides and water	76	76.00
vi. Parrot and squirrel attacks	70	70.00
vii. Attack by pest and disease	10	10.00
viii. Flower plucking	51	51.00
(b) Marketing problems		
i. Inadequate demand	67	67.00
ii. Lack of proper marketing channel	75	75.00
(c) Problems relating to consumption		
i. Not habituated to eat regularly	43	43.00

Source: adapted from Afsar (2013)

3.5.2 Marketing problems

Inadequate demand. There was no organized market for sunflower seeds and oil in the study area. From Table 13, it can be seen that 67.00% of growers identified inadequate demand for sunflower in a local market as a serious problems.

Lack of proper marketing channel. Lack of sunflower oil millers for oil extraction and lack of proper marketing channels were identified as constraints to adoption. About 75.00% of farmers reported that the marketing facilities were very poor for sunflower (Table 13).

3.5.3 Problems related to consumption

Not habituated to eat regularly. Consumption of sunflower was also an important obstacle. Indeed, 43.00% of sunflower growers stated that they could not sell their product in the local market because the people were not accustomed to regularly consuming sunflower oil.

3.5.4 Suggestions for improving sunflower production

The selected farmers provided the following suggestions for overall improvement of sunflower production:

- Farmers need training about scientific methods of sunflower cultivation so that they can take initiative to reduce the cost of production.
- Institutional credit should be made available on easy terms and conditions to the concerned producers.
- Supply of an adequate quantity of quality seeds should be ensured at the right time in the study area.
- Fair prices for quality inputs and reasonable price for output should be ensured to farmers.
- Parrot is the main threat to sunflower cultivation and parrots ate sunflower seeds during sowing and harvesting times. Extension personnel should work immediately to solve this problem.

- Widespread extension work is needed to popularize the benefits of production and consumption of sunflowers.
- Farmers should make use of the sunflower byproducts to recoup a portion of their production costs. For example, they can use the plant as a house building material similar to straw, as food for domestic animals or as organic manure for the field. If they can sell it in the market (even at a small price) their profit from sunflower cultivation will be relatively higher.

4. Conclusion and recommendations

The study confirms that both the rice-sesame and rice-sunflower cropping patterns are profitable. Although both rice-sesame and rice-sunflower farmers earned profits, productivity varied amongst the farmers as reflected by the study's profitability analysis. Households following a rice-sunflower cropping pattern have higher incomes and benefit from a better food security status than households cultivating rice and sesame.

There are bright prospects for the expansion of sunflower due to its high nutritional value and a rising demand elsewhere in the country. Therefore, the following policy recommendations have been made for increasing the production and financial returns of sunflower production:

- There should be a marketing policy so that farmers can get fair prices for their products.
- We noticed that there was great variation in input use and other farm practices in the study areas. Most farmers did not follow the recommended doses of inputs. Extension work should be geared up in the study area so that farmers can improve their knowledge about recommended doses of the inputs used for sunflower cultivation. Seed preservation techniques should be developed so that farmers can preserve their own seeds and thereby reduce seed cost.

Apart from the above-mentioned specialized policies for rice and sunflower farmers, some common policies could also be undertaken for the greater interest of farmers and better management of Polder 30. Specifically, efficient water management and a producers' cooperative may solve many of the problems of growers of rice and sunflower in the study area. The concerned authority may formulate the relevant rules and regulations in this regard and thus, positive steps could be taken for the food and nutrition security of the people of the coastal region of Bangladesh.

Acknowledgements

The authors express their deep gratitude and heartfelt indebtedness to Dr Aditi Mukherji, Dr Marie Charlotte-Buisson, International Water Management Institute (IWMI), New Delhi, India and to Dr Manoranjan K Mondal, International Rice Research institute (IRRI), Dhaka, Bangladesh for their valuable suggestions for the completion of this study. The authors are grateful to IWMI and CPWF for providing the funds for conducting this study. The article is based on the MS thesis of the first author, Mahnaz Afsar, submitted to the Department of Agricultural Economics, Bangladesh Agricultural University (BAU), Mymensingh, Bangladesh in 2013.

References

Afsar, M. 2013. Impact of rice-sunflower cropping pattern on income and food security of farm households in Polder 30 of Batighata Upazila in Khulna district of Bangladesh. MS Ag Econ thesis, Bangladesh Agricultural University, Mymensingh.

Babatunde, R.O., O.A. Omotesho and O.S. Sholotan. 2007. Factor influencing food security status of rural farming households in North Central Nigeria. *Agricultural Journal* 2(3): 351-57.

BBS 2010. Household Income and Expenditure Survey 2010, Bangladesh Bureau of Statistics, Ministry of Planning, Dhaka.

Chuenpagdee, R. and D. Pauly, 2004. Improving the state of coastal areas in the Asia-Pacific region, Coastal *Management* 32:3-15.

Fatema, K. 2012. An economic investigation into dilemma of rice versus shrimp farming in some selected areas of Dacope Upazila (polder no. 30) under Khulna district of Bangladesh. MS Ag Econ thesis, Bangladesh Agricultural University, Mymensingh.

Feleke, S. T., R. L. Kilmer and C. H. Gladwin. 2005. Determinants of food security in Sothern Ethiopia at household level. *Agricultural Economics Journal* 33:351-63.

Hoddinott, J. 1995. Operationalizing Household Security and Development Strategies. International Food Security Policy Research Institute (IFPRI), Technical Guideline No. 1, Washington, USA.

Hossain, M. 2014. *Impact of Price Hike on Food Security in Bangladesh*, Lap Lambert Academic Publishing, Deutschland, Germany.

Kidane, H., Z. G. Alemu and G. Kundhlande. 2005). Causes of household food security in Koredegaga Peasant Association, Oromiya Zone, Ethiopia', *Agricultural Economics Journal* 4:543-60.

Mannaf, M. 2012. An economic study on maize production and its impact on food security in selected areas of Bogra district. MS Ag Econ thesis, Bangladesh Agricultural University, Mymensingh.

Miah, T.H. 2014. Economic analyses of on-farm and off-farm income generating activities in the project areas of the Coastal Livelihoods Adaptation Project (CLAP). A report prepared for GIZ-CLAP, Dhaka, Bangladesh.

Nasrin, M. 2011. Land tenure system and food security in some selected areas of Mymensingh district. MS Ag Econ thesis, Bangladesh Agricultural University, Mymensingh.

Osmani, S.R. and M. Ahmed. 2013. *Vulnerability to shocks and Coping Strategies in Rural Bangladesh*, Working Paper No. 21, Institute of Microfinance, Dhaka.

Primavera, J.H. 1997. Socio-Economic Impacts of Shrimp Culture. *Aquaculture Research* 28: 815-27.

Talaue-McManus, L. 2006. Pressures on rural coasts in the Asia- Pacific region in Harvey, N. (ed.). *Global Change and Integrated Coastal Management: The Asia- Pacific region* Springer, Dordrecht, the Netherlands, 197-229.

WFP (1988), 'Agricultural Production & National Food Balance', Bangladesh, Dhaka.

Appendix Table 1 - Nutrient Composition

Items	Energy (per 100 Sol) kcal	Items	Energy (per 100 Sol) kcal	Items	Energy (per 100 Sol) kcal
Coarse Rice	365	Meat	146	Egg	179
Atta (Wheat)	341	Beef	136.40	Milk (Cows)	70
Dal	344	Mutton	194	Oil(Soybean)	900
Lentil	343	Chicken	125.29	Spices	146
Fish	159	Duck	130	Onion	50
Rohi	120.55	Vegetables	48	Garlic	145
Telapia	127.50	Potato	80.20	Chili	40.71
Mrigal	98	Brinjal	42	Turmeric	349
Pangas	170.23	Helencha shalk	41	Dry fish	279.79
Sarputi.	161	Data shak	28.66	Hen	153

Note: 1 medium egg is 63 to 73 grams (average 68 grams).

Source: WFP (1988)

Appendix Table 2 - Farmers' willingness toward crop production

Farmers' opinions regarding crop cultivation	Number of respondents	% of total
In favor of sesame cultivation	80	40.00
In favor of sunflower cultivation	50	25.00
In favor of both sesame and sunflower cultivation	70	35.00
Total	200	100.00

Source: adapted from Afsar (2013)

Oilseed crops in rice-based cropping systems in southern Bangladesh

M.H. Rashid[1*], F. Hossain[2], D.K. Nath[2], P.C. Sarker[2], A.K.M. Ferdous[2] and T. Russell[2]

[1]Bangladesh Rice Research Institute, Bangladesh, hrashid67@yahoo.com
[2]International Rice Research Institute, Bangladesh, f.hossain@irri.org, d.nath@irri.org, p.sarker@irri.org, a.ferdous@irri.org, t.russell@irri.org

Abstract

The agro-ecological conditions and traditional rice-based farming practices of southern Bangladesh have resulted in lower crop diversity and cropping intensity than in other parts of Bangladesh. The hypothesis of the work here was that there is good scope to intensify the existing *aman-boro* cropping system (practiced in more favorable areas) through replacement of the long or medium duration rainy season rice varieties with short duration, high yielding varieties and the inclusion of oil seed crops between the rice crops. In the less favorable traditional aman-fallow areas, the hypothesis was that there is good scope to intensify production and increase income through growing sunflower. However, a major constraint to timely establishment of crops after *aman* harvest is that soils are too wet for tillage. Therefore, field trials and farmer participatory demonstrations on evaluation of short duration BARI mustard varieties, replacement of farmers' *aman* varieties with short duration *aman* varieties, inclusion of oilseeds in the cropping sequence, and oil seed crop establishment methods were conducted. High yielding mustard varieties were validated against farmers' local varieties in *aman*-mustard-jute and *aman*-mustard cropping sequences. Establishment of oil seeds with no tillage (zero till) and tillage were compared. For mustard, this involved relay sowing by broadcasting on the wet soil surface prior to *aman* harvest, or tillage after harvest and prior to seeding. Sunflower was established after *aman* harvest by dibbling into non-tilled soil, or following conventional tillage, soil moisture at maturity of the *aman* rice. Early maturing varieties of *aman* produced similar yields to farmers' varieties, and allowed for the inclusion of short duration oil seed mustard without affecting *boro* rice production. The yield of the short duration BARI mustard varieties was higher than that of the farmers' variety. In medium salinity soils, sunflower, a salt tolerant crop, produced yields of 1.9 to 2.6 t ha^{-1}, compared with yields of 2.4 to 3.1 t ha^{-1} in low salinity soils. Yield of sunflower declined as sowing was delayed beyond 5 December and dibbling into non-tilled soil allowed for earlier sowing rather than waiting for the soil to dry sufficiently for tillage. Sunflower and mustard were profitable and both provided farmers with an extra income of USD626 to 653 ha^{-1}. System productivity was improved and labor costs were reduced by adopting zero tillage systems for both mustard (relay intercropping with rice) and sunflower (dibble planting with rice stubble retention). Finally seed supply, processing and marketing need to be addressed to enable expansion of oilseed crops.

Key message: Relay intercropping of mustard and dibbled planting of sunflower are profitable interventions in rice-based cropping systems in southern Bangladesh.

Keywords: mustard, sunflower, tillage, dibbling, short duration

1. Introduction

Cropping systems in the coastal zone of Bangladesh are dominated by rice, as in other parts of Bangladesh, but cropping intensity is low for several reasons. Much of the coastal zone suffers from poor drainage and thus rice is usually transplanted into stagnant water where only the tall, late maturing and low yielding local varieties can survive. Further, the soil remains saturated during the winter season, which delays the sowing of dry season crops. Soil and water salinity increase as the dry season progresses, further limiting the ability to grow dry season crops. Even in the less saline (<4 dS m^{-1}) areas of the coastal zone, it is difficult to fit oilseed crops such as mustard in the short fallow period between the rainy season rice crop (transplanted *aman,* T.

Aman) and winter season (*boro*) rice. Prior to the introduction of *boro* rice in the 1980s, T. Aman was frequently followed by oilseed crops such as mustard (*Brassica juncea*) and sesame (*Sesamum indicum*) or grain legume crops such as lentil (*Lens culinaris*) and mungbean (*Vigna radiata*). In many areas, *boro* replaced oilseed and grain legume crops. In addition, many farmers in southwest Bangladesh cannot grow oilseed crops such as mustard or soybean because the soils are too saline in the latter part of the dry season.

Present domestic edible oilseed production in Bangladesh is 722,000 tons, which meets only one-third of national demand (BBS 2013). Present per capita food oil consumption is only 10 g day^{-1} compared with the recommended intake of 22 g day^{-1} (Rahman and Khan 2005). Bangladesh has one of the lowest fat intake levels in the world. Only 12% of total energy requirement is derived from fats. This is far below the recommended 35% for six- to twelve-month old children and the recommended 20 to 35% for pregnant and lactating mothers (Michaelsen et al. 2011). Children have high demand in relation to their size for energy foods. When the body is not supplied with enough energy from carbohydrates it converts whatever proteins are in their food to energy, which can cause protein deficiency and stunted growth. Stunting (below average height for age) in Bangladesh, at 41% of children under five years, is high (Bangladesh Demographic and Health Survey 2013). Increasing the oil content of children's foods would be more likely to occur if households grew oilseed crops and produced oil for family consumption. The constraints of oilseed expansion are largely related to use of long duration *aman* varieties, and inadequate knowledge of crop management under saline conditions. The constraints to oil seed production need to be overcome by replacing the existing *aman* varieties with short duration modern rice varieties and by introducing salt tolerant varieties of oilseed crops. The development of short duration rice varieties such as BRRI dhan33, BRRI dhan39 and BINA dhan7, and of high yielding mustard varieties such as BARI sarisha14 and BARI sarisha15, have created an opportunity to fit mustard between the *aman* and *boro* crops (BARC 2001; Islam 2013). This would increase the productivity of rice-based cropping systems (Rashid et al. 2012b). Also, in Faridpur and Barisal regions, there are areas of *aman*-mustard-jute and *aman*-mustard-fallow cropping sequences with low yielding local mustard varieties that could be replaced by high yielding mustard varieties to increase system productivity.

In coastal Bangladesh, planting of dry season crops is often delayed until January or even February because water remains on the land until December, at which time the weather becomes cold and foggy, and it is only after the weather starts to warm up in the latter part of January that significant soil drying starts to take place. Cultivation using a two-wheel, tractor operated power tiller is only possible once the topsoil has dried below field capacity. As a result, valuable soil moisture is lost while waiting for the soil to dry, and the late planted crops are exposed to damaging levels of soil and water salinity in March and April. Further, these late planted crops are at risk of being damaged by pre-monsoon rains that start from early May. Early planting, preferably in November and December, is essential to prevent the crops from exposure to increasing soil salinity and the pre-monsoon rains. In the case of small seeded crops like mustard, early planting can be achieved by broadcast sowing shortly prior to rice harvest. The seed then germinates on the moist soil under the rice canopy. In the case of larger seeded crops like sunflower, the seed can be dibbled just after rice harvest using a small stick or finger to create a hole for the seed (Rashid et al. 2012a). Another possible approach, yet to be fully tested, is to use power tiller operated seeders (PTOS) to directly sow crops into the rice stubble. This approach could be used for all types of oil seed crops but currently has only been tested on sesame. Therefore, farmer participatory trials and demonstrations were conducted to test and develop systems for the inclusion of oilseed crops in rice-based cropping systems in the coastal zone of Bangladesh.

2. Materials and methods

2.1 Study sites

Adaptive trials on varietal performance of mustard were conducted in Brahmankanda and Noapara villages under Bhanga Upazila of Faridpur District, on clay loam soils. The sites are strongly influenced by the south-western monsoon. The average annual rainfall is 1546 mm, with more than 80% occurring from mid-June to the end of September. Monthly mean minimum temperature of the area is 12.6^{0}C in January and maximum is 35.8°C in May.

Another field trial was conducted at Pankhali village under Dacope Upazila of Khulna District to determine the effect of sowing date on dibbled sunflower. Pankhali is about 1 m above sea level and belongs to Agro-Ecological Zone 13. The average annual rainfall of the area is 1710 mm. Monthly mean minimum temperature is 12.5^{0}C in January and maximum is 35.5°C in May. The soil of the experimental field is loam in texture.

Farmer participatory demonstrations of mustard varieties, alternative establishment methods for mustard and sunflower, and cropping system intensification, were conducted in several upazilas of Khulna, Satkhira, Bagerhat Districts in Khulna Division, Patuakali District in Barisal Division, and Jhenaidah District in Faridpur Division. Greater Khulna, Barisal and Faridpur are 1 to 2 m above sea level. The average annual rainfall of each region is 1710, 1955 and 1467 mm, respectively, with monthly mean minimum temperature of 12.5, 12.1 and 11.2^{0}C, and mean maximum temperature of 35.5, 35.1 and 37.1^{0}C, respectively. The soil of the demonstration plots was loam in Kaligonj Upazila in Jhenaidah, Dumuria Upazila of Khulna, Sadar and Kolaroa Upazilas of Satkhira, Fakirhat Upazila of Bagerhat, and Babugnoj Upazila of Barisal. Soils of other locations were clay to clay loam in texture. The soils of sites selected for the *aman*-mustard-*boro* cropping system and establishment experiments were of low salinity (<2 dS m^{-1}). The demonstration plots of sunflower in Patuakhali and in Kolaroa and Sadar Upazilas of Satkhira were slightly saline (<4 dS m^{-1}). The peak soil salinity of the other sunflower demonstration plots ranged from 6 to 9 dS m^{-1} at crop maturity in April.

2.2 Adaptive trials and demonstration

2.2.1 Adaptive trials

Rice-mustard-jute is one of the major cropping sequences in Brahmankanda and Noapara villages of Bhanga Upazila under Faridpur District. Farmers usually grow *T. Aman* (BRRI dhan39), Indian varieties of jute (JRO-524) and local mustard (Choitali). Mustard and sunflower trials were carried out in these villages.

Mustard. High yielding mustard varieties, BARI sarisha11 and BARI sarisha16 were grown side-by-side with Choitali in six farmers' fields, each field considered as one replicate. All mustard varieties were sown on the same day, and the farmers' usual *aman* and jute varieties were retained in the system. The trial was laid out in a randomized complete block (RCB) design, and plot size was 100 m^2.

Sunflower. The effect of sowing time of dibbled planted sunflower was studied with six sowing dates (25 November, 5, 15 and 25 December, and 5 and 15 January) after *aman* harvest at a single site, Pankhali of Khulna District. The treatments were assigned in a RCB design with three replications and plot size 100 m^2.

2.2.2 Farmer participatory demonstrations

Demonstrations of mustard varieties, mustard establishment method (relay sown before harvest or broadcast onto tilled soil after harvest) and the *aman*-mustard-*boro* cropping sequence were implemented in plots of 1320 m^2 in numerous farmers' fields in many locations from 2012 to 2014 (Table 1). Many demonstrations of dibbled and tilled sunflower were also conducted in plots of 800-1320 m^2.

Table 1. Demonstrated technologies and locations, 2012-2014

Demonstration technology	Name of villages	Upazila	District	No. of demonstrations/village
Aman-mustard-*boro; aman -boro*	i) Baratia ii) Bashghata	i) Dumuria ii) Satkhira Sadar	i) Khulna ii) Satkhira	i) 6 ii) 30
Relay sown (zero till) and tilled mustard in *aman*-mustard-*boro* system	i) Tipna, Chuknagar ii) Parkukrail, Ramer danga, Alipur, Daulatpur iii) Chaltabaria, Sultanpur iv) Magri v) Nagarghata vi) Jaria vii) Mathanpur	i) Dumuria ii) Satkhira Sadar iii) Kaligonj iv) Debhata v) Tala vi) Fakirhat vii) Kaligonj	i) Khulna ii) Satkhira iii) Satkhira iv) Satkhira v) Satkhira vi) Bagerhat vi) Jhenaidah	i) 3, 4 ii) 3, 3, 3, 4 iii) 3, 3 iv) 5 v) 9 vi) 5 vi) 12
Mustard varieties under relay and tilled methods of planting	i) Chaltabaria, Sultanpur, Datpur, Varasimla, Khamarpara ii) Bohera, Kamta, Magria iii) Jafarpur, Jhaudanga, Alaipur, Panikouria iv) Bashghata v) Nagarghata vi) Kundorria	i) Kaligonj ii) Debhata iii) Kolaroa iv) Satkhira Sadar v) Tala vi) Ashashuni	i) Satkhira ii) Satkhira iii) Satkhira iv) Satkhira v) Satkhira vi) Satkhira	i) 7, 9, 2, 6, 2 ii) 18, 2, 10 iii) 21, 9, 19, 10 iv) 4 v) 30 vi) 30
Local and improved mustard variety in rice-mustard sequence	Baradi Gorangol	Gournadi	Barisal	7

Table 1 (cont.). Demonstrated technologies and locations, 2012-2014

Demonstration technology	Name of villages	Upazila	District	No. of demonstrations/village
No tilled and tilled dibbled sunflower	i) Mohammadpur, Atulia, Patrakhola, Dhumghat, Koikhali, Joyakhali, Bayeshkhali ii) Varasimla, Marka, Khamarpara iii) Parkukrail iv) Naggolghara v) Juge Pukuria, Nagarghata vi) Pankhali, Kholisha vii) Fatehpur viii) Bisot ix) Guptamari, Parsolua, Debitola x) Ponchu, Tipna, Jolerdanga xi) Islampur xii) Char Miazan xiii) Hetalia, Gabura xiv) Manijhuri xv) Hoglapasha xvi) Protappur	i) Shaymnagar ii) Kaligonj iii) Satkhira Sadar iv) Debhata v) Tala vi) Dacope vii) Bagerhat Sadar viii) Kachua ix) Batiaghata x) Dumuria xi) Kolapara xii) Bauphal xiii) Patuakhali Sadar xiv) Amtali xv) Patharghata xvi) Babugonj	i) Satkhira ii) Satkhira iii) Satkhira iv) Satkhira v) Satkhira vi) Satkhira vii) Bagerhat viii) Bagerhat ix) Khulna x) Khulna xi) Patuakhali xii) Patuakhali xiii) Patuakhali xiv) Barguna xv) Barguna xvi) Brisal	i) 12,11, 18, 8, 7, 7, 9 ii) 15, 10, 6 iii) 10 iv) 11 v) 7, 8 vi) 18 vii) 6 viii) 6 ix) 7, 7, 7 x) 27, 13, 10 xi) 6 xii) 6 xiii) 6, 6 xiv) 6 xv) 6 xvi) 6
No tilled and tilled dibbled sunflower and salinity effect	i) Mohammadpur, Patrakhola, Dhumghat ii) Varasimla iii) Nurerchalk	i) Shaymnagar ii) Kaligonj iii) Debhata	i) Satkhira ii) Satkhira iii) Satkhira	i) 6, 7, 7 ii) 15 iii) 7

Aman-mustard-boro. The farmers in the selected villages cultivate medium duration *aman* varieties such as BR10, BRRI dhan30 and Swarna, which are harvested in the last week of November. They then sow *boro* in seedbeds in December that are ready for transplanting in mid-January to the first week of February. Farmer participatory demonstrations were conducted in which the medium duration *aman* variety was replaced with a short duration variety (BRRI dhan39 or BINA dhan7), and mustard was added to the system during 2012 to 2014 (Table 1). The mustard varieties BARI sarisha14 and BARI sarisha15 were established by broadcasting and relay sowing seven to ten days prior to *aman* harvest, or following harvest and tillage with a power tiller, depending on soil moisture at the time of maturity of the rice. After mustard harvest, the *boro* crop was transplanted into puddled soil and harvested in April.

Aman-mustard-fallow. In Gournadi, Barisal, farmers cultivate a short duration, local *aman* variety (Rajashail) followed by a local mustard variety called Maghi. BARI sarisha15 was compared with Maghi sarisha in seven farmers' fields. *Aman* rice was transplanted in mid-August and harvested in the first week of November. Mustard was sown during to the third week of November and harvested in February.

Aman-sunflower. Representative fields were selected where farmers practice an *aman*-fallow cropping system in villages in Khulna and Barisal. Farmer participatory demonstrations on crop establishment method in sunflower (the hybrid Hysun33) and the effect of soil salinity on sunflower production were conducted in 2012-13 and 2013-14.

2.3 Crop management practices

In the *aman*-mustard-*boro* cropping sequence, the short duration rice varieties and mustard varieties were grown following the BRRI and BARI recommended crop management practices (BRRI 2011; BARI 2012). *Aman* rice was rainfed in both non-saline and saline locations. The seeds of high yielding *aman* varieties (BR10, BR23, BRRI dhan41, BRRI dhan53 and BRRI dhan54) were sown during the first fortnight of July in the saline areas and transplanted in late July/early August. In Khulna region, the sunflower seed was dibbled just after *aman* harvest. In Barisal region, sunflower seed was sown into hand-dug furrows made after harvest and tilling using a two-wheel tractor with a power tiller. The recommended management practices for rice and sunflower were followed (BRRI 2011; Rashid et al. 2012a). No till dibbled sunflower was sown in the standing rice stubble (20-25 cm high) 20 to 30 days before the tilled sunflower, and one to two irrigations were applied to the sunflower crops.

2.4 Data collection and analyses

Grain yield was estimated by harvesting an area of 10 m^2 from the centre of each plot and expressed as t ha^{-1} at 14, 9 and 9% moisture contents for rice, mustard and sunflower, respectively. The productivity of mustard and sunflower was determined as rice equivalent yield (REY), which was calculated as follows:

$$REY = \frac{Sunflower\ or\ mustard\ \ yield\ (kg\,/\,ha)\ x\ sunflower\ or\ mustard\ \ price\,(Tk./\,kg)}{Price\ \ of\ paddy\ (Tk./kg)}$$

Electrical conductivity (EC) of the topsoil (0-15 cm) was measured at the sites of three upazilas of Satkhira in the tilled and non-tilled plots of the sunflower demonstrations. EC was measured in a 1:5 soil: water suspension (EC1:5) and was converted to soil saturation extract EC (ECse) by multiplying by conversion factors of 14 for loam, 10 for clay loam, 9 for light clay and 6 for heavy clay soil following the method of Watling (2007). Analysis of variance was done using CropStat Version 7.2, and differences were considered significant only at $P < 0.05$. Multiple linear regression analyses using SPSS version 11.5 were run to determine the effects of soil salinity on seed yield of sunflower. Soil salinities, on the day of seeding (0 DAS) and at 30 and 60 DAS and maturity, were the independent variables and seed yield was the dependent variable.

For the economic analyses, the cost of inputs (hire of power tiller and thresher rental for land preparation and threshing, labor for different operations, seed, fertilizer, pesticide, irrigation, etc.) and the farm gate prices of outputs (paddy, seeds of mustard or sunflower) were calculated based on their local market price. The cost of labor, including family labor, and all input costs were included in the total variable cost (TVC) (Tables 2 and 3). The gross margin (GM) per hectare for each crop management or cropping sequence option was calculated by deducting the total variable cost from the gross return. The benefit cost ratio (BCR) was calculated by dividing the gross return (GR) by TVC.

Table 2. Compiled variable costs used in the financial analysis of technologies demonstrated in 2012-2014

Demonstration technology	Seed cost ($ ha^{-1})		Fertilizer cost ($ ha^{-1})		Pesticide cost ($ ha^{-1})	
Aman-mustard-*boro; aman-boro*	A-M-B[1]	A-B[2]	A-M-B	A-B	A-M-B	A-B
	41.7	33.5	278	225	142	138
Relay sown (zero till) and tilled mustard in *aman*-mustard-*boro* system in Khulna Relay	Tilled	Relay	Tilled	Relay	Tilled	
	42.3	40.8	255	255	141	138
Relay sown (zero till) and tilled mustard in *aman*-mustard-*boro* system in Jessore	Relay	Tilled	Relay	Tilled	Relay	Tilled
	31.7	30.2	427	397	153	91.6
Mustard variety under till and relay method of planting	Relay	Tilled	Relay	Tilled	Relay	Tilled
BARI sarisha14	8.30	6.80	63.5	82.9	-	-
BARI sarisha15	8.30	6.80	78.0	73.1	-	-
Local and improved mustard varieties in rice-mustard sequence in Barisal	Local	Improved	Local	Improved	Local	Improved
	4.40	5.80	87.4	100	-	-
No tilled dibbled and tilled sunflower	No tilled	Tilled	No tilled	Tilled	No tilled	Tilled
	12.3	12.3	186	169	-	-

[1]A-M-B = Aman-Mustard-Boro

[2]A-B = Aman-Boro

Table 3. Compiled variable costs used in the financial analysis of technologies demonstrated in 2012-2014

Demonstration technology	Tillage cost ($ ha^{-1})		Irrigation cost ($ ha^{-1})		Labour cost ($ ha^{-1})	
Aman-mustard-*boro*; *aman-boro*	A-M-B[1]	A-B[2]	A-M-B	A-B	A-M-B	A-B
	146	126	309	282	901	749
Relay sown (zero till) and tilled mustard in *aman*-mustard-*boro* system in Khulna Relay	Tilled	Relay	Tilled	Relay	Tilled	
	102	164	303	305	588	611
Relay sown (zero till) and tilled mustard in *aman*-mustard-*boro* system in Jessore	Relay	Tilled	Relay	Tilled	Relay	Tilled
	160	203	411	401	997	1100
Mustard variety under till and relay method of planting	Relay	Tilled	Relay	Tilled	Relay	Tilled
BARI sarisha 14	-	53.8	23.2	35.5	110	124
BARI sarisha 15	-	52.8	34.7	34.3	136	118
Local and improved mustard varieties in rice-mustard sequence in Barisal	Local	Improved	Local	Improved	Local	Improved
		60.2	64.6	15.4	48.5	119135
	No tilled	Tilled	No tilled	Tilled	No tilled	Tilled
No tilled dibbled and tilled sunflower		-	77.0	35.1	51.9	228319

[1]A-M-B = Aman-Mustard-Boro

[2]A-B = Aman-Boro

3. Results and discussion

3.1 Rice-mustard based cropping systems

3.1.1 System productivity of aman-fallow-boro and aman-mustard-boro

In the *aman*-mustard-*boro* cropping system demonstrated in 30 farmers' fields of Khulna and Satkhira, grain yield of short duration *aman* was similar to that of the farmers' medium duration varieties with similar crop management at around 5.6 t ha^{-1} (Table 4). On average, mustard produced 1.59 t ha^{-1} seed. The yield of *boro* was similar following mustard or fallow (5.73 and 5.90 t ha^{-1}, respectively), showing that growing mustard between *aman* and *boro* crops did not reduce *boro* yield. Rice equivalent yield of the *aman*-mustard-*boro* was significantly higher (by 43%) than that of the *aman-fallow-boro* system. The higher REY in *aman*-mustard-*boro* also resulted in a higher BCR and gross margin (by 105%) (Table 5).

Table 4. Grain, seed yield of *T. Aman*, mustard and *boro* rice and rice equivalent yield of *aman*-mustard-*boro* and rice-fallow-rice cropping pattern in Khulna and Satkhira, 2012-13

Cropping sequence	Farmer (no.)	Grain/seed yield (t ha^{-1})			REY of cropping system
		T. Aman	Mustard	Boro	
Aman-mustard-*boro*	30	4.71[1]	1.59	5.73	15.2
Aman-fallow-*boro*	6	4.75[2]	-	5.90	10.65
$LSD_{0.05}$	-	ns[3]	-	ns	0.76
CV (%)	-	2.9	-	4.2	7.5

[1] grain yield of short duration rice varieties (BRRI dhan39 and BINA dhan7)

[2] medium duration rice (BR10)

[3] not significant

Table 5. Economic return from *aman*-mustard-*boro* and *aman*-fallow-*boro* cropping sequence in Khulna and Satkhira, 2012-13

Cropping pattern	Farmer (no.)	Gross return (USD ha^{-1})	TVC (USD ha^{-1})	GM (USD ha^{-1})	BCR
Aman-mustard-*boro*	30	3038	1816	1222	1.67
Aman-fallow-*boro*					
(Farmers' practice)	6	2051	1554	596	1.38

Note: Price USD t^{-1}: Mustard seed: 584.4, *aman* paddy: 194.8, *boro* paddy: 207.8, 1USD = 77 BDT

3.1.2 Rice-mustard-fallow

In the *aman*-mustard-fallow cropping system in Barisal District, BARI sarisha15 gave a significantly higher (by 37%) seed yield than Maghi sarisha (Table 6). This was due to more pods per plant and seeds per pod, and higher seed weight, in BARI sarisha15. Gross margin of BARI sarisha15 was 133% higher than the local variety (Table 7). BARI sarisha15 remained in the field 14 days longer than the local mustard variety. However, the longer duration of BARI sarisha 15 did not affect establishment of the next crop as the mustard crop is followed by fallow until establishment of the next *aman* crop.

Table 6. Seed yield and yield component of mustard varieties under rice-mustard-fallow cropping system at Gournadi, Barisal, 2013-14

Variety	Farmer (no.)	Plant height (cm)	Plant m^{-2}	Pod $plant^{-1}$	Seed pod^{-1}	Thousand seed weight (g)	Seed yield (t ha^{-1})	Growth duration (days)
BARI sarisha15	7	115	74	61.7	21.7	3.05	1.63	84
Maghi sarisha (FP)	7	64	106	32.2	13.7	2.45	1.10	70
$LSD_{0.05}$	-	2	5	2.7	0.7	0.15	0.01	2
CV (%)	-	2.1	4.2	4.4	3.2	4.0	4.5	1.8

Table 7. Economic return of mustard varieties under the *aman*-mustard-fallow system at Gournadi, Barisal, 2013-14

Variety	Farmer (no.)	Gross return (USD ha^{-1})	Total variable cost (USD ha^{-1})	Gross margin (USD ha^{-1})
BARI sarisha15	7	849	355	494
Maghi sarisha	7	498	286	212

Note: Seed price (USD t^{-1}): BARI sarisha15 seed: 520.9, Maghi sarisha: 452.7, 1USD= 77 BDT

3.1.3 Productivity of the aman-mustard-boro cropping system with and without tillage in mustard

Mustard established in tilled soil yielded 1.76 and 1.27 t ha^{-1} in Khulna and Jessore regions, respectively, and net return from the *aman*-mustard-*boro* system was USD 1240 and 1440 ha^{-1}, respectively (Tables 8 and 9). Relay-sown mustard produced a lower seed yield of 1.21 and 0.99 t ha^{-1} in Khulna and Jessore, respectively, with net return of USD 999 and 1550 ha^{-1}. The higher net return from mustard in Jessore region was due to higher market price for mustard following storage for a longer period by the farmers. Although the relay mustard earned lower net return than the tilled mustard, the system was found promising as it ensured early planting of mustard and hence early transplanting of *boro* rice, which is a concern to the farmers.

Table 8. Seed yield and economic return of relay and tilled mustard in *aman*-mustard-*boro* cropping system, Khulna region, 2013-14

Tillage in mustard	Farmer (no.)	Grain/Seed yield (t ha^{-1})			REY (t ha^{-1})	TVC (USD ha^{-1})	Gross return (USD ha^{-1})	Gross margin (USD ha^{-1})
		T. Aman	Mustard	Boro				
Tilled	18	3.94	1.76	4.85	13.49	1515	2753	1238
Relay	27	3.85	1.21	4.78	11.84	1431	2430	999
$LSD_{0.05}$	-	ns	0.17	ns	0.65	-	-	-
CV (%)	-	10.0	20.1	9.3	8.7	-	-	-

Note: Price USD t^{-1}: Mustard seed: 519.5, Aman paddy: 194.8, Boro paddy: 220.8, 1USD = 77 BDT

Table 9. Seed yield and economic return of relay and tilled mustard in *aman*-mustard-*boro* cropping system, Sadar and Kaligonj Upazila, Jhenaidah, 2013-14

Tillage in mustard	Farmer (no.)	Grain/Seed yield (t ha^{-1})			REY (t ha^{-1})	TVC (USD ha^{-1})	Gross return (USD ha^{-1})	Gross margin (USD ha^{-1})
		T. Aman	Mustard	Boro				
Tilled	12	5.08	1.27	6.36	15.0	2263	3707	1444
Relay	12	5.05	0.99	6.18	14.2	2180	3729	1549
$LSD_{0.05}$	-	0.23	0.09	Ns	0.6	-	-	-
CV (%)	-	5.1	9.4	9.4	4.8	-	-	-

Note: Price USD t^{-1}: Mustard seed: 649.4, Aman paddy: 246.8, Boro paddy: 279.2, 1USD = 77 BDT

3.1.4 Productivity of mustard varieties under tilled and relay method of seeding in aman-mustard-boro cropping sequence

The interaction between variety and establishment method was significant in Khulna region (Table 10). In tilled soil, yield of BARI sarisha15 was slightly but significantly higher than that of BARI sarisha14. The same trend occurred with relay sowing, but the difference was not significant. Yield with relay planting was much lower than yield with tillage prior to sowing for both varieties.

Table 10. Seed yield of mustard varieties and economic return from relay and tilled mustard under *aman*-mustard-*boro* cropping sequence in Satkhira, 2013-14

Establishment method of mustard	Variety	Farmer (no.)	Seed yield (t ha^{-1})	TVC (USD ha^{-1})	Gross return (USD ha^{-1})	Gross margin (USD ha^{-1})	BCR
Tilled	BARI sarisha14	59	1.64	303	944	641	3.32
	BARI sarisha15	47	1.89	285	1092	807	4.03
Relay	BARI sarisha14	15	1.26	204	728	524	3.84
	BARI sarisha15	58	1.31	257	754	497	3.49
$LSD_{0.05}$	Est. method (M)	-	0.28	-	-	-	-
	Variety (V)		ns	-	-	-	-
	M X V		0.06	-	-	-	-
CV (%)			9.0	-	-	-	-

Note: Price USD t^{-1}: Mustard seed: 576.9, 1USD = 77 BDT

3.1.5 Mustard variety in aman-mustard-jute cropping system

The interaction between variety and location was also significant for two locations in Faridpur (Table 11). There was a consistent trend for higher seed yield of BARI sarisha11 than BARI sarisha16 at both locations; however, the difference was only significant at Brahmankhanda. Seed yield of the local variety Choitali was significantly lower than that of both BARI varieties at both locations. The stover yield of all varieties was similar. The growth duration of BARI sarisha11 was six to eight days longer than that of Choitali. Economic analysis indicated an increase in gross margin of USD 171 and 202 ha^{-1} by replacing Choitali with BARI sarisha 11 in Noapara and Brahmankanda, respectively.

Table 11. Seed, stover yield and economic return of mustard varieties in an *aman*-mustard-jute cropping system at two locations of Bhanga, Faridpur, 2013-14

Location	Variety	Farmer (No.)	Seed yield (t ha^{-1})	Stover yield (t ha^{-1})	Growth duration (days)	Gross return (USD ha^{-1})	Total variable cost (USD ha^{-1})	Gross margin (USD ha^{-1})
Brahman kanda	BARI sarisha11	6	2.03	4.23	109	1206	485	721
	BARI sarisha16	6	1.86	4.13	113	1182	500	682
	Choitali (FP)	6	1.66	4.00	101	1016	497	519
Noapara	BARI sarisha11	6	1.94	4.10		1162	492	669
	BARI sarisha16	6	1.82	3.95		1169	489	680
	Choitali (FP)	6	1.62	3.82		990	492	498
$LSD_{0.05}$	-	-						
Variety (V)	-	-	0.10	ns		-	-	-
Location (L)	-	-	0.12	ns		-	-	-
(LXV)	-	-	0.14	ns		-	-	-
(CV %)	-	-	6.4	8.6		-	-	-

Note: Price (USD t^{-1}): Mustard seed: 519.5, Stover: 39, 1 USD= 77 BDT, ns =not significant

3.2 Aman-sunflower cropping system

3.2.1 Planting date of sunflower

Sunflower dibbled on 25 November and 5 December without tillage produced similar seed yield (~3 t ha^{-1}), significantly higher than yield of all later sowings. There was a trend for yield to decline as sowing was delayed from 5 December to 15 January, with the lowest yield (2.51 t ha^{-1}) for January 15 planting. The results indicate that farmers lose 22 kg ha^{-1} of grain yield worth USD 11.4 ha^{-1} for every day that planting is delayed after 5 December. While a yield of 2.5 t ha^{-1} for the 15 January planted sunflower is still a good yield, the later planted sunflower would also be at greater risk of damage from early monsoon rains (which did not occur in the study year) as the crop would not be ready for harvest until the end of April.

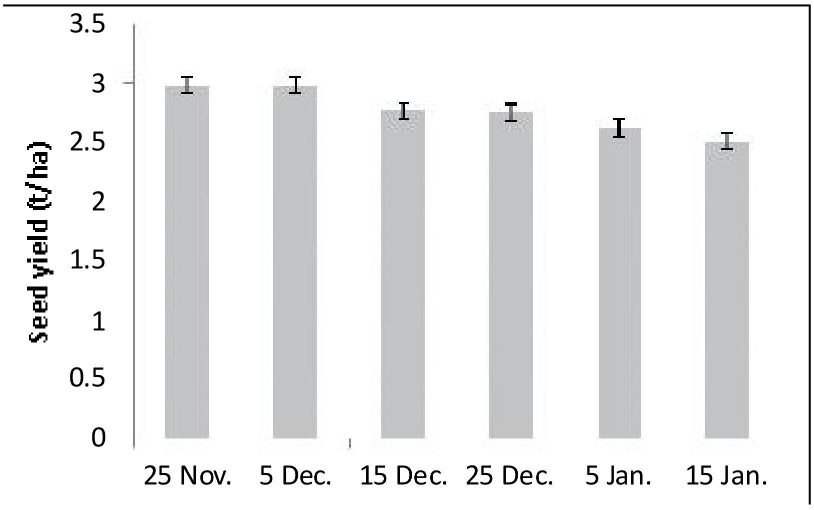


Fig. 1. Seed yield of sunflower as affected by sowing date (error bars indicate the LSD at 5% level of significance).

3.2.2 Establishment method in sunflower and soil salinity effect

Data collected from 150 demonstrations in Khulna region showed that crop establishment method did not affect the seed yield of sunflower (Tables 12 and 13). Seed sown by dibbling gave similar seed yield (2.29 t ha^{-1}) to seeding in tilled soil (2.39 t ha^{-1}). But the former method earned 19% higher gross margin due to the cost of land preparation and earthing up. Moreover, dibbled crops were ready for harvest at least 20 days earlier than the crops planted in tilled soil, reducing the risk of damage by early monsoon storms. April and May 2014 were much drier than normal, with no significant pre-monsoon storms.

Initial soil salinity ranged from 0.5 to 2.5 dS m^{-1} across the sunflower demonstration sites (Fig. 2). Soil salinity increased with time after sowing up to maturity (Table 13), and there was strong positive linear relationship (R^2 = 0.72**) between initial and final soil salinity (Fig. 2). The highest seed yield was achieved in Kaligonj (2.52 to 2.55 t ha^{-1}) where soil salinity at crop maturity (ECse 6.8 dS m^{-1}) was least. Yield was least at Debhata (2.08 to 2.09 t ha^{-1}) where the salinity was highest (9.88 dS m^{-1} at crop maturity). The results of the multiple linear regression show that soil salinity at seeding (X1) had a significant and negative effect on yield, and the coefficient (-0.347) had the largest magnitude (Table 14). Soil salinity at other stages had no significant effect on seed yield, although the effect of salinity at harvest was almost significant, with a negative co-efficient about one-third of that for salinity at sowing.

The yield of sunflower seeded after *aman* harvest varied from 2.4 to 3.1 t ha^{-1} across locations in Barisal (Table 15). The highest seed yield was in Bauphal (3.08 t ha^{-1}), which was similar to seed yield in Patharghata, Amtali and Kolapara. The lowest seed yield was in Gabua of Patuakhali Sadar Upazila, mainly due to smaller head size and fewer seeds per head due to lack of water for a second irrigation. The BCR and the gross margin showed a similar trend to that of seed yield except for Babugonj (Table 16). Although the seed yield was lower in Babugonj, the gross return and gross margin was higher due to its higher market price in the locality.

Table 12. Seed yield and economic return from dibbled and tilled sunflower in an *aman*-sunflower cropping sequence in Khulna region, 2013-14

Establishment method	Farmer (no.)	Seed yield (t ha^{-1})	TVC (USD ha^{-1})	Gross return (USD ha^{-1})	Gross margin (USD ha^{-1})	Increased GM over tilled (%)	BCR
Dibbled	150	2.29	461	1172	711	19	2.75
Tilled	90	2.39	629	1225	596	-	1.95
$LSD_{0.05}$	-	Ns	-	-	-	-	-
CV (%)	-	20.4	-	-	-	-	-

Table 13. Seed yield of dibbled and tilled sunflower and soil salinity at different locations of Satkhira in an *aman*-sunflower cropping sequence, 2013-14

Location	Establishment method	Farmer (no.)	Seed yield (t ha^{-1})	Soil salinity (dS m^{-1})			
				0 DAS	30 DAS	60 DAS	Maturity
Shaymnagar	Dibbled	18	2.08	1.20	4.16	5.59	7.22
	Tilled	2	2.09	1.20	4.25	6.15	7.25
Kaligonj	Dibbled	11	2.55	0.94	4.12	5.32	6.80
	Tilled	3	2.52	1.00	4.65	6.05	7.73
Debhata	Dibbled	-	-	-	-	-	-
	Tilled	7	1.89	1.68	4.40	6.32	9.88
$LSD_{0.05}$	Est. method (M)	-	ns	ns	ns	ns	1.02
	Location (L)		0.15	ns	ns	ns	1.19
	M X L		0.22	ns	ns	ns	1.72
CV (%)	-	-	8.6	-	-	-	19.2

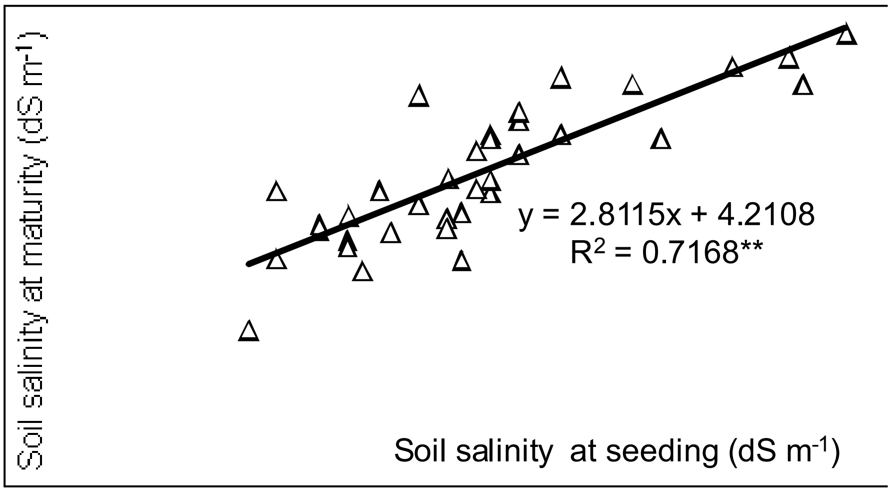


Fig. 2. Relationship between soil salinity at seeding and maturity stages of sunflower in Satkhira.

Table 14. Standardized coefficients for explaining the effect of salinity on seed yield of sunflower in the sunflower establishment method farmer participatory demonstrations in Satkhira (N=42)

Soil salinity	Symbol	Unstandardized coefficients		Standardized coefficients	t value	Significance
		B	Std. Error	Beta		
(Constant)	Intercept, a	2.374	0.240		9.896	0.000
At 0 DAS	X1	-0.347	0.164	-0.588	-2.120	0.042
At 30 DAS	X2	0.034	0.097	0.110	0.347	0.731
At 60 DAS	X3	0.158	0.111	0.658	1.423	0.165
At maturity	X4	-0.105	0.058	-0.592	-1.819	0.079

Table 15. Seed and stalk yield and yield component of sunflower under an *aman*-sunflower-fallow cropping system at different locations of Barisal, 2013-14

Location	Plant height (cm)	Plant m^{-2}	Head diameter (cm)	Seed $head^{-1}$	Thousand seed weight (g)	Seed yield (t ha^{-1})	Stalk yield (t ha^{-1})	Growth duration (days)
Kolapara	126	3.27	18.5	1169	78.8	2.82	4.17	110
Bauphal	176	3.40	19.2	1231	79.7	3.08	5.10	117
Hetalia (Patuakhali Sadar)	164	3.67	17.5	1044	74.5	2.70	3.85	114
Amtali	173	3.60	17.8	1115	74.6	2.91	4.02	112
Patharghata	146	3.40	18.5	1192	78.2	3.01	4.35	111
Gabua (Patuakhali Sadar)	163	3.63	15.9	914	74.5	2.37	3.75	113
Babugonj	191	3.47	17.2	1100	76.2	2.62	3.55	123
$LSD_{0.05}$	6	0.29	1.1	122	2.2	0.28	0.59	2
CV (%)	3.4	7.0	5.2	9.4	2.5	8.7	12.2	1.7

Table 16. Economic return of sunflower under an *aman*-sunflower cropping system at different locations of Barisal, 2013-14

Location	TVC (USD ha^{-1})	Gross return (USD ha^{-1})	Gross margin (USD ha^{-1})	BCR
Kolapara	698	1286	588	1.84
Bauphal	662	1438	776	2.17
Hetalia (Patuakhali Sadar)	654	1207	553	1.85
Amtali	716	1311	595	1.83
Patharghata	699	1368	669	1.96
Gabua, Patuakhali Sadar	658	1082	424	1.64
Babugonj	743	1569	826	2.11

4. Conclusions and recommendations

- Oil seed crops can be introduced within the existing rice-based cropping systems of the coastal zone of Bangladesh without compromising productivity of other crops in the rotation.
- Mustard can be grown between a*man* and *boro* crops by replacing medium duration *aman* varieties with short duration modern varieties.
- New mustard varieties of BARI Sarisha 11 and BARI Sarisha 15 provide significantly higher seed yield than local varieties.
- The income of growers can be increased and with higher BCR by growing oilseed crops.
- Mustard marketing and processing is well established in coastal Bangladesh, but the areas where it can be grown are relatively limited due to soil salinity.
- Seed of new mustard varieties is not readily available and what is available is mixed. Production of mustard seed in isolation seems to be difficult to achieve. Maintaining proper isolation distance between seed production farms and production of seed of the most preferred variety in an area can solve this problem.
- Early planted sunflower gives a significantly higher grain yield than January sown sunflower and its earlier harvest reduces the risk of damage from early monsoon rain.
- Sunflower can be grown even after medium duration *aman* varieties such as BRRI dhan41 or BRRI hhan 54 in soils where salinity increases to >7 dS m^{1} for the second half of the crop.
- Soil salinity at sowing is a major determinant of sunflower yield and so planting sunflower in fields with lower soil salinity at seeding should be encouraged. A simple test for farmers to determine soil salinity and thus suitability for cultivation of sunflower is needed.

Sunflower has a promising market in urban areas where it can be marketed under the low cholesterol label. Both sunflower and mustard have potential to increase farmers' income but lack of quality seed, higher cost of seed of improved varieties, poor oil extraction technology and defective links to major market players are currently constraints to wide scale adoption.

Acknowledgements

The authors thank the United States Agency for International Development (USAID) for the support to carry out this study through Cereal System Initiative for South Asia-Bangladesh Project (CSISA-BD). Thanks are extended to the community who supported to evaluate the trials and demonstrations in their fields.

References

Bangladesh Demographic and Health Survey, January 2013.

BARC (Bangladesh Agricultural Research Council). 2001. A compendium: Packages of Technologies. In: *A handbook for farming systems development*. ed M.F. Haque, M.A. Razzaque and Abu Akteruzzaman, p.12. BARC, Dhaka.

BARI. 2011. *BARI technology (commodity)*. http://www.bari.gov.bd/index.php?option=com_advancedsearch&view=advancedsearch

BBS 2013. Statistical Yearbook of Bangladesh. 2012. Bureau of Statistics. Statistics and Informatics Division. Ministry of Planning, Government of the People's Republic of Bangladesh, Dhaka. Pp. 140-142.

BRRI (Bangladesh Rice Research Institute). 2011. *Modern rice cultivation*. 16th edition. p. 72.

Islam, M. R. 2013. *Maximization of crop yield in t. aman-mustard-boro cropping pattern by agronomic manipulation.* Half Yearly Progress Report, KGF, BARC.

Michaelsen, K.F., G.K. Dewey, A.B. Perez-Exposito, M. Nurhasan, I. Lauritzen, and N. Roos. 2011. *Food sources and intake of n-6 and n-3 fatty acids in low-income countries with emphasis on infants, young children (6-24 months), and pregnant and lactating women*. Maternal and Child Nutrition. Blackwell Publishing Ltd *Maternal and Child Nutrition* (2011), **7** (Suppl. 2), pp. 124–140.

Rahman M. M. and S. I. Khan. 2005. Food security in Bangladesh: Food availability. In: ed. *Government of the People's Repubpic of Bangladesh and World Food Programme-Bangladesh*. p.9. Workshop held at IDB Bhavan, Agargaon, Dhaka, Bangladesh, 19-20 October, 2005.

Rashid, M. H., S. Nasrin, M. K.I. Rony, D. Mahalder, S.Begum. 2012a. *Sunflower cultivation after harvesting of t. aman rice in saline area* (In *Bangla*). Folded brochure. International Rice research Institute, 2/2 Banani, Dhaka 1213, Bangladesh.

Rashid, M.H., M.K.I. Rony, S. Nasrin. 2012b. *Increasing productivity of rice-rice cropping system adopting short duration rice and mustard and relay cropping.* Paper presented in the International Conference on Environment, Agriculture and Food Sciences, held in Phuket, Thailand on 11-12 August, 2012. pp. 13-16. Planetary Scientific Research Center.

Rony, M.K.I., M.H. Rashid, S. Nasrin, M.A. Saleque. 2013. Effect of zero tillage on Boro rice cultivation in ghers of south-western Bangladesh. *Bangladesh Journal of Agronomy*. 16(1): 105-107.

Watling, K. 2007. Measuring salinity. Fact Sheet. Department of Natural Resources and Water. Queensland Government, Australia. L 137. http://joomla.speedweb.com.au/soil2015/images/sampledata/publications_tab/schoolresources/factsheets/07_measuring-salinity.pdf

Triple rice in a year: Is it a feasible option for the low salinity areas of the coastal zone of Bangladesh?

N. K. Saha[1,2], M. K. Mondal[1], E. Humphreys[1], J. Bhattacharya[1,2], M. H. Rashid[2], P. C. Paul[3] and S. P. Ritu[3,4]

[1]International Rice Research Institute, Philippines, n.saha@irri.org, m.mondal@irri.org, e.humphreys@irri.org, j.bhattacharya@irri.org
[2]Patuakhali Science and Technology University, Bangladesh, mhrashid_pstu@yahoo.com
[3]Bangladesh Rice Research Institute, Bangladesh, plcpauliwm@yahoo.com
[4]Current address: Sylhet Agricultural University, Bangladesh, sanjidap05@gmail.com

Abstract

The cropping intensity and productivity of the coastal zone of Bangladesh is much lower than that of the country as a whole. In the coastal zone most farmers grow a single, low yielding, late maturity *aman* variety during the rainy season, and a large portion of the land is fallow for much of the dry season. There is a general perception that during the dry season the river water is saline throughout the coastal zone; however, most of the rivers in the Barisal Division remain non-saline and suitable for rice irrigation throughout most or all of the year. Furthermore, there is a perception that modern, high yielding and early maturity *aman* varieties cannot be grown in the coastal zone due to water stagnation. However, with separation of lands of different elevation using small levees, and by draining excess water from the fields at low tide, modern *aman* varieties can be successfully grown. Given this and the recent availability of the first high yielding, short duration *aus* variety for Bangladesh, it should be possible to intensify production to two and three high yielding crops per year in much of Barisal Division. Increasing productivity of the coastal zone is now a high priority of the Government of Bangladesh. Studies were therefore conducted in Patuakhali District to determine the feasibility of growing three rice crops per year and to evaluate planting date and *aman* variety options. The experiment was conducted for two years (2012-14) with three *aus* sowing dates (10, 25 April and 1 May), four *aman* varieties (BRRI dhan33, BRRI dhan49, BRRI dhan52, BRRI dhan53), and five *boro* sowing dates (15, 20, 30 November and 05, 15 December) in 12 *aus-aman-boro* cropping system combinations. Total in-field duration of the systems ranged from 277 to 312 d, showing the feasibility of growing three rice crops per year. Total system productivity ranged from 13.4 to 17.2 t/ha/yr; two to four times that of current farmer practice. The results show that cultivation of three rice crops per year in the low salinity coastal zone is a feasible technology for greatly increasing productivity of the coastal zone and contributing to the future food security of Bangladesh.

Key message: Triple rice cropping with total system production of around 16 t/ha is possible in the coastal zone of Bangladesh in areas where there is year-round fresh water availability, separation of lands of different elevation (e.g. using large bunds) and ability to drain at low tide.

Keywords: cropping system intensification, Patuakhali, *aus, aman, boro*

1. Introduction

Rice is the main food staple and the dominant crop in Bangladesh, occupying nearly 80% of the total cropped area. Rice is grown throughout the year. The crop grown during April to July is known as *aus*, rice grown during July to December is called *aman,* and that grown from November to May is known as *boro*. *Boro* is grown under irrigated conditions while the production of *aus* and *aman* is mostly rainfed. The main rainy or monsoon season (*kharif* 2) occurs from July to September/October, with significant pre-monsoon rain from May to June (*kharif* 1). There is very little rain from November to March/April, the dry season.

While Bangladesh as a whole is currently self-sufficient in rice production this is not the case for the coastal zone (Tuong et. al 2014). Rivers are tidal in the coastal zone with diurnal fluctuations of two to three m. The salinity of the rivers increases during the dry season, more so closer to the coastline and in the southwest. However, most of the agricultural lands of the coastal zone are protected from flooding and saline water intrusion as a result of the construction of polders. Despite this cropping intensity in this region is much lower than in other parts of the country. Over 50% of land remaining fallow during the dry season (BARC 2008) because of the lack (or perceived lack) of fresh water for irrigation, and because of soil salinity which increases as the dry season progresses. Most farmers in the coastal zone grow a single *aman* crop using traditional, tall varieties typically yielding only 2 to 3.5 t/ha. Old seedlings (up to 70 d) are typically transplanted in late July or August. Tall seedlings are required to survive stagnant flooding which occurs in the polders primarily as a result of rainfall, and this practice is common throughout the coastal zone. As the local varieties are photoperiod sensitive, they are not ready for harvest until December. The *aman* crop is often followed by a low yielding crop such as *keshari* (grasspea) or sesame.

In reality, there is abundant fresh water in the rivers throughout the year in significant areas of the coastal zone. This is particularly true in much of Barisal Division and it is predicted that this will continue to be the case even in the climate change scenario with a 22 cm mean sea level rise and a moderate precipitation change (Khan et al. these proceedings). Furthermore, there is a dense network of former river distributaries (*khals* or canals) inside the polders that can be used to deliver fresh water from the large rivers surrounding the polders. Despite this, the area under *aus* (0.27 Mha) and *boro* (0.14 Mha) cultivation is very low when compared with the area under *aman* (0.71 Mha) (N.K. Saha, pers. comm.). A major constraint to cropping system intensification is the low level of adoption of non-photoperiod sensitive, high yielding *aus* and *aman* varieties with shorter duration than traditional varieties. Modern *aus* and *aman* varieties cannot tolerate water stagnation, hence their low level of adoption. Thus while much of Bangladesh experienced a rapid increase in production as a result of the introduction of input responsive, high yielding crop varieties, the development of irrigation (mostly groundwater) and cropping system intensification to two to four high yielding crops per year, the coastal zone missed out on this 'Green Revolution'. It is possible to grow modern aus *and aman* varieties with systematic operation of the sluice gates to drain out excess water at low tide, so in theory it should be possible to grow three rice crops per year in parts of the coastal zone where fresh water is available year-round.

Ritu et al. (these proceedings) have demonstrated the possibility of intensifying to an *aus-aman* system using a short duration, high yielding *aus* variety (HYV *aus*) and non-photoperiod sensitive HYV *aman* without jeopardizing the yield of the *aman* crop. Furthermore, Sharifullah et al. (2009) have shown the feasibility of an HYV *aman-boro* system in the coastal zone, with sowing of the *boro* crop (mid-November) advanced in comparison with the common practice in northern Bangladesh to reduce irrigation water requirements. However, the feasibility of combining all three crops in a year has not been shown in the coastal zone. The general objective of the research presented here was to explore sowing date and *aman* variety combinations for fitting three rice crops together in a single year. The main hypotheses were that: (i) with the use of short duration HYV *aus,* non-photoperiod sensitive HYV *aman*, and a medium duration *boro* variety it is possible to implement *aus-aman-boro* cropping systems with total system yield in excess of 15 t/ha, and (ii) *boro* yield and thus system productivity will be higher with earlier establishment.

2. Methods

2.1 Experimental site

A field experiment was conducted on the experimental farm of Patuakhali Science and Technology University, Dumki, Patuakhali-8602, Bangladesh from 2012 to 2014. The field was located at $22^0$27'51.063"N latitude, $90^0$22'56.873"E longitude and 3 m above mean sea level. The soil was a clay loam and the site had a cropping history of T.*aman*-fallow/*khesari*/mungbean-fallow. The field was in a low part of the farm and about 50 m from a tidal canal whose water remained non-saline throughout the year. The field was surrounded with bunds that were raised to 70 cm high and 50 cm wide to provide protection from flooding that can occur when high rainfall results in runoff from surrounding lands.

2.2 Experimental design

The experiment was designed to compare options for triple rice (*aus-aman-boro)* cropping systems. *Aus* crops were grown from April to July, *aman* from July to November and *boro* from November to April starting with the 2012 *aman* crop. The experiment had an unbalanced factorial design with three *aus* establishment practices, four *aman* varieties and two *boro* sowing dates in a split-split plot design with four replicates. The experiment compared 12 cropping system (CS) options (Table 1, Fig. 1). The details of the treatments are:

Three *aus* establishment practices (E) in main plots (10 m x 10 m):
E1: Sown on 10 April, transplanted 1 May
E2: Sown on 25 April, transplanted 15 May
E3: Direct (wet) seeded on 1 May

The Vietnamese variety OM1490 (moderately salt tolerant, short duration - 100 d seed to seed) was used in all *aus* treatments. This variety was released in Bangladesh as BRRI dhan65 in October 2014.

Two *aman* varieties (V) in sub plots (5 m x 10 m):
For the first two *aus* treatments (E1 and E2) two medium duration *aman* varieties were grown -
V1: BRRI dhan49 (duration 135 d)
V2: BRRI dhan52 (duration 145 d, submergence tolerant)

For the wet seeded *aus* (E3) two short duration *aman* varieties were grown -
V3: BRRI dhan33 (duration 118 d)
V4: BRRI dhan53 (duration 125 d)

Transplanting of the *aman* crops was not permitted less than 10 d after harvest of each *aus* treatment because farmers are busy at harvest and it takes time to prepare their fields for establishment of the next crop. Thus *aman* crops were planted within 12 to 18 d after *aus* harvest.

Two *boro* sowing dates (D) in sub-sub plots (5 m x 5 m):

Within each *aus-aman* treatment combination, the first *boro* sowing date was selected to ensure that transplanting did not take place less than 10 d after harvest of the *aman* crop, and not earlier than 15 November as previous research in Khulna (Mondal et al. 2010) had shown that earlier sowing led to serious yield loss due to cold damage during the reproductive stage. The second *boro* sowing date was 15 d after the first. As a result, there were a total of five *boro* sowing dates ranging from 15 November to 15 December (Table 1).

Table 1. Cropping system treatments

Aus establishment method/sowing date (E)[1]	*Aman* variety (V)	*Boro* sowing date (D)	Cropping system (CS)
E1: 10 April	V1: BRRI dhan49	D1= 15 November	CS1
		D2 = 30 November	CS2
	V2: BRRI dhan52	D1= 15 November	CS3
		D2 = 30 November	CS4
E2: 25 April	V1: BRRI dhan49	D1= 30 November	CS5
		D2= 15 December	CS6
	V2: BRRI dhan52	D1= 30 November	CS7
		D2= 15 December	CS8
E3: 1 May	V3: BRRI dhan33	D1= 20 November	CS9
		D2= 05 December	CS10
	V4: BRRI dhan53	D1= 20 November	CS11
		D2= 05 December	CS12

[1]E1, E2 transplanted, E3 direct (wet) seeded

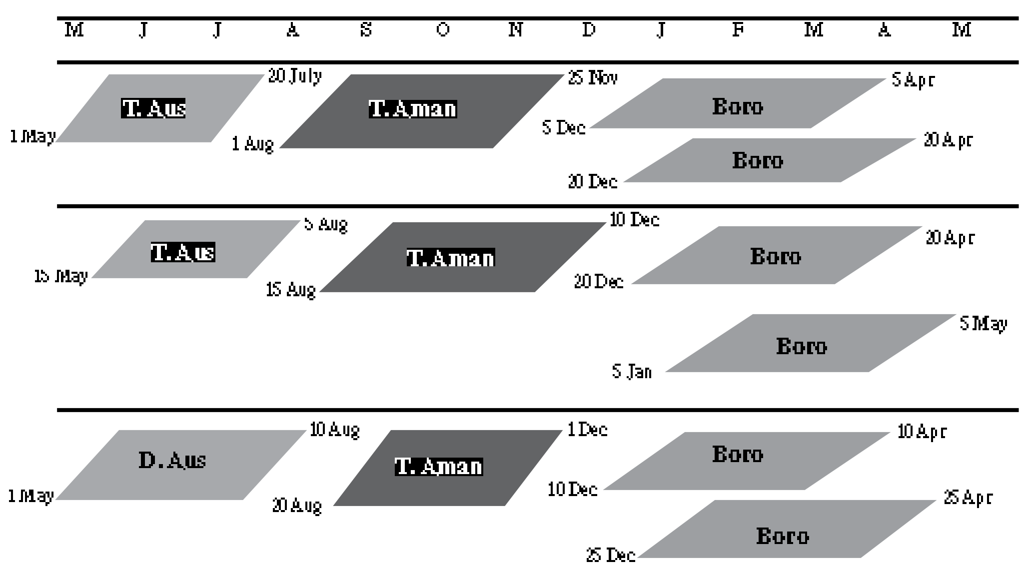


Fig. 1. Proposed *aus-aman-boro* crop calendar.

2.3 Tillage and crop establishment

All plots were plowed three to four times (wet tillage) using a power tiller powered by a two-wheel tractor. Final land leveling with a wooden plank drawn by an ox was done after basal application of fertilizer. Rice seeds were soaked for 12 to 24 h and incubated for 48 to 72 h for germination. For the transplanted crops, the pre-germinated seeds were sown on the seed bed at 28 g/m^2. Ten days after emergence, urea was applied to the seedbed at 32 kg N/ha (BRRI 2011). Transplanting was done when the seedlings had four leaves (usually about 21 d after sowing, DAS), with two to three seedlings per hill, and a hill spacing of 20 cm x 20 cm in all crops. In the direct seeded *aus*, pre-germinated rice seeds were hand sown in lines on the surface of the puddled soil at a row spacing of 20 cm and a seed rate of 40kg/ha.

2.4 Fertilizer application

Urea, triple superphosphate, muriate of potash, gypsum and zinc sulphate were applied to each crop as per BRRI (2010) recommendations. Urea was applied at 120 kg N ha^{-1} to the *boro* crops and at 100 kg N ha^{-1} to the *aman* crops in four equal splits: before the last leveling, 25 d after transplanting (DAT), 5 to 7 d before panicle initiation (DBPI) and at heading. For the transplanted *aus*, urea was applied at 100 kg N ha^{-1} in three equal splits before the last leveling, 5 to 7 DBPI and at heading. For the direct seeded *aus*, urea was also applied at 100 kg N ha^{-1} but in four equal splits at 10 to 15 d after emergence (DAE), 30 to 35 DAE, 45 to 50 DAE (5 to 7 DBPI) and 60 to 65 DAE (heading). All other fertilizers were applied at 60 kg P_2O_5, 40 kg K_2O, 60 kg $CaSO_4$ and 10 kg $ZnSO_4$ per ha before the last leveling.

2.5 Water management

The *aus* crops were established using supplemental irrigation as needed and thereafter grown on rainfall, as with the establishment and growth of the *aman* crops. At times of excessive rainfall during the *aus* and *aman* crops, water was drained from the experimental field by gravity and/or by pumping. Water was drained whenever the depth exceeded the plant height and the depth was lowered to 10 to 25 cm depending on the height of the crop. All *boro* crops were fully irrigated. Water was pumped from the nearby *khal* using a 4 horsepower pump powered by diesel. The *boro* rice was irrigated whenever water depth fell below 1 cm and water was added until the ponded water depth reached 5 cm. Irrigation was stopped 10 to 15 d before harvest. The salinity of the irrigation water was always <1.0 dS/m.

2.6 Weed, pest and disease control

Systemic pesticides (BRRI, 2011) were applied during each N application to all crops to prevent crop damage. When infestations occurred, recommended pesticides were sprayed. As a result, pest and disease control were good in all crops except for the early sown *boro* 2012-13 and all *aman* 2013 crops, which were heavily infested by brown spot disease. Brown spot was controlled in later sowings of *boro* 2012-13 and in all 2013-14 *boro* crops using recommended pesticides; however, it could not be controlled in the 2013 *aman* crops. Good weed control was achieved by applying a post-emergence weedicide (pyrazosulfuron-ethyl@125 g/ha) 3 to 5 DAT into standing water and the water was held on the plots for 2 to 3 d after treatment. Manual spot weeding was also done prior to urea topdressing. The experimental site was surrounded by a plastic barrier with traps to prevent damage by rats, and covered by netting each season when the earliest crop approached maturity to prevent bird damage. Prior to installing the bird nets there was yield loss in the earliest sowing of the first *aus* crop due to bird attack at the milky dough stage.

2.7 Data collection

Grain and straw yield of each plot were determined in a 3 m x 2 m (150 hills) area in the middle of each sub-sub-plot. The samples were threshed, cleaned and the grain and straw weighed. Grain moisture content was determined using a moisture meter and straw sub-samples were weighed and dried at 70°C to determine moisture content. Grain yield is presented at 14% moisture content and straw yield at 0% moisture content.

2.8 Data analysis

The effect of the treatments on yield of the *aus, aman* and *boro* crops, and of the total cropping system, was compared using one-way ANOVA (12 cropping systems or "treatments"). For the first two *aus* establishment methods, a split-split plot design ANOVA was also used to determine if there were interactions between *aus* establishment method, *aman* variety and *boro* sowing date. Least significant difference (lsd) at 5% probability was used to test for differences between means. The analyses were done using the STAR, version 2.0.1 (Statistical Tool for Agricultural Research) program developed by IRRI (STAR 2014).

3. Results and discussion

3.1 Duration of crops in the main field:

The duration of each crop in the main field determines the number of crops that can be accommodated annually in the crop sequence. The crop duration reported for all transplanted crops is from transplanting to physiological maturity (PM, 80% of grains golden), in cases where seedlings are raised in a separate nursery. The crop duration for the direct seeded *aus* crops is from seeding to PM.

3.1.1 Aman

The duration of BRRI dhan49 and 52 was usually in the range of 96 to 102 d, except for the first sowing in 2012 when duration was 114 to 116 d (Table 2). The longer duration of the first sowing in 2012 was probably because the crop was submerged twice (from 5 to 12 DAT and from 36 to 39 DAT) as a result of heavy rainfall and flooding from surrounding areas prior to raising the height of the surrounding bund to 70 cm. The second sowing of these varieties was also submerged from 22 to 25 DAT in 2012, which may explain the fact that duration was 5 d longer in the first year than the second year. There was no submergence of the third sowing in 2012 and no submergence of any *aman* crops in 2013. The duration of BRRI dhan33 sown on 30 July was only 86 and 83 d in the first and second years, respectively, 9 d less than that of BRRI dhan53 sown on the same date each year. The reason for the slightly shorter duration (by 3 to 4 d) of the short duration varieties in the second year is not known. Mean daily temperature from sowing to transplanting was similar throughout the growing season each year.

The duration of all *aman* varieties in the absence of submergence was generally similar to that observed by others in the region. Roy et al. (2003) found 120 d duration of BRRI dhan33 transplanted as 30 d old seedlings in August in Barisal district, about a week longer than in our study. However, this work was done at BRRI Regional Station at Barisal, which is affected by tidal flooding. The duration of BRRI dhan52 ranged from 111 to 121 d in the studies of Sharma et al. (2013) at Amtali (Barguna District), similar to the values in our study. For BRRI dhan53, duration was about 10 d earlier than that observed by others (118 to 127 d) (Sharma et al. 2013; Islam and Gregorio 2013). Possible reasons for the longer duration in other studies include periods of submergence or water stagnation (critical information which is often not reported in variety evaluation trials) and the method used to determine duration, in particular maturity date (physiological maturity as in our study, or “harvest maturity” when the grain is considered dry enough for the farmers to harvest), information which is also seldom reported.

Table 2. Duration of crops from establishment to PM during 2012-13 and 2013-14 (days)

Cropping System (CS)	Treatment combinations[1,2]	2012-13				2013-14			
		Aman	*Boro*	*Aus*	Total system duration	*Aman*	*Boro*	*Aus*	Total system duration
CS1	E1V1D1	116	119	77	312	101	119	74	294
CS2	E1V1D2		116		309		109		284
CS3	E1V2D1	114	119		310	101	119		294
CS4	E1V2D2		116		307		109		284
CS5	E2V1D1	101	116	78	295	96	109	75	280
CS6	E2V1D2		109		288		105		276
CS7	E2V2D1	102	116		296	97	109		281
CS8	E2V2D2		109		289		105		277
CS9	E3V3D1	86	116	96	298	82	118	91	291
CS10	E3V3D2		115		297		106		279
CS11	E3V4D1	95	116		307	91	118		300
CS12	E3V4D2		115		306		106		288

[1] E = *aus* sowing date (E1: 10 April, E2: 25 April, E3: 1 May); V = *aman* variety (V1: BRRI dhan49, V2: BRRI dhan52, V3: BRRI dhan33, V4: BRRI dhan53); D = *boro* sowing date (D1: 10 d after *aman* harvest, D2: 25 d after *aman* harvest)

[2] E1 and E2 transplanted, E3 wet seeded

3.1.2 Boro

Boro crop duration was in the range of 105 to 119 d and declined with delay in sowing, more so in the second year (Fig. 2). The decrease in duration with delay in sowing was due to higher temperatures during the vegetative period. The duration of the 30 Nov/early Dec sowings was 7 to 9 d longer in 2012-13 than in 2013-14 and this was associated with much lower temperatures from late November to mid-January in the second year (Fig. 3).

In a saline location (BRRI Regional Station in Satkhira), Salam et. al. (2010) found that duration of BRRI dhan 28 was longer (136 d) than in our study. Islam and Gregorio (2013) reported even longer duration (140 d) of BRRI dhan28 in participatory variety selection (PVS) trials at several sites in salinity prone coastal zone districts, but this was during the wet season and the method for determination of duration was not reported.

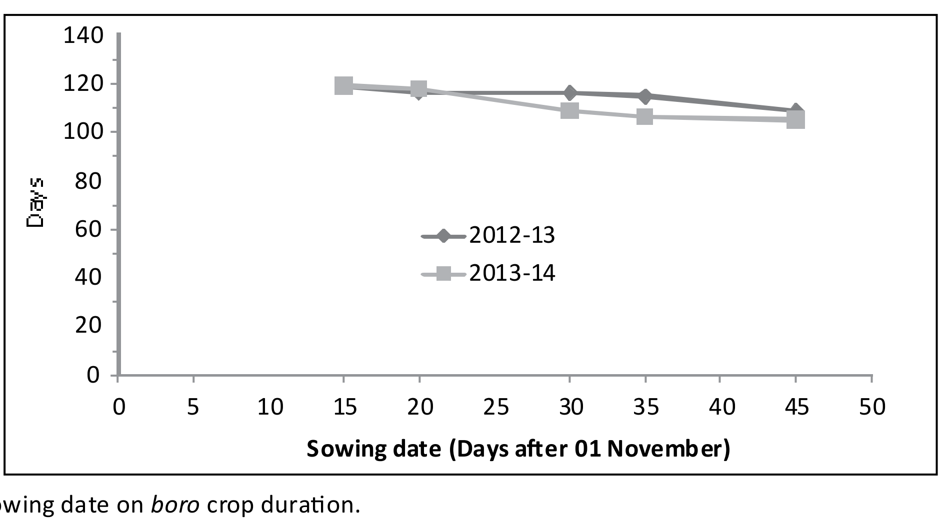


Fig. 2. Effect of sowing date on *boro* crop duration.

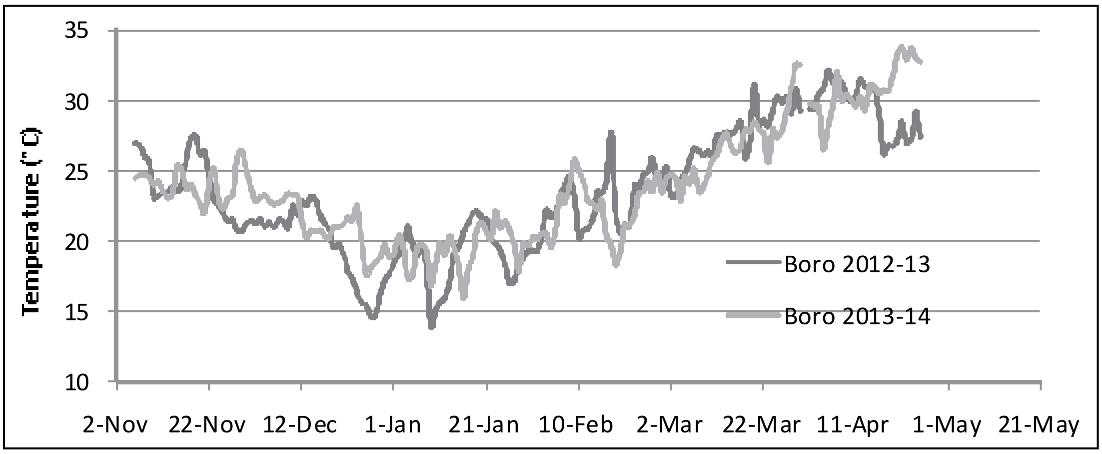


Fig. 3. Daily mean temperature during *boro* 2012-13 and 2013-14.

3.1.3 Aus

There was little variation in the duration of the *aus* crops, regardless of seeding date, establishment method and year (Table 2). Transplanted crops took 98 and 95 d to mature (seed to seed) in 2013 and 2014, respectively, whereas direct seeded treatments took 96 and 91 d, respectively. The slightly longer duration in 2013 was probably due to slightly lower temperatures during the grain filling stage than in 2014. Duration of the same variety (OM1490) in the Mekong delta of Vietnam was reported to be shorter, at 85 to 90 d (Lang et al. 2010).

3.1.4 Total crop duration in the main field

The total duration of crops in the main field ranged from 288 to 312 d in 2012-13, and from 277 to 300 d in 2013-14 (Table 2). However, it is usually better for farmers to allow their crops to dry in the field for a few days (the time required depending on weather at the time of PM) before harvesting. Therefore, a more realistic estimate of duration in farmers' fields would be from about 290 to 330 d. This allows for an average turn-around between crops of about 12 to 25 d, which suggests that all sowing date x variety combinations evaluated in this experiment are feasible for farmers. The shortest in-field duration each year was with transplanted *aus* sown on 25 April followed by BRRI dhan49 or 52, and with the later *boro* sowing (15 December), systems CS6 and 8. There were no consistent trends for the longest duration cropping system, partly because of submergence of the early *aman* crops in 2012.

3.2 Grain yield

3.2.1 Aman

Aman yields ranged from 5 to 6 t/ha in 2012 and from 4.5 to 5.3 t/h in 2013. Yields of all sowing date x variety combinations were lower in 2013 than 2012 due to a severe attack of brown spot. In 2012, there was a consistent trend for higher yield of earlier sown BRRI dhan49 and 52 (CS1, 3) than for 15 d later sowings (CS2, 4), with significantly higher yield of early BRRI dhan49 than both varieties sown later (Table 3). However, yields of both these variety x sowing date combinations were similar in 2013. Yield of BRRI dhan33 sown on 1 August was significantly lower than yield of all other variety x sowing date combinations in 2012, and of BRRI dhan49 and 52 for both sowings in 2013.

High yields of BRRI dhan49 and 52 were achieved despite inundation twice for 4 to 8 d within the first 10 weeks after the first transplanting in 2012, and for 4 d during the third week after the second transplanting. Yields were similar to those achieved with these varieties under favourable conditions at Mymensingh, where

Shormy (2012) reported a yield of 5.5 t/h for BRRI dhan49, and Uddin (2013) reported a yield of 5.4 t/ha for BRRI dhan52. The results demonstrate the feasibility of achieving high yields of modern *aman* varieties provided that excess water is drained rapidly following inundation as a result of heavy rainfall. The results also demonstrate the importance of separating lower and higher lands to protect lower lands from inundation from surrounding lands.

Yields of the shorter duration variety BRRI dhan53 in our experiment (4.7 to 5.4 t/ha) were similar to or higher than mean yields reported from PVS trials in salinity prone coastal districts (4.8 t/ha, Islam and Gregorio 2013) and in a low salinity region of the coastal zone (4.7 t/ha, Sharma et al. 2013). Yields of an even shorter duration variety (BRRI dhan33, 4.5 to 5.0 t/ha) tended to be lower than those of BRRI dhan53, with some significant differences each year. Yields of BRRI dhan33 were similar to yields obtained in on-station experiments in favourable environments at Mymensingh (5.0 t/ha, Rahman et al. 2004), Madaripur (5.4 t/ha, Quddus et al. 2012) and Dhaka (4.6 t/ha, Masum et al. 2013).

Table 3. Grain yield of component crops and the total system during 2012-13 and 2013-14, as affected by *aus* establishment method (E), *aman* variety (V) and *boro* sowing date (D)

Cropping System (CS)	Treatment combina-tions[1,2]	2012-13 yield (t/ha)			1st year system yield (t/ha/yr)	2013-14 yield (t/ha)			2nd year system yield (t/ha/yr)
		Aman	*Boro*	*Aus*		*Aman*	*Boro*	*Aus*	
CS1	E1V1D1	6.0	4.9	4.1	15.0	5.2	6.1	3.7	15.1
CS2	E1V1D2		5.6	4.1	15.7	5.1	7.3	3.4	15.8
CS3	E1V2D1	5.8	5.0	4.0	14.7	4.9	6.2	3.9	15.1
CS4	E1V2D2		5.4	3.8	15.0	5.1	7.2	3.6	15.8
CS5	E2V1D1	5.6	6.0	3.8	15.3	5.2	7.4	4.3	16.9
CS6	E2V1D2		6.3	3.6	15.4	5.3	6.8	4.5	16.6
CS7	E2V2D1	5.5	5.6	3.7	14.9	5.2	7.4	4.6	17.2
CS8	E2V2D2		5.9	3.8	15.2	5.0	7.4	4.4	16.8
CS9	E3V3D1	5.0	4.9	3.6	13.4	4.6	7.1	4.4	16.1
CS10	E3V3D2		5.9	3.5	14.4	4.5	7.5	4.2	16.2
CS11	E3V4D1	5.4	5.1	3.5	14.0	4.7	7.0	4.2	15.8
CS12	E3V4D2		5.9	3.5	14.8	4.8	7.3	4.2	16.3
LSD (p=0.05)		0.4	0.4	NS	0.9	0.3	0.5	0.5	0.9
C.V. (%)		4.6	5.2	9.1	4.2	4.0	5.3	9.2	3.9

[1] E = *aus* sowing date (E1: 10 April, E2: 25: April, E3 1 May); V = *aman* variety (V1: BRRI dhan49, V2: BRRI dhan52, V3: BRRI dhan33, V4: BRRI dhan53); D = *boro* sowing date (D1: 10 d after *aman* harvest, D2: 25 d after *aman* harvest)

[2] E1 and E2 transplanted, E3 wet seeded

3.2.2 Boro

There was a consistent trend for increasing yield with delay in sowing of *boro* from mid-November to late November/early December (Fig. 4). Yield was much lower in the first year than the second year for all sowing dates because of the long cold period and serious attack of brown spot disease. It is a common observation that stressed plants are highly vulnerable to brown spot. In the second year brown spot was not a problem. The higher yield in the second year was associated with higher panicle density for all but the last (15 Dec) sowing, and more so for earlier sowings. The higher yield in the second year was also associated with more florets per panicle (for all but the first sowing), and more so for later sowings.

Boro yields were in the range of those observed by others. Salam et. al. (2010) reported yield of BRRI dhan28 of 5.7 t/ha at a saline location in Satkhira in 2006/7, while Mondal et al. (2010) obtained 4.6 and 5.0 t/ha for 15 and 7 November sowings in the same year, at a saline site in Khulna. In the previous year at the same site, yields ranged from 5.0 to 5.6 t/ha for the same sowing dates. Islam and Gregorio (2013) reported a yield of 7.6 t/ha in PVS trials in the southwest coastal zone during the 2009 and 2010 wet seasons.

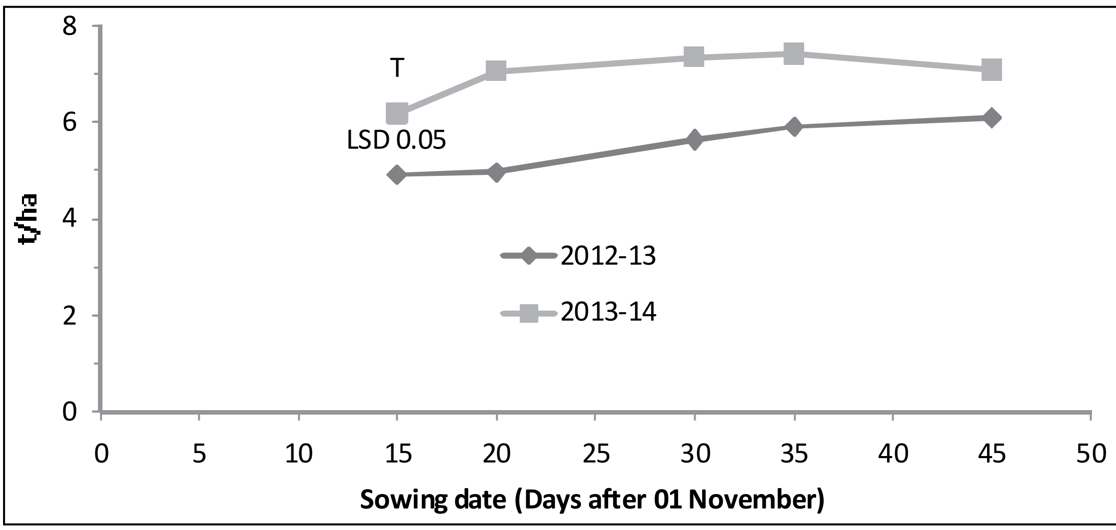


Fig. 4. Effect of sowing date on yield of *boro* (vertical bar is lsd (p=0.05) for the interaction between year and sowing date).

3.2.3 Aus

Aus yield ranged from 3.5 to 4.1 t/ha (Table 3), similar to the yields of BRRI dhan65 obtained by Ritu et al. (these proceedings) in a medium salinity area of Khulna when water was not limiting. In Vietnam, Lang et al. (2010) reported a yield of 5.6 t/ha despite the shorter duration in that environment. Das (2008) reported the yield of OM 1490 (BRRI dhan65) was 3.6 t/ha with the growth duration of 91 d at Kismat Fultola and recommended to incorporate this variety for increasing cropping intensity in the coastal zone. In the first year of the present study, there was a trend for *aus* yield to decline as sowing was delayed, but with no significant differences. In 2014, yield of the first sowing was significantly lower than yields of the other two sowing dates because of bird attack at the milky dough stage (despite the use of net, small birds finds ways to ensure their food security), resulting in low floret fertility and low grain weight.

3.2.4 Total system yield

Total system yield ranged from 13.4 to 15.7 t/ha/yr in 2012-13 and from 15.1 to 17.2 t/ha/yr in 2013-14 (Table 3). There was no correlation between yield of respective systems in the first and second years. However, yield of systems with transplanted *aus* seeded on 25 April (CS5-8) was significantly higher than yield of most other systems in the second year and among the highest yielding systems in the first year.

In 2012-13 there were no interactions between *aus* establishment treatment, *aman* variety (BRRI dhan49, BRRI dhan52) and *boro* sowing date on system yield. However, in 2013-14 there was a significant *aus* X *boro* treatment interaction (Table 4). With early *aus* sowing (10 April), system yield was less with early *boro* sowing than sowing that occurred 15 d later. However, with later *aus* sowing (25 April) system yield was not affected by *boro* sowing date.

Table 4. Interaction between *aus* establishment practices (E) with *boro* sowing dates (D) of the eight cropping systems during 2013-14

Aus establishment method (E)	Boro sowing date (D)			
	Grain yield (t/ha/yr)		Straw yield (t/ha/yr)	
	D1	D2	D1	D2
E1	15.1	15.8	13.7	12.5
E2	17.1	16.7	12.1	12.3
L.S.D. (P=0.05)	0.6		0.8	

3.3 Straw yield

3.3.1 Aman

Straw yield ranged from 4.8 to 6.2 t/ha in 2012, and from 3.1 to 5.0 t/ha in 2013 when the crop was affected by brown spot disease. In 2012 straw yield of BRRI dhan49 for both sowings and BRRI dhan52 for the second sowing was significantly higher than that of most other *aman* variety x sowing date combinations (Table 5). In the first sowing, after submergence for 8 d, additional muriate of potash (20 kg K_2O/ha) was applied. This may be the cause of the higher straw yield of BRRI dhan52 for the first sowing, as evidenced by higher tillering of the first sowing than the second sowing (data not presented). In 2013, straw yield of the later sown shorter duration varieties (BRRI dhan33 and 53) was significantly lower than that of all other treatments. *Aman s*traw yield of all varieties was lower in 2013 than 2012 by up to 2 t/ha, probably due to brown spot infestation.

In the favourable environment of Mymensingh, Shormy (2012) found straw yield of BRRI dhan49 to be 4.3 to 5.8 t/ha, slightly lower than the range in our experiment (4.6 to 6.2 t/ha). The higher straw yields in the first year of our experiment were probably due to submergence leading to taller plant height and longer growth duration. Also at Mymensingh, Uddin (2013) reported straw yield of BRRI dhan52 of 5.2 t/ha, compared with values of 4.8 to 6.6 t/ha in 2012 and 4.3 to 5.1 t/ha in 2013 in our experiment. Straw yield of BRRI dhan33 in 2012 was 5.2 t/ha, and only 3.1 to 3.4 t/ha in 2013 due to brown spot disease. Reports of straw yield of BRRI dhan33 in the literature also range widely, from 3.4 to 5.9 t/ha in the favourable on-station environments at Madaripur and Mymensingh (Rahman et al. 2004; Quddus et al. 2012)

Table 5. Straw yield of component crops and the total system during 2012-13 and 2013-14, as affected by *aus* establishment method, *aman* variety and *boro* sowing date

Cropping System (CS)	Treatment combinations[1,2]	2012-13 Straw yield (t/ha)			1st year system straw yield (t/ha/yr)	2013-14 Straw yield (t/ha)			2nd year system straw yield (t/ha/yr)
		Aman	*Boro*	*Aus*		*Aman*	*Boro*	*Aus*	
CS1	E1V1D1	6.0	4.2	3.6	13.8	4.6	5.7	3.3	13.5
CS2	E1V1D2		4.5	3.3	13.7	4.9	4.6	3.0	12.5
CS3	E1V2D1	6.6	4.2	3.7	14.5	4.3	6.0	3.6	13.9
CS4	E1V2D2		3.7	3.3	13.6	5.0	4.3	3.1	12.4
CS5	E2V1D1	6.2	4.0	4.0	14.2	4.7	4.5	3.1	12.3
CS6	E2V1D2		4.5	3.3	14.1	5.0	4.3	3.1	12.4
CS7	E2V2D1	4.8	4.0	4.0	12.8	5.1	4.0	2.9	12.0
CS8	E2V2D2		4.5	3.5	12.8	4.3	4.7	3.1	12.1
CS9	E3V3D1	5.2	3.8	2.9	11.9	3.4	4.9	4.0	12.3
CS10	E3V3D2		3.9	3.5	12.6	3.1	4.1	3.6	10.7
CS11	E3V4D1	4.9	4.1	3.2	12.3	3.6	4.8	3.3	11.7
CS12	E3V4D2		4.3	3.5	12.7	3.5	3.6	3.4	10.4
LSD (p=0.05)		1.0	NS	NS	1.6	0.8	0.9	NS	1.5
C.V. (%)		12.1	15.1	15.5	8.3	12.3	13.1	20.0	8.4

[1] E = *aus* sowing date (E1: 10 April, E2: 25: April, E3 1 May); V = *aman* variety (V1: BRRI dhan49, V2: BRRI dhan52, V3: BRRI dhan33, V4: BRRI dhan53); D = *boro* sowing date (D1: 10 d after *aman* harvest, D2: 25 d after *aman* harvest)

[2] E1 and E2 transplanted, E3 wet seeded

3.3.2 Boro

There was a significant interaction between year and sowing date on straw yield of *boro* (Fig. 5). In 2012-13, straw yield of *boro* was similar for all sowing dates. However, in 2013-14, straw yield of early (15 November) sown BRRI dhan28 was significantly higher than that of all other *boro* sowing dates in that year, and of all sowing dates in the previous year.

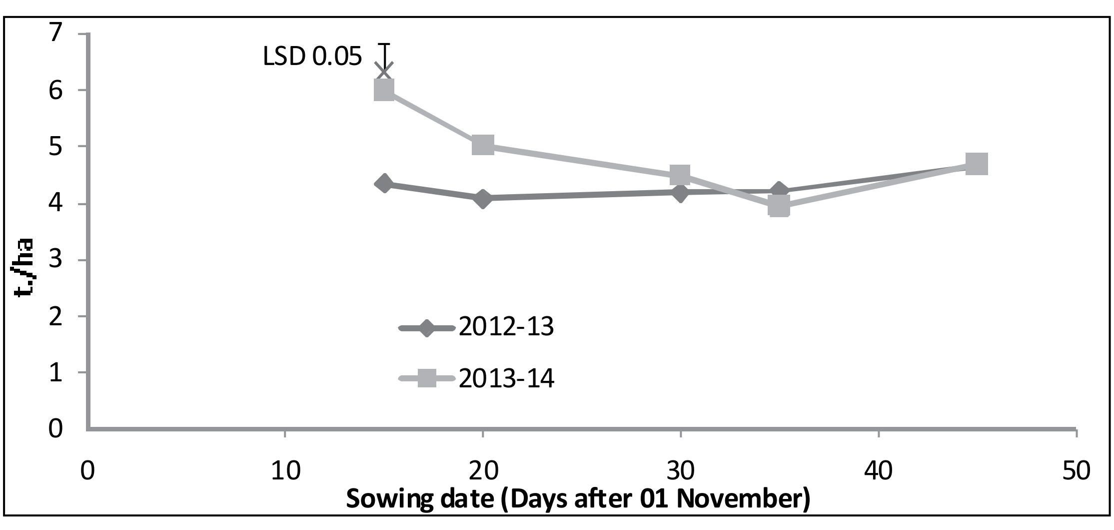


Fig. 5. Effect of sowing date on straw yield of *boro* (vertical bar is lsd (p=0.05) for the interactions between year and sowing date.

3.3.3 Aus

Straw yield of *aus* was not affected by sowing date or establishment method in either year, and was similar across years (Table 5).

3.3.4 Total system straw yield

Total system straw yield ranged from 11.9 to 14.5 t/ha in 2012-13, and from 10.4 to 13.9 t/ha in 2013-14 (Table 5). In both years, BRRI dhan49 (both sowing dates) tended to have the highest straw yield, followed by BRRI dhan52 for the first sowing.

In 2012-13, there were no interactions between *aus* establishment treatment (E1, E2), *aman* variety (BRRI dhan49, BRRI dhan52) and *boro* sowing date on system straw yield. In 2013-14, there was a significant interaction between *aus* establishment method and *boro* sowing date on straw yield (Table 4). Highest yield was obtained for early sown *aus* (10 April) combined with early sown *boro* than for all other combinations. With later *aus* sowing, system straw yield was not affected by *boro* sowing date.

4. Conclusions and recommendations

The results show that *aus-aman-boro* cropping systems using HYV are feasible in areas of the coastal zone where there is year-round availability of fresh water, provided that there is separation of lower and higher lands, and that drainage of the *aman* and *aus* crops can be implemented as needed. Total system yield ranged from 13.4 to 17. 2 t/ha in the 12 systems over two years, but most treatment combinations yielded in excess of 15 t/ha each year. Thus, there can be considerable flexibility in sowing date and *aman* variety in successfully implementing a triple rice system. However, successful implementation requires community coordination; both for water management and for cropping system synchronization, as isolated crops and small fields maturing earlier than other crops in the landscape are highly vulnerable to attack from pests such as rats and birds. Optimization of the systems for different regions requires further agronomic trials in a few strategic locations, combined with crop modeling and participatory farmer evaluation. This will need to include development of environmentally friendly and sustainable methods of disease and pest control.

Acknowledgements

The work presented in this paper was part of G2 'Productive, profitable and resilient agriculture and aquaculture systems', a project of the CGIAR Challenge Program on Water and Food (CPWF) and the CSISA Bangladesh project, funded by USAID. We are grateful to Akbar Ali, Jahid Hasan and Elias Hossain (BRAC staff) for their assistance in conducting the study in the field and laboratory, and the farm manager (Mr. Moniruzzaman) of PSTU for necessary help in field preparation.

References

Bangladesh Agricultural Research Council (BARC). 2008. Estimation of Fallow Land Area and Crop Production Plan for Barisal, Pirojpur, Jhalakati, Bhola, Patuakhali and Bagerhat Districts. A report submitted to the ministry of agriculture, govt. of Bangladesh. May 2008. (In Bangla).

Bangladesh Bureau of Statistics (BBS). 2008. Yearbook of Agricultural Statistics of Bangladesh. Ministry of Planning, Govt. of People's Republic of Bangladesh, Dhaka.

Bangladesh Bureau of Statistics (BBS). 2009. Yearbook of Agricultural Statistics of Bangladesh. Ministry of Planning, Govt. of People's Republic of Bangladesh, Dhaka.

BRRI (Bangladesh Rice Research Institute). 2011. *Adhunik Dhaner Chash*. Dhaka: MRI printing press.

Cereal Systems Initiative for South Asia (CSISA) in Bangladesh. 2011. Annual progress report. Submitted to United States Agency for International Development (USAID) Dhaka, Bangladesh. Submitted by International Rice Research Institute (IRRI), WorldFish Center (WF) and International Maize and Wheat Improvement Center (CIMMYT). November 2011.

Das, D. 2008. Yield performance of six Vietnam rice varieties in the coastal saline environments of Khulna district. MS diss., Khulna University, Bangladesh.

Hamid A. 2010. Rice production in tidal ecosystem: farmers fail to harness the benefits of green revoluation, pp 1-7. In Crop Production in the Coastal Ecosystem - Challenges and Opportunities. (ed. M. Jafar Ullah). Agrarian Research Foundation, Dhaka. November 2010.

Islam M.R. and G.B. Gregorio. 2013. Progress of salinity tolerant rice variety development in Bangladesh. *SABRAO J. Breed. Genet* 45 (1): 21-30.

Jasim uddin Md,. 2013. Fertilizer management in three modern T. Aman rice varieties. MS diss., Bangladesh Agricultural University, Mymensingh.

Lang N.T., B.C. Buu, N.V. Vite and A.M. Ismail. 2010. Strategies for improving and stabilizing rice productivity in the coastal zones of the Mekong Delta, Vietnam. *Tropical deltas and coastal zones: food production, communities and environment at the land-water interface*. ed. Hoanh C. T., Szuster B. W., Suan-Pheng K., Inmail A. M. and Noble A. D., 9:209-222. UK: CPI Antony Rowe Ltd.

Masum, S.M., M.H. Ali, M.S.H. Mandal, I.F. Chowdhury and K. Parveen. 2013. The effect of nitrogen and zinc application on yield and some agronomic characters of rice cv. BRRI dhan33. Intl. Res. J. Appl. Basic. Sci. 4 (8): 2256-2263

Mondal M.K., T.P. Tuong, A.K.M. Sharifullah and M.A. Sattar. 2010. Water supply and demand for dry-season rice in the coastal polders of Bangladesh. *Tropical deltas and coastal zones: food production, communities and environment at the land-water interface*. ed. Hoanh C.T., Szuster B.W., Suan-Pheng K., Inmail A.M. and Noble A.D., 9: 264-278. UK: CPI Antony Rowe Ltd.

Mondal, M.K., T.P. Tuong, A.K.M. Sharifullah and M.A. Sattar. 2010. Water Supply and Demand for Dry-season Rice in the Coastal Polders of Bangladesh. pp. 264-265.

Quddus M. A., M. H. Rashid, M. A. Hossain, H. M. Naser and J. Abedin Mian. 2012. Integrated nutrient management for sustaining soil fertility through chickpea-mungbean-t.aman cropping pattern at madaripur region. *Bangladesh J. Agr. Res.* 37(2): 251-262.

Rahman M. S., M. A. Haque and M. A. Salam. 2004. Effect of different tillage practices on growth and yield contributing characters of transplanted Aman Rice (BRRI dhan33). *J. Agron*. 3(2): 103-110.

Rahman Md. M. 2012. Enhancement of resilience of coastal community in Bangladesh through crop diversification in adaptation to climate change impacts. Masters diss. BRAC University.

Ritu, S.P., M.K. Mondal, T.P.Tuong, S.U. Talukdar, E. Humphreys. 2015. An aus-aman system for increasing productivity of a moderately saline region of the coastal zone of Bangladesh. In "Revitalizing the Ganges Coastal Zone". Eds E. Humphreys et al. CPWF Conference Proceedings, 21-23 October 2014, Dhaka (these proceedings).

Salam M.A., M.R. Islam, M. S. Rahman, M.A. Rahman, M.A.R. Bhuiyan, Z.I. Seraj, T.L. Aditya, M.K. Uddin, M.K. Mondal, A.M. Islam, D.L. Adoarda, R.D. Mendoza, E.B. Tumimbang-Raiz and G.B. Gregorio. 2010. Rice varieties and cultural management practices for high and sustained productivity in coastal wet lands of southern Bangladesh. *Tropical deltas and coastal zones: food production, communities and environment at the land-water interface*. ed. Hoanh C. T., Szuster B.W., Suan-Pheng K., Inmail A.M. and Noble A.D., 9: 183-198. UK: CPI Antony Rowe Ltd.

Sharifullah, A., Tuong, T.P., Mondal, M.K., and D.T. Franco. 2009. Assessing water supply and demand for dry season rice in coastal polders of Bangladesh. In: Humphreys, E. and R.S. Bayot (eds.). *Increasing the productivity and sustainability of rainfed cropping systems of poor smallholder farmers.* Proceedings of the CGIAR Challenge Program on Water and Food International Workshop on Rainfed Cropping Systems, Tamale, Ghana, 22-25 September 2008. The CGIAR Challenge Program on Water and Food, Colombo, Sri Lanka.

Sharma N., M.R.A. Sarkar, M.A. Rahman and M.R. Islam. 2013. Varietal evaluation of rice for improving productivity in southern Bangladesh. *International journal of Bioresearch* 15(4): 7-13.

Shormy, S.A.S .2012. Organic nutrient management on yield, nutrient content and their uptake by T. Aman rice. MS diss.,Bangladesh Agricultural University, Mymensingh.

SRDI (Soil Resources Development Institute). 2010. *Saline soils of Bangladesh*. SRMAF project, Ministry of Agriculture, Govt. of Bangladesh. Dhaka: SFSDP-SRDI Publication.

STAR. 2014. Biometrics and Breeding Informatics, PBGB Division, International Rice Research Institute, Los Baños, Laguna. Available at http://bbi.irri.org/.

Tuong T.P., E. Humphreys, Z.H. Khan, A. Nelson, M. Mondal. M. Buisson and P. George. 2014. Messages from the Ganges Basin Development Challenge: Unlocking the Production Potential of the Polders of the Coastal Zone of Bangladesh through Water Management Investment and Reform. The CGIAR program on Challenge Program for Water and Food.

Rice-rice-*rabi* cropping systems for increasing the productivity of low salinity regions of the coastal zone of Bangladesh

J. Bhattacharya[1,2], M. K. Mondal[2], E. Humphreys[2], N. K. Saha[1,2], M. H. Rashid[1], P. C. Paul[3] and S. P. Ritu[3,4]

[1]Patuakhali Science and Technology University, Bangladesh mhrashid_pstu@yahoo.com
[2]International Rice Research Institute, Bangladesh and Philippines j.bhattacharya@irri.org, m.mondal@irri.org, e.humphreys@irri.org, n.saha@irri.org
[3]Bangladesh Rice Research Institute, Bangladesh plcpauliwm@yahoo.com
[4]Current address: Sylhet Agricultural University, Bangladesh sanjidap05@gmail.com

Abstract

Cropping intensity in the coastal zone of Bangladesh (173%) is lower than the national average of 199%. In the coastal zone, farmers typically grow a single crop of rice (*aman*) during the rainy season using low yielding and late maturing local varieties, sometimes followed by a low input and low yielding pulse or sesame crop. The possibility of increasing productivity by a growing high yielding, short duration and salt tolerant *aus* variety prior to establishing high yielding *aman* varieties, without jeopardizing yield of the *aman* crop, has been previously shown. The work here sought to build on this by evaluating the feasibility of intensifying to an *aus-aman-rabi* cropping system using a short duration *aus* variety (BRRI dhan65), a medium duration, high yielding *aman* variety (BRRI dhan44), and high yielding or high value *rabi* crops (maize - Pacific984; sunflower - Hysun33). This involved conducting a replicated field experiment for two years at Patuakhali with the objectives of evaluating the effects of *aus* sowing date (20 March, 5 and 20 April, 5 May), *rabi* crop species (maize, sunflower) and mulch (0, 5 t/ha of rice straw during the *rabi* crops) on the feasibility and the productivity of the *aus-aman-rabi* system. The longest total system in-field crop duration was about 330 d. This allowed for an average turn-around time between crops of about 12 d, thus demonstrating the feasibility of intensification to an *aus-aman-rabi* system for a range of crop establishment dates. Total rice equivalent yield ranged from 13.9 to 19.3 t/ha/yr. *Rabi* crop yield was the main determinant of trends in total system rice equivalent yield, which declined as establishment date of the *rabi* crops was delayed beyond 15-30 December. The *rabi* crops required irrigation, with water pumped from a nearby tidal *khal* in which salinity of the water remained below 1 dS/m throughout the two years. The *aus* and *aman* crops were grown on rainfall throughout the year except for the 20 March sown *aus* crop, which required irrigation for puddling and transplanting. This work shows that it is possible to implement highly productive *aus-aman-rabi* cropping systems in areas of the coastal zone of Bangladesh protected from tidal flooding (as in the polders), where there is fresh water in the rivers year-round, and where the sluice gates are managed to drain excess water at low tide as needed during the rainy season to enable the production of an early maturity, high yielding *aman* variety.

Key message: It is possible to intensify to rice-rice-*rabi* systems producing around 18 t/ha/yr of rice equivalent yield in low salinity regions of the coastal zone of Bangladesh where drainage is possible during the rainy season.

Keywords: intensification, drainage, water management, maize, sunflower

1. Introduction

More than 30% of the cultivable land in Bangladesh is in the coastal zone (SRDI, 2010). However, cropping intensity, at 173%, is lower than the national average of 199% (BBS, 2011). In the coastal zone farmers typically grow a single crop of rice (*aman*) during the rainy season using tall, late planted and low yielding local varieties that are photoperiod sensitive and thus do not mature until December. Unlike the rest of

Bangladesh, farmers in the coastal zone have not widely adopted modern high yielding rice varieties (HYV) because their shorter stature makes them unsuitable for the high water depths that often prevail in the coastal zone. While about 1 Mha of the coastal zone is protected from diurnal tidal flooding by embankments, much of this land experiences water stagnation (prolonged periods of flooding at depths of 20 to 50 cm) during the rainy season as a result of heavy rainfall and/or mis-management of the sluice gates connecting the canals inside the polders to the tidal rivers surrounding them. Further, the lack of separation of higher and lower lands within the polders exacerbates the problem of water stagnation in the lowest lands.

In the coastal zone the local *aman* crop is sometimes followed by a low input, low yielding relay-sown legume (common in parts of Barisal Division) or a late-sown (mid-February to early March) sesame or mungbean crop (common in parts of Khulna Division). The late-sown sesame and mungbean crops are often damaged by the early *kharif* rains and cyclonic events that are common (every three to four years) in May. The late harvest of the local *aman* varieties also prevents the cultivation of high yielding *rabi* crops such as maize, sunflower and wheat. Thus large areas of land (approximately 810,000 ha) lie fallow during the dry season (Hasan et al. 2013) due to the late *aman* harvest, the lack of ready access to fresh water, and increasing soil salinity as the dry season progresses.

In reality, fresh water is abundant in much of the south-central coastal zone (Barisal Division) throughout the year (Khan et al., these proceedings). Here, the dominant cropping patterns are: pulse-fallow-*T.Aman* (55%), fallow-fallow-*T. Aman* (20%) and pulse-*T. Aus*-*T. Aman* (25%) (BRRI, 2012). Most farmers use local *aman* varieties yielding 2-3 t/ha of rice and those who grow *aus* harvest an additional 3-4 t/ha/yr.

The main hypothesis of the work presented in this paper is that with good water management (especially drainage, but also irrigation during the dry season) the use of modern HYVs with earlier maturity than local rice varieties, it is possible to greatly increase cropping system productivity in low salinity regions of the coastal zone. More specifically, we hypothesized that it is possible to implement highly productive *aus-aman-rabi* cropping systems using a short duration, salt tolerant high yielding *aus* variety, a medium duration, high yielding *aman* variety, and high yielding hybrid maize or sunflower crops. We also hypothesized that the productivity of an *aus-aman-rabi* system is likely to be affected by the establishment date of each crop, and in particular the establishment date of the *rabi* crops, as yield of some *rabi* crops declines with delay in sowing after mid-November/early December (Shahadat and Rahman 2012; Rashid et al. 2014). However, earlier sowing of *rabi* crops also means earlier sowing dates for all other crops in the system. Therefore, our third hypothesis was that high yield could be maintained with early establishment of *aus* and *aman* crops. Our fourth hypothesis was that the later the establishment of the *rabi* crop, the greater the requirement for irrigation during the dry season, and the greater the risk of damage from early *kharif* rains or cyclones. It is well established that mulching reduces soil evaporation and thus the rate of soil drying so we also hypothesized that this would reduce the irrigation requirement for the *rabi* crops. Therefore, we conducted a cropping system experiment with the objective of evaluating the effects of *aus* sowing date, *rabi* crop species and mulching on: (i) the feasibility (of successfully growing three crops in succession in a single year), and (ii) the productivity of an *aus-aman-rabi* system in the south-central coastal zone of Bangladesh.

2. Methodology

2.1. Experimental site

An *aus-aman-rabi* field experiment was conducted on the research farm of Patuakhali Science and Technology University, Bangladesh, starting with the *aman* 2012 crop and ending with the *aus* 2014 crop. The experimental field was located at 22° 46′38.02″ N latitude and 90° 38′74.5″ E longitude at an altitude of 3 m above sea level. The field was situated about 50 m from a canal connected to the river *Payra,* which enabled drainage of excess water at low tide and provided a source of irrigation water during the dry season. Salinity of the canal water was always <1 dS/m. The soil at the experimental site is a clay loam and the site had a cropping history of T.*aman*-fallow/*khesari*/mungbean-fallow.

2.2. Experimental design

The experiment compared *aus-aman-rabi* cropping system options. Four *aus* sowing dates (main plots), two *rabi* crops (sub-plots), and two *rabi* mulch treatments (sub-sub-plots) were evaluated in a split plot design with four replicates. Thus a total of 16 cropping system combinations were compared (Table 1, Fig. 1). Sub-sub-plot size was 6 m x 5 m. The treatments were:

Aus sowing date
A1 = 20 March
A2 = 05 April
A3 = 20 April
A4 = 05 May

Rabi crop species
C1 = maize
C2 = sunflower

Rabi mulch treatment
M1= rice straw mulch at 5 t/ha
M2 = no mulch

The *aus* variety was OM 1490, a short duration (~100 d) high yielding and salt tolerant Vietnamese rice variety that was recently (October 2014) released in Bangladesh as BRRI dhan65. The *aman* variety was BRRI dhan44, with a growth duration of ~145 d. The *aman* crops were planted not less than 10 d after harvest of each *aus* crop, as farmers are busy at the time of harvest and it takes time to prepare the land for establishment of the next crop. This resulted in *aman* sowing dates of 20 June, 05 and 20 July, and 05 August in A1-A4, respectively (Table 1).

Hybrid maize (Pacific-984, duration 120-130 d) and sunflower (Hysun33, duration 100-110 d) were grown in the *rabi* season. The maize and sunflower were established not less than 10 d after harvest of the *aman* crop, which resulted in target sowing dates of 30 November, 15 and 30 December and 15 January in A1-A4, respectively (Fig. 1). However, in the first year, the first and second *rabi* sowings were delayed to 15 and 20 December due to waterlogging at the desired time of sowing.

Table 1. The 16 *aus-aman-rabi* cropping system combinations

Cropping system (CS)	*Aus* sowing date (A)	*Aman*	*Rabi*			Treatment combinations[1]
			Sowing date	*Species (C)*	Mulch tmt (M)	
CS1	A1 20 March	>10 d after *aus* harvest	>10 d after *aman* harvest	C1 Maize	M1	A1C1M1
CS2					M2	A1C1M2
CS3				C2 Sunflower	M1	A1C2M1
CS4					M2	A1C2M2
CS5	A2 05 April	>10 d after *aus* harvest	>10 d after *aman* harvest	C1 Maize	M1	A2C1M1
CS6					M2	A2C1M2
CS7				C2 Sunflower	M1	A2C2M1
CS8					M2	A2C2M2
CS9	A3 20 April	>10 d after *aus* harvest	>10 d after *aman* harvest	C1 Maize	M1	A3C1M1
CS10					M2	A3C1M2
CS11				C2 Sunflower	M1	A3C2M1
CS12					M2	A3C2M2
CS13	A4 05 May	>10 d after *aus* harvest	>10 d after *aman* harvest	C1 Maize	M1	A4C1M1
CS14					M2	A4C1M2
CS15				C2 Sunflower	M1	A4C2M1
CS16					M2	A4C2M2

[1] A1, 2, 3, 4 = *aus* sown on 20 March, 05 April, 20 April and 05 May, respectively;
C1 = maize, C2 = sunflower; M1 = rice straw mulch (5 t/ha), M2 = no mulch

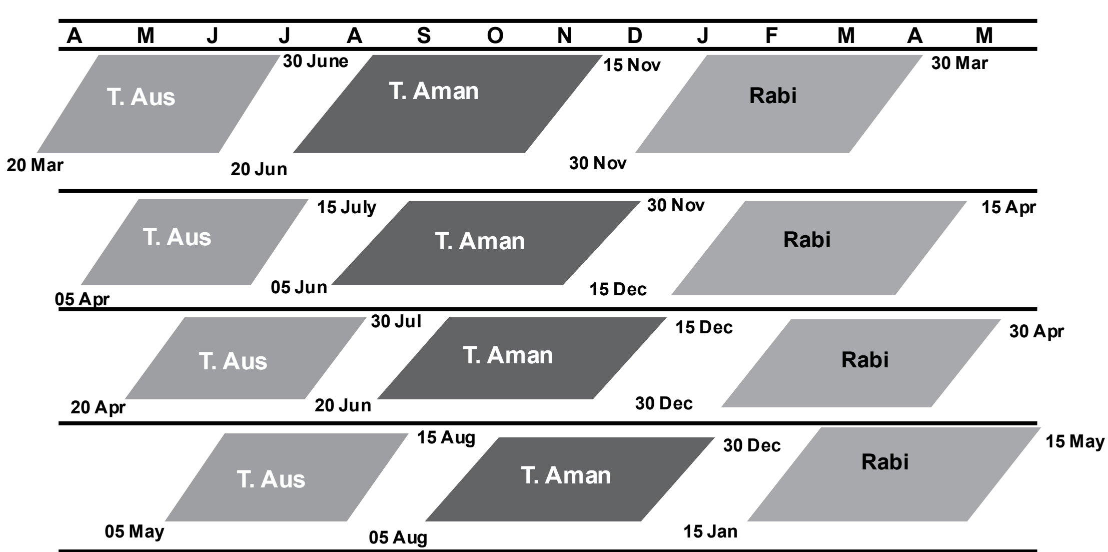


Fig. 1. Proposed crop calendar for the 16 *aus-aman-rabi* cropping system treatment combinations.

2.3 Experimental layout

The experimental area was surrounded by a large bund (50 cm high and 20 cm wide) to protect the site from flooding from adjacent lands. Each sub-sub-plot was surrounded by bunds 20 cm high and 20 cm wide to minimize water flows between adjacent plots.

2.4 Cultural Practices

2.4.1 Land preparation

For rice, the flooded soil was tilled three to four times using a two-wheel tractor with a power tiller, followed by one leveling ('laddering') using a wooden ladder that was manually pulled. Final land leveling with a hand pulled plank was done after basal application of fertilizer. For *rabi* crops, the land was prepared by a power tiller powered by a 2-wheel tractor once the soil moisture had declined to about field capacity, followed by one leveling using a wooden ladder pulled manually. Basal fertilizer was applied at the time of final land preparation.

2.4.2 Crop establishment

For rice, a seedbed was prepared in a separate place near the experimental field. The seed was soaked in water for 12 h and incubated for 48-72 h and then the germinated seeds were sown on the seedbed at a rate of 30 kg/ha. Urea (32 kg N/ha; BRRI, 2011) was applied 10 d after sowing. Twenty-one day-old seedlings were transplanted with two to three seedlings per hill and a hill spacing 20 cm x 20 cm for both the *aus* and *aman* crops. Seeds of maize (15 kg/ha) and sunflower (5 kg/ha) were sown in 2-4 cm deep furrows made using a hand furrower. Planting geometry for maize was 75 cm x 25 cm and geometry for sunflower was 60 cm x 45 cm.

2.4.3 Fertilizer application

Urea, triple superphosphate, muriate of potash, gypsum and zinc sulphate were applied to the *aus* and *aman* crops as per BRRI recommendations (BRRI, 2011) at 100 kg N, 60 kg P_2O_5, 40 kg K_2O, 60 kg $CaSO_4$ and 10 kg $ZnSO_4$ per hectare to each crop. All the fertilizer and one-fourth of the N were applied prior to the final land leveling. The remaining N was top-dressed in three equal splits at 25 d after transplanting (DAT), 5-7 d before PI and at heading in the *aman* crops. For the *aus* crops, all fertilizer and one-third of the N were applied prior to leveling, and the remaining N was applied 5-7 d before PI and at heading.

Fertilizer application to maize and sunflower was as per BARI recommendations (BARI, 2011). For maize, N, P_2O_5, K_2O, $CaSO_4$, $ZnSO_4$ and B were applied at 253-144-168-33-4-2 kg/ha, respectively. These nutrients were supplied as urea, triple superphosphate, muriate of potash, gypsum and zinc sulphate. One-third of the N and all the other fertilizers were broadcast prior to the final leveling, and the remaining N was applied in two equal splits just prior to the first (about 25 DAS) and second (about 50 DAS) irrigations. For sunflower N, P_2O_5, K_2O, $CaSO_4$, $ZnSO_4$ and B were applied at 92-84-90-27-2-2 kg/ha, respectively. Half of the N and all of the other fertilizers were broadcast prior to the final land preparation. The remaining N was top dressed at the flower primordial stage (45 DAS). Fertilizer (basal and top dress) was broadcast in the first year and in bands 15 cm from the seed row in the second year.

2.4.4 Water management

The *aus* and *aman* crops were established and grown on rainfall, with the exception of the 20 March sown *aus* crops for which irrigation from the *khal* was required for puddling and transplanting. Water was drained from the experiment field when rainfall raised the water depth beyond about 30 cm, by gravity and/or by pumping.

The *rabi* crops were grown using residual soil moisture and irrigation water pumped from the nearby canal as needed. The water was sprayed across the soil surface using a handheld hose. Pre-sowing irrigation was provided for later sowings when the soil was too dry for good germination and crop establishment. Vacuum gauge tensiometers were installed to guide irrigation scheduling. The tensiometers were installed in tight fitting holes that were sealed at the top, with the ceramic cups at 37.5 cm. The tensiometers were located mid-way between four plants. For maize and sunflower, irrigation was applied when soil tension had increased to 50 kPa and 70 kPa, respectively.

2.4.5 Weeding

Weed control was excellent in all crops. The *aman* and *aus* crops were weeded manually as needed prior to urea topdressings. For maize and sunflower, hand weeding was done at 20 to 25 days after emergence (DAE) and 40 to 50 DAE (prior to urea topdressing and earthing up).

2.4.6 Insect pest and disease control

Disease and insect pests in the rice and *rabi* crops were controlled by following BRRI and BARI recommendations (BRRI, 2011; BARI, 2011) when necessary. In general pests and diseases were well-controlled, apart from an outbreak of blast disease during the first *aman* crop that led to some yield loss from the first and second sowings. The field was surrounded by a plastic barrier with rat traps to prevent rat damage, and was covered at susceptible stages with a net to prevent bird damage.

2.5 Data collection

2.5.1 Yield

For rice, grain yield was determined in a 3 m x 2 m area in the middle of each sub-sub-plot. The samples were threshed and cleaned, and sub-samples of the grain and straw were oven dried at 70° C to calculate moisture content. Dry grain yield was converted to 14% moisture content, while straw yield was reported dry. Seed yield of maize and sunflower were determined in 3 m x 2 m and 2.25 m x 1.75 m areas, respectively, in middle of each plot. Grain moisture content was determined, and yield was reported at 12% moisture content for both crops. Rice equivalent yield (REY, t/ha) of *rabi* crops was calculated as: REY = yield of *rabi* crop (t/ha) x price of *rabi* crop (Tk/kg) / price of rice (Tk/kg).

2.5.2 Water

Irrigation water. The discharge rate of the pump was calculated from the time taken to fill a 180 L drum. The depth (mm) of irrigation provided to the *rabi* crops was determined from the duration of irrigation of each plot, the discharge rate, and plot area. Total irrigation during the *rabi* crops was determined.

Field water depth. The depth of standing water in the rice plots was monitored using seepage scales (measuring tapes) that were installed in each plot.

2.6 Analysis of data

The data were analyzed using ANOVA with a 3-factor split plot design for all but the first *aman* crop, for which a single factor ANOVA was used as at this stage the only treatment was sowing date. Comparison of means was done using the least significance difference (LSD) at 5% probability. The analyses were done using CropStat version 7.2 (IRRI, 2007).

3. Results and discussion

3.1 Crop duration

3.1.1 Aman

Each year, the duration of the *aman* crop from transplanting to PM decreased with delay in sowing, slightly in 2012 (from 113 to 109 d) and considerably in 2013 (from 112 to 96 d) (Table 1). Duration of the first sowing was similar each year, but shorter for later sowings in 2013, the difference increasing up to 13 d with delay in sowing. The results for 2013 are consistent with the fact that BRRI dhan44 is a photoperiod sensitive variety.

The apparent absence of photoperiod sensitivity in 2012 may be due to the fact that the third and fourth sowings were inundated for 7 and 5 d, respectively, two to four weeks after transplanting, but there was no prolonged inundation in 2013.

3.1.2 Rabi crops

The duration of maize from sowing to harvest ranged from 124 to 132 d, and of sunflower from 107 to 116 d (Table 1). There was a slight decline in duration with delay in sowing, which was more evident in the second year when there was a greater range of sowing dates. In that year duration of maize declined by 6 d between sowing on 30 November and 15 January, while duration of sunflower declined by 8 d over the same period. The decline in duration with delay in sowing is consistent with the warmer weather experienced by the later sown crops. The use of straw mulch consistently delayed maturity, but only by a couple of days.

Table 2. Field duration of each crop and the total cropping system

Cropping System (CS)	Treatment[1]	2012-13				2013-14			
		Aman	*Boro*	*Aus*	Total	*Aman*	*Boro*	*Aus*	Total
CS 1	A1C1M1	113	129	77	319	112	132	77	321
CS 2	A1C1M2		126		316		130		319
CS 3	A1C2M1		115		305		116		305
CS 4	A1C2M2		111		301		115		304
CS 5	A2C1M1	113	129	79	321	108	129	77	314
CS 6	A2C1M2		128		320		128		313
CS 7	A2C2M1		114		306		115		300
CS 8	A2C2M2		110		302		113		298
CS 9	A3C1M1	111	128	78	317	102	128	76	306
CS 10	A3C1M2		126		315		126		304
CS 11	A3C2M1		112		301		112		290
CS 12	A3C2M2		109		298		111		289
CS 13	A4C1M1	109	127	76	312	96	126	73	295
CS 14	A4C1M2		125		310		124		293
CS 15	A4C2M1		110		295		108		277
CS 16	A4C2M2		108		293		107		276

[1] A1, 2, 3, 4 = *aus* sown on 20 March, 05 April, 20 April and 05 May respectively; C1 = maize, C2 = sunflower; M1 = rice straw mulch (5 t/ha), M2 = no mulch

3.1.3 Aus

The duration of *aus* from transplanting to PM ranged from 73 to 79 d over the four sowing dates (from 20 March to 5 May) and two years (Table 2). There was little effect of time of sowing on duration of *aus*, except for slightly reduced duration (by 3 to 4 d) with the last sowing date.

3.1.4 Total system in-field duration

Total in-field duration of the three crops ranged from 293 to 321 d with maize in the system, and from 276 to 305 d with sunflower in the system. The longest duration systems allowed an average of 15 d between each crop. Given that the aus and aman crops were harvested at PM, and that there will be a delay of a few days between PM and harvest of *aus* and *aman*, this means an in-field duration of about 330 d for the longest duration systems, and an average of about 12 d between harvest of one crop and transplanting of the next if all crops are harvested on time.

3.2 Grain yield

3.2.1 Aman

Grain yield of *aman* ranged from 3.2 to 5.4 t/ha over the two years, similar to the observations of others (Rashid and Khan, 2006; Masum et al. 2008; CCC, 2009; Biswas et al., 2011). Sattar and Abedin (2012) and Sharma et al. (2013) suggested that BRRI dhan 44 was a suitable variety for increasing productivity in tidal southern Bangladesh.

There were no significant interactions between sowing date, *rabi* crop and mulch treatment on the yield of *aman*. However, in both years there was a significant effect of sowing date on yield. In 2012, yield of aman was least for earlier sowings (Fig. 2). In contrast, in the second year, yield of the first three sowings was similar and yield of the last sowing was significantly lower than yield of the first sowing. The much lower yields of the first two sowings in 2012 were probably due to inundation for several days (twice) within the first four weeks after transplanting and to heavy infestation of brown spot and blast diseases which started during panicle initiation to flowering. Infestation of the later crops was well-controlled by spraying. Raising of the bund around the experimental site and drainage at low tide prevented prolonged inundation and saved the earlier crops in 2012, demonstrating the feasibility of growing high yielding *aman* varieties in this region provided there is separation of lower and higher lands by small levees and removal of excess water as a result of heavy rainfall by systematically draining at low tide.

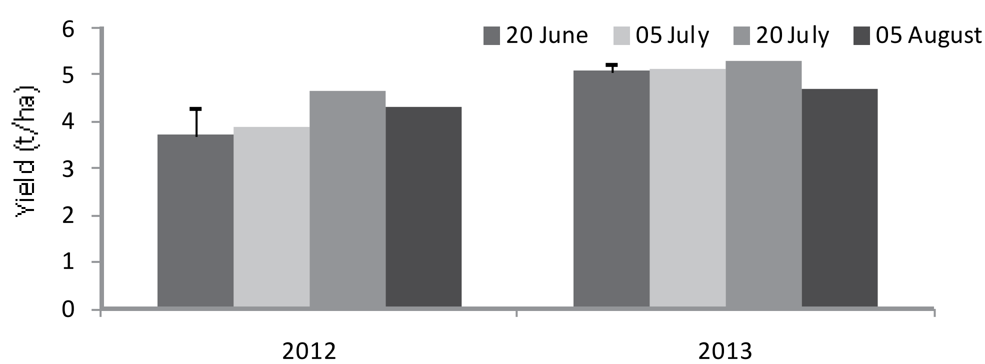


Fig. 2. Grain yield of aman as affected by sowing date (vertical bars are $lsd_{0.05}$ for comparing means within year).

3.2.3 *Rabi crops*

Yield of maize and sunflower ranged from 6.9 to 8.8 and 2.3 to 3.7 t/ha, respectively, over the two years. These results are similar to the findings of others in the coastal zone (Rahman, 2012) and in other parts of Bangladesh (Ali et al., 2008; Alom et al., 2009; Sarker et al., 2014).

There were no significant interactions between sowing date and mulch treatment on yield of maize or sunflower. Each year, yield of maize was slightly but significantly decreased with mulch, whereas yield of sunflower was significantly increased with mulch (Figs 3a,b). The reasons for this are not known, but one possibility is the reduced rate of drying of the soil under mulch, and thus the tendency for greater waterlogging, together with the fact that sunflower is more tolerant to waterlogging and extracts more soil moisture than maize (Schmidt, 1995).

Sowing date also significantly affected the yield of maize and sunflower each year, with similar trends for both crops but the trends were slightly different across years (Figs 5a,b). In 2012-13, maximum yield of maize and sunflower occurred with 20 and 30 December sowings, while 15 December and 15 January sowings had significantly lower yield. In contrast, in 2013-14, yields were largest with 15 December sowing and declined significantly with later sowings. In the second year, the decline in yield of sunflower with the last sowing was much greater than in the first year or for maize in both years. CIMMYT (2005) also reported that yield of hybrid maize decreased with delay in sowing after 20 December, while Rashid et al. (2014) also found that yield of Hysun33 decreased with late *rabi* sowing in a coastal saline area of Bangladesh. The lower yield of the first sowing date in our experiment was probably due to waterlogging due to over-irrigation after sowing in an attempt to restrict soil cracking.

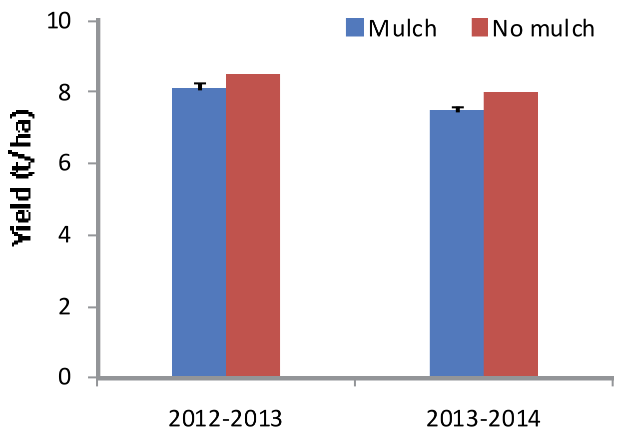


Fig. 3a. Effect of mulch treatment on yield of maize (vertical bars are $lsd_{0.05}$ for comparing means within year).

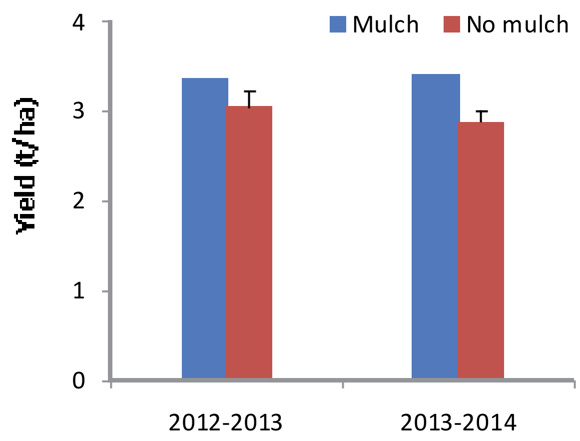


Fig. 3b. Effect of mulch treatment on yield of sunflower (vertical bars are $lsd_{0.05}$ for comparing means within year).

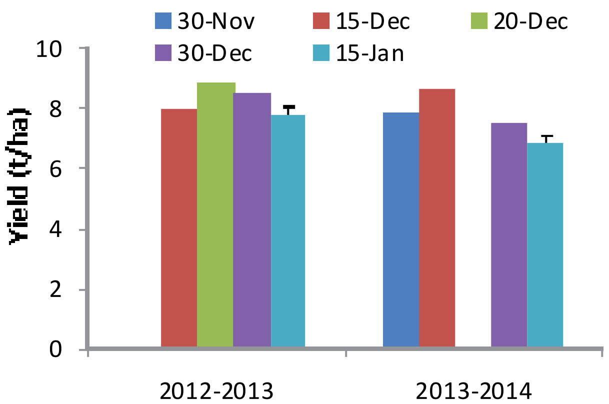


Fig. 4a. Effect of *aus* sowing date on yield of maize (vertical bars are $lsd_{0.05}$ for comparing means within year). (*Aus* sowing date treatments resulted in the range of *rabi* sowing dates indicated in the legend.)

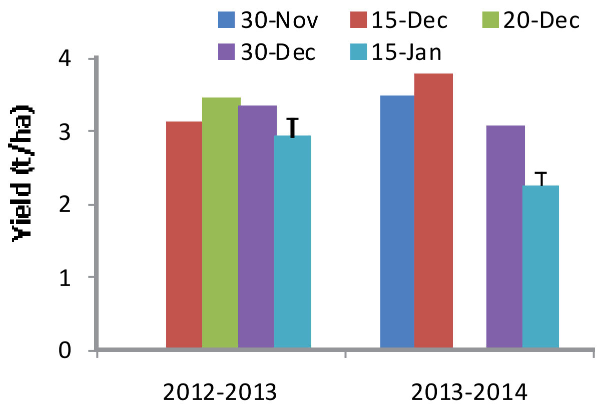


Fig. 4b. Effect of *aus* sowing date on yield of sunflower (vertical bars are $lsd_{0.05}$ for comparing means within year). (*Aus* sowing date treatments resulted in the range of *rabi* sowing dates indicated in the legend.)

3.2.3 Aus

Grain yield of *aus* treatments ranged from 3.8 to 4.6 t/ha over the two years, similar to the yields observed by Ritu (2011) in a medium salinity area of the coastal zone.

There were no significant interactions between sowing date, *rabi* crop and mulch treatment on yield of *aus* each year. There was a consistent trend for highest *aus* yield with the first sowing (20 March), with significantly higher yield than most or all other sowing dates (Fig. 5).

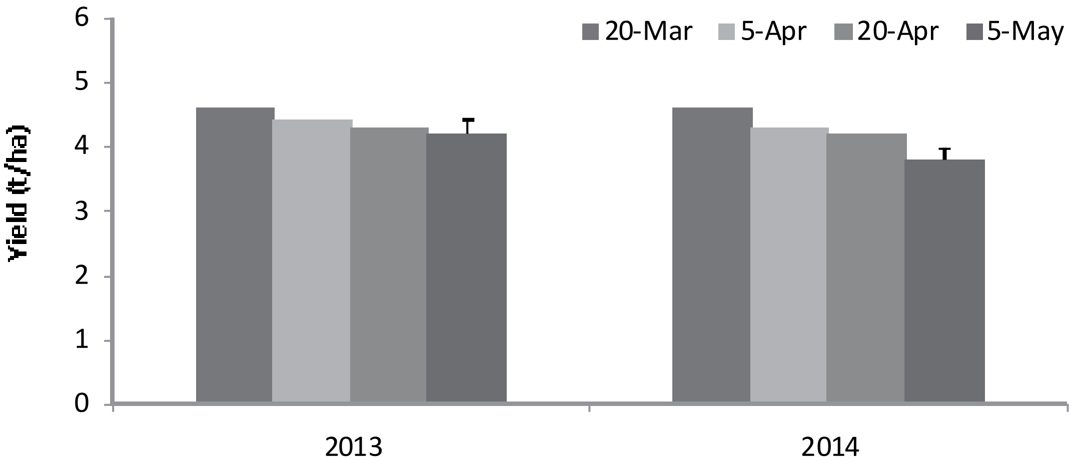


Fig. 5. Effect of sowing date on grain yield of *aus* (vertical bars are $lsd_{0.05}$ for comparing means within year).

3.2.4 System yield

Total system rice equivalent yield (REY) ranged from 13.9 to 19.3 t/ha/yr over the two years. Each year, there was a significant interaction between *rabi* crop and mulch treatment. Mulch increased the yield of the sunflower systems by 0.8 to 1 t/ha each year, whereas there was a small but significant decline in yield of the maize systems (Figs 6a,b).

In the first year, REY increased with delay in sowing date to 30 December (Fig. 7a). In the second year there was also significant interaction between *rabi* crop and sowing date on system yield. Yield was highest for systems in which *rabi* crops were sown on the first two dates, and declined significantly as sowing was delayed to the third and fourth dates (Fig. 7b). However, the decline was greater with the last sowing date of sunflower. The trends in *rabi* yield had a strong influence on system yield because REY of the *rabi* crops was more than 50% of total system yield.

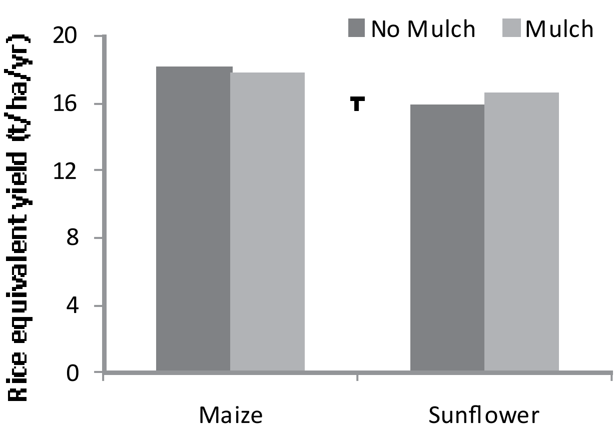


Fig. 6a. Interaction of *rabi* species and mulch treatment on system yield in 2012-2013 (vertical bar is $lsd_{0.05}$ for comparing all treatment combinations).

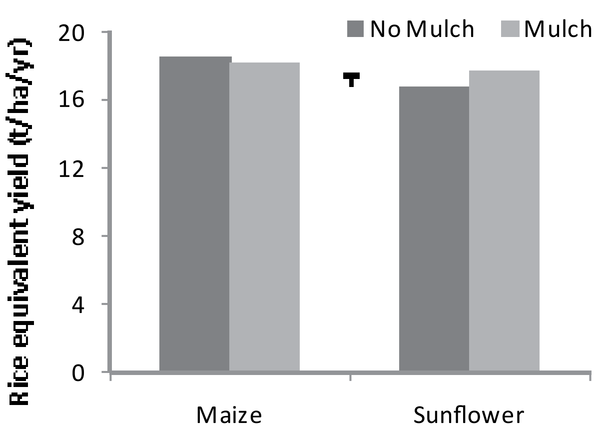


Fig. 6b. Interaction of *rabi* species and mulch treatment on system yield in 2013-2014 (vertical bar is $lsd_{0.05}$ for comparing all treatment combinations)

.

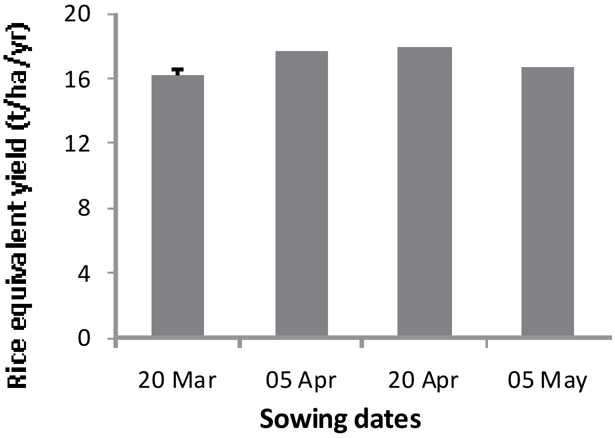


Fig. 7a. Effect of *aus* sowing date on system yield in 2012-2013 (vertical bars are $lsd_{0.05}$ for comparing means within year).

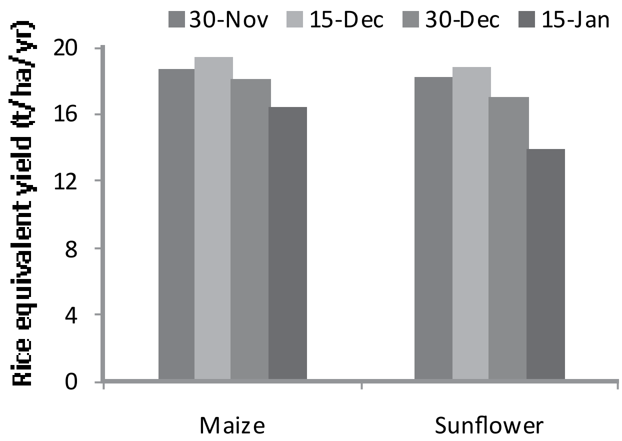


Fig. 7b. Interaction between *aus* sowing date and *rabi* species on system yield in 2013 (vertical bars are $lsd_{0.05}$ for comparing means within year). (*Aus* sowing date treatments resulted in the range of *rabi* sowing dates indicated in the legend.)

4. Discussion

The results clearly demonstrate the biological feasibility of intensifying to high yielding *aus-aman-rabi* cropping systems in the coastal zone of Bangladesh in regions where fresh water is available year-round to enable irrigation of *rabi* crops, and for establishment and early growth of the *aus* crop in years when the early *kharif* rains are inadequate. The other key requisite is the ability to drain excess water in order to enable the cultivation of modern non-photoperiod sensitive short to medium duration *aman* varieties and to enable drainage of water a couple of weeks prior to *aman* harvest. This is essential to allow the soil to dry sufficiently for timely establishment of the *rabi* crops, the yield of which declines as sowing is delayed beyond mid November/early December (Shahadat and Rahman 2012; Rashid et al. 2014).

5. Conclusion and recommendations

This work shows that it is possible to implement highly productive *aus-aman-rabi* cropping systems in areas of the coastal zone of Bangladesh protected from tidal flooding (as in the polders) and where there is fresh water in the rivers year-round. We successfully implanted highly productive *aus-aman-rabi* cropping systems by using modern, high yielding rice and *rabi* varieties and draining excess water at low tide when needed during the rainy season. Total rice equivalent yield of the systems tested ranged from 13.9 to 19.3 t/ha/yr. This was achieved using a short duration, high yielding *aus* variety (BRRI dhan65), a medium duration, high yielding *aman* variety (BRRI dhan44), and hybrid varieties of maize (Pacific 984) and sunflower (HySun33). *Rabi* crop yield was the main determinant of trends in total system rice equivalent yield, which declined as establishment date of the *rabi* crops was delayed beyond 15-30 December.

Acknowledgements

This paper presents findings from G2 ‘Productive, profitable and resilient agriculture and aquaculture systems’, a project of the CGIAR Challenge Program on Water and Food (CPWF). We extend our appreciation to Akbar Ali, Jahid Hasan and Elias Hossain (BRAC staff) for their contributions to this study.

References

Ali, M.Y., S.R. Waddington, D. Hodson, J. Timsina, and J. Dixon. 2008. Maize-rice cropping systems in Bangladesh: Status and research opportunities. Mexico, D.F.: CIMMYT.

Alom M. S., N. K. Paul and M. A. Quayyum. 2009. Performances of different hybrid maize (*Zea mays* l.) varieties under intercropping systems with groundnut (*Arachis hypogaea* l.). *Bangladesh journal of agriculture research* 34(4): 585-95.

BARI (Bangladesh Agricultural Research Institute). 2011. *Krishi Projukti Hatboi*. Dhaka: Bengal Com printing press.

Biswas, K. K., S. Ahmed and M. R. Karim. 2011. Effect of nitrogen levels and spacing on the performance of BRRI dhan44. *Eco-friendly agriculture journal* 4(11): 726-29.

BRRI (Bangladesh Rice Research Institute). 2011. *Adhunik Dhaner Chash*. Dhaka: MRI printing press.

BRRI (Bangladesh Rice Research Institute). 2012. *Climate Change Impacts, Vulnerability and Adaptation: Sustaining Rice Production in Bangladesh* (Bioforsk-BRRI-CEGIS Collaborative Project) Report on Farmers Group Discussion (FGD) in Salinity Study Area of Patuakhali and Barguna District.

CCC (Climate Change Cell). 2009. Impact Assessment of Climate Change and Sea Level Rise on Monsoon. Climate Change Cell, Department of Environment, Ministry of Environment and Forest, Dhaka, Bangladesh.

CIMMYT (International Maize and Wheat Improvement Center). 2005. Food security in Bangladesh: Improving wheat, maize and papaya production and impacts of arsenic contamination. Annual report (July 2004-June 2005).

CPWF (Challenge Program for Water and Food). 2011. *The Ganges Basin Development Challenges:*

Increasing the Resilience of Agriculture and Aquaculture Systems in the Coastal Zone of the Ganges Delta. http://sites.google.com/site/cpwfbdceoi/ganges-bdc-research.

Hasan Md. N., M. S. Hossain, Md. R. Islam, and Md. A. Bari. 2013. *Trend in the availability of agricultural land in Bangladesh*. National food policy capacity strengthening programme. Soil resources development institute, Dhaka.

IRRI, 2007. CropStat for Windows, Version 7.2 Metro Manila, Philippines.

Masum, S. M., M. H. Ali and M. J. Ullah. 2008. Growth and yield of two *T. aman* rice varieties as affected by seedling number hill^{-1} and urea super granules. *Journal of agriculture education technology* 11(1&2): 51-58.

Rahman Md. M. 2012. Enhancement of resilience of coastal community in Bangladesh through crop diversification in adaptation to climate change impacts. Masters diss. BRAC University.

Rashid M. H. and M. A. H. Khan. 2006. Tillering Dynamics and Productivity of BRRI dhan44 as Influenced by Spacing and Nitrogen Management Technique. *Journal of Agriculture and Rural Development* 4(1&2): 47-52.

Rashid M. H., S. Nasrin, and D. Mahalder. 2014. Zero tilled dibbled sunflower enables planting earlier and harvests more in the coastal saline area of Bangladesh. *International journal of environmental science and development* 5(3): 260-64.

Ritu S. P. 2011. Crop and water management for increasing rice cropping intensity and productivity of the coastal region of Bangladesh. PhD diss. Bangladesh Agriculture University.

Sarker Md. A. Z., Md. A. Alam, A. Hossain, Md. and A. Mannaf. 2014. Agro-economic performance of crop diversification in rice based cropping systems of northwest Bangladesh. *Agriculture, forestry and fisheries* 3(4): 264-70.

Sattar S. A. and M. Z. Abedin. 2012. Options for coastal farmers of Bangladesh adapting to impacts of climate change. Paper presented at the international conference on environment, agriculture and food sciences, August 11-12, in Phuket, Thailand.

Schmidt H. Walter. 1995. *Single crop sunflower production*. Agronomy facts index (AGF-107-95). Ohio State University Extension. Available at http://ohioline.osu.edu/agf-fact/0107.html.

Shahdat M. K., and M. A. Rahman. 2012. *Effect of sowing time on yield of hybrid maize in Barisal region*. Bangladesh agricultural research institute, agronomy division, RARS, Barisal, Bangladesh.

Sharma N., M. R. A. Sarkar, M. A. Rahman and M. R. Islam. 2013. Varietal evaluation of rice for improving productivity in southern Bangladesh. *International journal of Bioresearch* 15(4): 7-13.

SRDI (Soil Resources Development Institute). 2010. *Saline soils of Bangladesh*. SRMAF project, Ministry of Agriculture, Govt. of Bangladesh. Dhaka: SFSDP-SRDI Publication.

Opportunities for cropping system intensification in the coastal zone of Bangladesh

M.K. Mondal[1], P.L.C. Paul[2], E. Humphreys[1], T.P. Tuong[1], S.P. Ritu[2,3] and M.A. Rashid[2]

[1]International Rice Research Institute, Bangladesh and Philippines m.mondal@irri.org, e.humphreys@irri.org, t.tuong@irri.org
[2]Bangladesh Rice Research Institute, Bangladesh plcpauliwm@yahoo.com, arashidiwm@yahoo.com
[3] Current address: Sylhet Agricultural University, Bangladesh sanjidap05@gmail.com

Abstract

Despite huge investment to protect the land of coastal Bangladesh by constructing polders and continuous implementation of development projects, agricultural productivity of the region remains very low. Most farmers grow a single, low yielding (2-3.5 t/ha) *aman* crop using traditional, late maturing varieties and much of the land lies fallow for several months each year. There has been little adoption of modern, high yielding *aman* varieties (HYV) and where *rabi* crops are grown after *aman* harvest yields are less than 1 t/ha. The present study was conducted to demonstrate the potential for raising productivity through cropping system intensification and diversification in low and medium salinity regions of the coastal zone. The study selected Polder 43/2F in Amtali *Upazila*, Barguna District as its low salinity site and Polder 30 in Batiaghata *Upazila*, Khulna District as its medium salinity site. At Amtali, HYV *aus-aman-boro* and *aus-aman-rabi* cropping systems with total system rice equivalent yield of 14 to 20 t/ha/yr were successfully implemented over three years from July 2011 to June 2014. At Batiaghata, where fresh water scarcity is a major limitation during the dry season, HYV *aman-rabi* and *aman-boro* systems were implemented over the same period. The *aman-boro* systems consistently yielded 9 to 10 t/ha/yr provided that the *boro* crops were sown in early November. Here, traditional crops (sesame, mungbean) were grown after *aman* harvest. While improved management (line sowing, use of fertilizer, irrigation and improved varieties) improved *rabi* yield, yields never exceeded 1 t/ha. For stability of *rabi* yield, 'early' (timely) establishment is needed to avoid crop damage or destruction as a result of early *kharif* rains and cyclones in May, as happened in 2013. Results show that key ingredients for cropping system intensification and increasing crop productivity in the coastal zone include the use of early maturity (non-photoperiod sensitive) HYV *aman*, drainage during the *aman* crop following excessive rainfall, drainage in early November (if water is present) to allow timely *aman* harvest and thus timely establishment of the *rabi* and *boro* crops, and use of available freshwater for irrigation of the dry season crops.

Key message: Agricultural cropping system productivity can be more than doubled in the coastal zone of Bangladesh by using improved varieties and management practices, cropping system intensification and diversification, available water resources and good water management (especially drainage).

Keywords: rice, *rabi,* yield, Khulna, Barisal, Patuakhali

1. Introduction

The coastal zone of Bangladesh comprises low-lying lands within a dense network of rivers and canals. The rivers are tidal with diurnal fluctuations of 2 to 3 m and salinity of the rivers increases during the dry season, more so closer to the coastline and in the southwest (Khan and Kamal 2015). More than 30% of the cultivable land of the country is in the coastal zone (SRDI 2010). Of the 2.85 Mha of coastal and offshore lands, about 1.2 Mha are protected from flooding and saline water intrusion as a result of the construction of polders. Despite this, cropping intensity and productivity in this region is much lower than in other parts of the country (BBS 2011), with over 50% of the land remaining fallow during the dry season due to the lack of freshwater for irrigation, and soil salinity, which increases as the dry season progresses (BARC 2008).

There is a general perception that during the dry season the river water is saline throughout the coastal zone. In reality, most of the rivers in the south-central coastal zone (Barisal Division) remain non-saline throughout the year (Khan and Kamal 2015). It is predicted that this will continue to be the case, even in the climate change scenario with a 22 cm mean sea level rise and a moderate precipitation change (Khan et al. 2015). On the other hand, the river water in medium salinity areas such as Khulna District only remains suitable for irrigation from July to until early to mid-February, i.e., for the first couple of months of the *rabi* season (Mondal et al. 2006).

Although Bangladesh as a whole is currently self-sufficient in rice production, this is not the case for the coastal zone (MoA-FAO 2013; Tuong et al. 2014). The country faces enormous challenges to maintaining food self-sufficiency for its growing population, as there is little scope to further increase cropping system intensity, except in the underutilized coastal zone lands. Despite huge investment in water resources development and the availability of improved varieties of rice and *rabi* crops and inputs, which have greatly benefited other parts of Bangladesh, productivity in the coastal zone remains low. Thus, the polders are home to millions of very poor and vulnerable people whose livelihoods and food security depend on agriculture (BBS 2010; Kabir et al. 2014). Most farmers in this region grow a single *aman* crop using tall, late planted and low yielding local varieties that are photoperiod sensitive and thus do not mature until December. Tall seedlings are required in the rainy season to survive the stagnant flooding that occurs in the polders as a result of both high rainfall and poor management of the sluice gates connecting the canals inside the polders to the tidal rivers surrounding them. Further, the lack of separation of higher and lower lands within the polders exacerbates the problem of water stagnation in the lower lands. Unlike the rest of Bangladesh, farmers in the coastal zone have not widely adopted modern high yielding rice varieties (HYV) because their shorter stature makes them unsuitable for the high water depths that often prevail during the rainy season. In Barisal Division, the *aman* crop is sometimes followed by a low input, low yielding relay-sown grasspea crop and/or preceded by a nearly rainy season *aus* rice crop. In Khulna District the *aman* crop is sometimes followed by a late-sown (mid-February to early March) sesame or mungbean crop. The sesame and mungbean crops are often damaged by the early *kharif* rains and by cyclones that tend to occur in May every three to four years. Moreover, many fields (in the low lands) remain flooded until December, delaying harvest of *aman* and establishment of *rabi* crops. The late harvest of the local *aman* varieties and water logged soil prevent the cultivation of high yielding *rabi* crops such as maize, sunflower and wheat which need to be established in early December for maximum yield.

Mondal (1997) showed the feasibility of increasing productivity in the coastal zone by intensifying to an HYV *aman-rabi* system. The feasibility of a high yielding *aus-aman* system using a short duration high yielding *aus* variety and a non-photoperiod sensitive HYV *aman* variety has also been shown in medium salinity areas of the coastal zone (Ritu et al. 2015). Furthermore, Mondal et al. (2006) and Sharifullah et al. (2009) showed the feasibility of an HYV *aman-boro* system in the moderately saline coastal zone. This involved 'early' (timely) sowing of the *boro* crop (mid-November), irrigation directly from the river until salinity increased to about 4 dS/m, and finishing the crop on river water stored in the polder canal system prior to the river becoming too saline.

The present study was designed to take the next step in cropping system intensification - to demonstrate the potential in medium and low salinity areas of the coastal zone of Bangladesh for more productive double (*aman-boro/rabi*) and triple (*aus-aman-boro/rabi*) cropping systems, respectively.

2. Methodology

Cropping system intensification strategies were evaluated in non-replicated demonstrations in farmers' fields. The demonstrations were implemented at two locations: (i) a medium salinity location in Khulna Division (Hatbati village in 2011-12 and Kismat Fultola village in 2012-14, at nearby locations in polder 30), and; (ii) a low salinity site in Barisal Division (Bazarkhali village in polder 43/2/F) (Table 1). At Bazarkhali, fresh water is available year round. Here, triple cropping systems (*aus-aman-boro* and *aus-aman-rabi*) were tested. At Hatbati and Kismat Fultola fresh water becomes very scarce in the second half of the dry season and double systems of *aman-boro* and *aman-rabi* were evaluated. Field size at Bazarkhali was 20 m x 120 m for the *aus-aman-rabi* demonstrations, and 60 m x 30m for the *aus-aman-boro*. At Hatbati/Kismat Fultola, field size for the *aman-rabi* was 20 m x 80 m and 60 m x 30 m for the *aman-boro*. Thus, field size for all systems was typical of the size of farmers' fields. However, the fields were sub-divided to evaluate different management practices for the *aman* and *boro* crops.

2.1 Site characteristics

All sites were located adjacent to a *khal* connected to the surrounding river via a sluice gate in the polder embankment in order to facilitate drainage during the rainy season and to provide a source of water for irrigation during the dry season. Soil type was silty clay to clay loam. Further site details are provided in Table 1. The trials in polder 30 were shifted from Hatbati to Kismat Fultola in 2012 due to flooding from surrounding (higher) lands at Hatbati.

Table 1. Site details for the cropping system intensification trials, 2011-2014

Site details		
Village	Hatbati/Kismat Fultola	Bazarkhali
Upazila	Batiaghata	Amtali
District	Khulna	Barguna
Polder	30	43/2/F
Latitude	22^0 41' 00''N	22°11'33"N
Longitude	89^0 30' 00''E	90°15'41"E
Height above sea level	1-3 m	1-3 m
Salinity classification	Medium	Low
River water salinity (EC, dS/m))	0.2-24.0	0.2-2.4
Topsoil (0-15 cm) salinity (saturation extract EC, dS/m)	2-16	2-8
Soil texture	Silty clay	Clay loam
Predominant cropping systems	Sesame-*aman*-fallow	Fallow-*aman*-grasspea *Aus*-*aman*-fallow
Cropping systems evaluated	*aman-boro* *aman-rabi*	*aus-aman-boro* *aus-aman-rabi*

2.2 Variety selection

2.2.1 Rice

Modern, high yielding varieties (HYV) of rice were used in all systems (Table 2). To fit three crops per year, short duration varieties of *aus*, medium duration, non-photoperiod sensitive varieties of *aman*, and a medium duration *boro* variety were used. Some of the *aman* varieties were also known to have some tolerance to water stagnation. Local grain type preference for the *aman* varieties was also considered – bold in Amtali and slender in Batiaghata.

Table 2. Characteristics of the varieties used in the demonstrations at each location (BRRI 2010, BRRI 2013)

Variety	Duration[1] (days)	Photo-period sensitivity	Yield (t/ha)	Height (cm)	Stagnant flooding tolerance	Salinity/ drought tolerance	Grain type	Site[2]
Aus								
BRRI dhan42	100	N	3.5	100	Suitable for higher	Drought	Medium	BK
					rainfall areas			
BRRI dhan 43	100	N	3.5	100	Suitable for higher	Drought	Medium	BK
					rainfall areas			
BRRI dhan 48	110	N	5.5	105	Suitable for lowland		Medium bold	BK
BRRI dhan65								
(OM 1490)	100		3.5	90		Drought	Long slender	BK
Aman								
BRRI dhan 33	118	N	4.5	100			Bold	BK
BRRI dhan49	135	N	5.5	100			Medium slender	KF
BRRI dhan53	125	N	4.5	105	Y	Salinity	Medium slender	BK
BRRI dhan54	135	Y	4.5	115	Y	Salinity	Medium slender	BK, KF
BINAdhan-7	120	N	5.5	90			Slender	BK
Boro								
BRRI dhan28	140	N	6.0	90	N	N	Medium slender	BK, KF

[1] Duration from sowing to physiological maturity

[2] BK = Bazarkhali; KF = Kismat Fultola/Hatbati

2.2.2 Rabi crops

Hybrid and high yielding varieties of several *rabi* crops were evaluated in *aus-aman-rabi* and *aman-rabi* cropping systems (Table 3). As fresh water is available throughout the year at Bazarkhali, a range of longer duration cereals/oilseed and shorter duration high value *rabi* horticultural crops was evaluated. At Kismat Fultola/Hatbati, traditional crops grown on residual soil moisture, with limited irrigation with marginal quality and without irrigation, were evaluated.

Table 3. *Rabi* crop/variety characteristics

Species	Variety/ hybrid	Name	Duration[1] (days)	Yield (t/ha)	Stress tolerance/ Disease resistance	Site[2]
Maize	Hybrid	Pacific 984	125-135	8-10	Drought	BK
Sunflower	Hybrid	Hysun 33	90-110	3-4	Drought	BK
Watermelon	Hybrid	Asian2	70-90	40-55		BK
Chilli	Hybrid	Debgree	120-150	3-4		BK
Sesame	HYV	BARI Til4	90-100	1.0-1.4		BK, KF
Mungbean	HYV	BARI mug6	60-65	1.0-1.5	Yellow mosaic virus	BK, KF

[1] Duration from sowing to harvest maturity

[2] BK = Bazarkhali; KF = Kismat Fultola/Hatbati

Sources: BARI 2006 and BRAC 2011

2.3 Rice crop management

2.3.1 Sowing date

The sowing date of *aman* was chosen to ensure that the rice would be ready for harvest by mid-November so that the field could be drained in early November (if water was present). This would enable the soil to start to dry for ease of harvesting and enable soil preparation for *rabi* crops to be advanced. At Bazarkhali, sowing dates were late July/early August (Table 4). At Kismat Fultola/Hatbati, where longer duration *aman* varieties were grown, the sowing date was earlier (1 July).

The sowing date for *boro* in Bangladesh varies widely, from November to January, depending on farmer practice and location. As our objectives were to fit three crops per year at Bazarkhali and to minimize the stored water requirement to finish off the *boro* crop at Kismat Fultola, it was important to establish the *boro* rice as early as possible. However, planting too early can lead to cold damage during the reproductive stage and greatly reduce yield (Mondal et al. 2010). The latter authors showed that for sowings from 22 October to 15 November, the optimal sowing date at Kismat Fultola was in the second week of November. However, later sowing dates were not evaluated. Therefore, *boro* sowing dates from early November to late December were evaluated in this study (Table 4).

All *aus* crops were sown in mid-April and transplanted in early May, except in 2012 when the second sowing was done on 7 May and transplanted in the last week of May (Table 4). Ritu *et al*. (2015) had previously shown the feasibility of high yielding *aus-aman* systems with *aus* sowing in May.

Table 4. Sowing, transplanting and harvest dates and rice varieties/*rabi* crops in the cropping system trials from 2011 to 2014.

Cropping system	***Aus***			***Aman***			***Boro/Rabi***		
	Sowing	Transplanting	Harvest	Sowing	Transplanting	Harvest	Sowing	Transplanting	Harvest
Bazakhali									
Aus-Aman-Boro (20 m x 30 m)	10-18 Apr	5-9 May	24 Jul-12 Aug GD increased in 2013 due to submergence	25 Jul	15-18 Aug	20-28 Nov	15 Nov	6-11 Dec	12-18 Apr
							07 Dec	28-30 Dec	24-29 Apr
							30 Dec	25-30 Jan	2-5 May
	BRRI dhan48 20 m x 30 m plot			**BRRI dhan54** 20 m x 30 m plot			**BRRI dhan28** 6.5 m x 30 m plots		
Aus-Aman-Rabi (20 m x 120 m)	10 Apr 7 May	8 30 May	22 Jul 20 Aug Variation due to long/short HYVs	6 Aug	26 29 Aug	19 Nov 10 Dec	10 Dec – 24 Jan		30 Mar 13 May
	BRRI dhan 42 **BRRI dhan43** **BRRI dhan65 (OM 1490)** 20 m x 40 m plots			**BRRI dhan33** **BRRI dhan53** **BINA dhan7** **BR53 and BN7 harvested 1st wk Dec** 20 m x 40 m plots			**Maize** **Sunflower** **Mungbean** **Sesame** **Watermelon** **Chilli** 20 m x 20 m plots		
Kismat Fultola/Hatbati									
Aman-Boro (20 m x 30 m)	n/a			1 Jul	25 Jul	12-17 Nov	10 Nov	30 Nov–1Dec	1-24 Apr
							30 Nov	20 21 Dec	21 23 Apr
							20 Dec	10–23 Jan	3 May
				BRRI dhan49 20 m x 30 m plot			**BRRI dhan28** 20 m x 10 m plots		
Aman-Rabi	n/a			1 Jul	21-25 Jul	17-23 Nov	6 Feb-16 Mar		30 Apr-12 Jun
(20 m x 80 m)				**BRRI dhan54** 20 m x 80 m plot			**Mungbean** **Sesame** 10 m x 80 m plots		

Note: At Bazarkhali most *aman* harvested by 25 Nov, BR53 and BN7 harvested in the first week of Dec in two out of three years. In *aus-aman-boro*, BR48 harvested by 25 July in two out of three years, delayed harvest in 2013 due to submergence in mid-May for a week.

2.3.2 Rice crop management

All rice crops were managed according to BRRI recommendations (Table 5) (BRRI 2010). The lands were ploughed three to four times (wet tillage) using a power tiller powered by a two-wheel tractor. Final land leveling with a bamboo ladder drawn by the two-wheel tractor was done after basal application of fertilizer. Rice seeds were soaked for 12 to 24 h and incubated for 48 to 72 h for germination. The pre-germinated seeds were sown on the seed bed at 28 g/m^2. Ten days after emergence, urea was applied to the seedbed at 32 kg N/ha. Transplanting was done when the seedlings had four leaves, with two to three seedlings per hill, and a hill spacing of 20 cm x 20 cm in all crops, except in *aman* 2011 at Bazarkhali and *boro* 2011-12 at Hatbati, which had 25 cm x 15 cm spacing.

All fertilizers other than urea were broadcast just prior to the final land levelling. Urea was broadcast in equal splits at various times after transplanting (Table 5). Excess water from the *aus* and *aman* fields was drained before topdressing of urea. The *aus* and *aman* crops were primarily grown on rainfall, with gravity irrigation by letting in river water at high tide during dry spells. The *boro* crops were fully irrigated by pumping water from the *khal* to maintain a shallow water depth (2 to 5 cm).

Table 5. Details of rice crop management at Bazarkhali and Kismat Fultola/Hatbati

	Aus	*Aman*	*Boro*
Seedling age at transplanting (days)	20-23 (2 cases 25-27d)	21-24	21-27 (a few cases extended to 29-35 d) (4 leaves)
Number of seedlings per hill	2-3	2-3	2-3
Hill spacing	20 cm x 20 cm	20 cm x 20 cm 25 cm x 15 cm	20 cm x 20 cm 25 cm x 15 cm
Fertilizer rate (kg/ha) (N, P, K, Ca, Zn)	83-20-35-11-2	92-20-35-11-2	102-20-35-11-2
Fertilizer sources (kg/ha) Urea Triple superphosphate (TSP) Muriate of potash (MoP) Gypsum Zinc sulphate	180 100 70 60 10	200 100 70 60 10	220 100 70 60 10
Time of urea splits (DAT)	15, 30, 45	15, 30, 45/55 (short/med vars)	15, 30, 55
Insect control	Basudin Diazinon Virtako	Basudin Synothrene Virtako	Basudin at time of each urea application

2.3.3 Rice crop monitoring

The duration of each rice crop was determined as the number of days from the day of sowing on the seed bed to physiological maturity. Physiological maturity was taken as the stage when 80% of the grains had turned golden.

Grain yield was determined by harvesting a 5 m^2 area at five locations (four towards the corners and one in the middle) of each plot at Bazarkhali. At Hatbati/Kismatfultola, rice was harvested from a 2 m x 5 m area in the middle of each plot. The plants were manually threshed and the grain was cleaned and weighed. Grain moisture content was determined on a subsample using a grain moisture meter. Grain yield was calculated at 14% moisture content.

2.4 Rabi crops

2.4.1 Rabi crop treatments

Kismat Fultola/Hatbati. The mungbean and sesame plots were split into subplots with six management treatments in 4 m x 5 m sub-plots with two replicates:

M_1 = Farmer practice (farmers' variety, broadcast onto dry cultivated soil, no fertilizer, manual weeding)

M_2 = M_1 + line sowing

M_3 = M_2 + fertilizer + irrigation (no irrigation in 2013-14 due to fresh water scarcity)

M_4 = M_3 + mulch (5 t/ha of rice straw)

M_5 = M_4 + improved variety (BARI mung 6, BARI til 4)

M_6 = M_5 no mulch (in 2012-13 and 2013-14 only)

Bazakhali. At Bazarkhali the plots were split into sub-plots with and without mulch (5 t/ha rice straw). Sub-plot size was 10 m x 20 m and there was one replicate of each *rabi* crop x mulching treatment.

2.4.2 Sowing date

Sowing date (Table 6) of the *rabi* crops varied among crops, seasons and sites depending on soil moisture after *aman* harvest and the optimum sowing time for each crop, but all were sown within the recommended period (BARI 2006). Harvest dates were influenced by variety, sowing date, weather (temperature) and soil moisture (the growth duration of mungbean increased in 2013 at Kismatfultola due to rainfall).

Table 6. Sowing and harvesting dates of *rabi* crops at Bazarkahli and Kismatfultola/Hatbati from 2011 to 2014

Crop	Bazarkahli		Kismat Fultola/Hatbati	
	Sowing date	Harvest date	Sowing date	Harvest date
Chilli	10 Dec – 17 Jan	10 Apr – 10 May		
Maize	16 Dec – 9 Jan	27 Apr – 13 May		
Sunflower	16 Dec – 9 Jan	9- 25 Apr		
Watermelon	13 – 30 Dec	1 – 15 Apr		
Sesame	12 – 24 Jan	25 Apr – 3 May	08 Feb – 16 Mar	16 May – 12 Jun
Mungbean	11 -24 Jan	30 Mar-13 Apr	06 Feb – 06 Mar	30 Apr-29 May

2.4.3 Rabi crop management

The land was tilled by a power tiller powered by a two-wheel tractor when the soil had dried to around field capacity, followed by one leveling using a wooden ladder pulled by the tractor. The exception was land preparation for watermelon, for which 60 cm x 60 cm x 60 cm pits were dug at 2 m x 2 m spacing.

BARI recommended management was applied for all *rabi* crops (Table 7) (BARI 2006). Chili, mungbean, sesame, maize and sunflower were sown in 2-4 cm deep furrows made using a hand furrower, and watermelon was sown in pits. Chili was sown at 50 cm row spacing, mungbean and sesame at 30 cm spacing, and thinning was done two weeks after emergence to give 5 cm spacing between plants. Planting geometry was 75 cm x 25 cm for maize, 60 cm x 45 cm for sunflower, and 2 m x 2 m for watermelon. One seed per hill was sown for maize and sunflower, and two seeds per pit for watermelon. Earthing up was done in maize and sunflower 50-60 d after sowing (DAS).

Table 7. Sowing and fertilizer management in *rabi* crops at Bazarkhali and Kismat Fultola/Hatbati

Crops	Seed rate (kg/ha)	Spacing (row x plant)	Fertilizer (kg/ha) (cm x cm)					
			N	P	K	S	Zn	B
Chilli	0.8-1.0	50 x 5	92	35	75	27	2	2
Maize	15-20	75 x 25	258	58	140	33	4	2
Mungbean	25-30	25 x 5	50	22	54	2	2	2
Sesame	5.5-6.5	30 x 5	23	16	20	9	1	0
Sunflower	5	60 x 45	55	26	25	20	1	2
Watermelon	0.5-0.6	200 x 200	97	66	100	20	0	0

Fertilizer management. At Bazarkhali, fertilizer was applied to all the *rabi* crops, but at Hatbati /Kismatfultola, it was applied in M_3, M_4, M_5 and M_6 treatments only (Table 7).

At Bazarkhali, one-third of the N (50% in mungbean) and all the P, K, S, Zn and B were broadcast just prior to the final tillage operation, 1 d before seeding, with the exception of watermelon for which the fertilizer was applied to the pits 5 d before sowing. The rest of the urea was topdressed thrice in chili and watermelon, twice in maize, sesame and sunflower, and once in mungbean.

At Hatbati/Kismatfultola, half of the N and the full dose of P, K, S, Zn and B were applied during final land preparation. The remaining N was topdressed once or twice depending on rainfall and salinity of the *khal* water (once at Hatbati in 2012 just after rainfall on 10 April, and at Kismatfultola on 6 March 2013 after irrigation of mungbean, on 25 April 2013 after rainfall in sesame, and in 2014 after rainfall on 17 March.

Water management. At *Bazarkhali*, the *khal* was filled with river water by opening the sluice gate at high tide when needed, and then the gate was closed to store the water in the *khal* for irrigation. All *rabi* crops were irrigated by pumping water from the *khal*. Irrigation method varied depending on the crop and stage of growth, topdressing of N fertilizer, and soil moisture, and included watering of small seedlings with a watering can, spraying with a hose, and flood irrigation (Table 8). Chili and watermelon were irrigated five times using a hose and spray nozzle, and the other *rabi* crops were flood irrigated two to three times. Mulched and non-mulched plots were irrigated on the same day.

At Hatbati/Kismat Fultola the *rabi* crops were mainly grown using residual soil moisture and rainfall due to scarcity of good quality water. Two irrigations were applied to mungbean in 2013. Irrigation was not applied in 2012 due to timely rainfall (Fig. 1), and there was no irrigation in 2014 due to the high salinity of the water in the *khal* (Mondal et al. 2015).

Table 8. Irrigation of *rabi* crops at Bazarkhali and Kismat Fultola in 2011-12 to 2013-14.

Crop	Stage and time of irrigation(IR) (days after sowing, DAS)				
	IR1	IR2	IR3	IR4	IR5
Chili	25-40	50-55	65-70	80-85	95-100
Maize	6-8 leaf stage (30-40 DAS)	10-12 leaf stage (55-70 DAS)	Tasseling & silking stage (85-95 DAS)		
Mungbean	4-6 leaf stage (15-30 DAS)	Pod formation (50-55 DAS)			
Sesame	4-6 leaf stage (15-30 DAS)	Pod formation (50-70 DAS)			
Sunflower	6-8 leaf stage (30-40 DAS)	Flower bud initiation (50-60 DAS)	Flowering (70-80 DAS)		
Watermelon	10-20	30-40	45-55	65-75	85-95

Weeding. In non-mulched plots, weeding was done twice by hand at 20-25 and 40-50 d after emergence (DAE), prior to urea topdressing and earthing up in maize and sunflower. In other crops weeding was done during thinning. In mulched plots, weeding was not generally required, but sporadic hand removal was done when weeds appeared.

Pest and disease management. Disease and insect pest infestations were controlled well by spraying pesticides and insecticides when necessary. At Bazarkahli, Instar and Admire were sprayed once to control aphid in mungbean and Savin was applied five to six times to control red pumpkin beetle in watermelon. At Kismat Fultola, Bevistin and Nitro were sprayed to control yellow mosaic virus and Virtako to control semilooper in mungbean. No biocides were applied to other *rabi* crops.

2.4.4 Rabi crop monitoring

Most *rabi* crops were harvested when the leaves turned dry, brown and/or yellow. Sesame and mungbean were harvested when the pods were black, and chili when the fruit turned reddish. Several pickings were required for mungbean, chili and watermelon. Grain or fruit yield of the *rabi* crops was determined in a 4 m x 5 m harvest area in the middle of each plot for all crops except watermelon at Bazarkhali, and it was done for the whole plot (5 m x 10 m) at Hatbati/Kismat Fultola. The number of plants in the harvest area was also determined. For grain/seed yield of maize, sunflower, mungbean and sesame, the samples were threshed, cleaned and sun dried before weighing and determining moisture content using a grain moisture meter. Yield of maize, sunflower and mungbean was converted to 14% moisture content. The yield of chili and watermelon was determined immediately after harvest ("green" weight).

Rice equivalent yield (REY) of the *rabi* crops was calculated as: REY = rabi yield (t/ha) * *rabi* price (Tk/kg) / rice price (Tk/kg). The price of rice was Tk 16.25/kg at Amtali and Tk 18.75/kg at Batiaghata. Prices of *rabi* crops were the same at both locations: chili, Tk 25/kg; maize, Tk 16.25/kg; mungbean, Tk 82.5/kg; sesame, Tk 50/kg; sunflower, Tk 33.75, and; watermelon, Tk 5.71/kg.

2.5 Water monitoring

The depth of water in the paddy fields was measured daily using vertical scales installed in the plots at several locations. Salinity of the canal water was also measured daily using a portable EC meter.

2.6 Weather

Daily rainfall was measured at the field sites at Bazarkhali and Kismat Fultola. Daily rainfall, maximum and minimum temperature, and sunshine hours at Khepupara (in Patuakhali District) and Khulna were collected from the Bangladesh Meteorological Department for the period 2011 to 2014. The weather station at Khulna is about 8 km north of the experimental sites at Hatbati and Kismat Fultola, while the station at Khepupara is about 24 km south of the experimental site at Bazarkhali.

3. Results

3.1 Weather

3.1.1 Rainfall

Monthly rainfall totals at Khepupara and Khulna meteorological stations were generally similar to the long-term averages, with a few exceptions (Figs. 1a,b). At both locations rainfall was extremely high in August 2011, with totals in excess of 600 mm at Khulna and 900 mm at Khepupara. The monsoon season ended late in 2013, with unusually high rainfall at both sites in October (301 mm at Khulna, 457 mm at Khepupara). Pre-*kharif* rainfall was also unusually high in May 2013 at both locations due to cyclone Mohasen (430 mm at Khulna, 518 mm at Khepupara), and in June 2014 at Khulna only (555 mm).

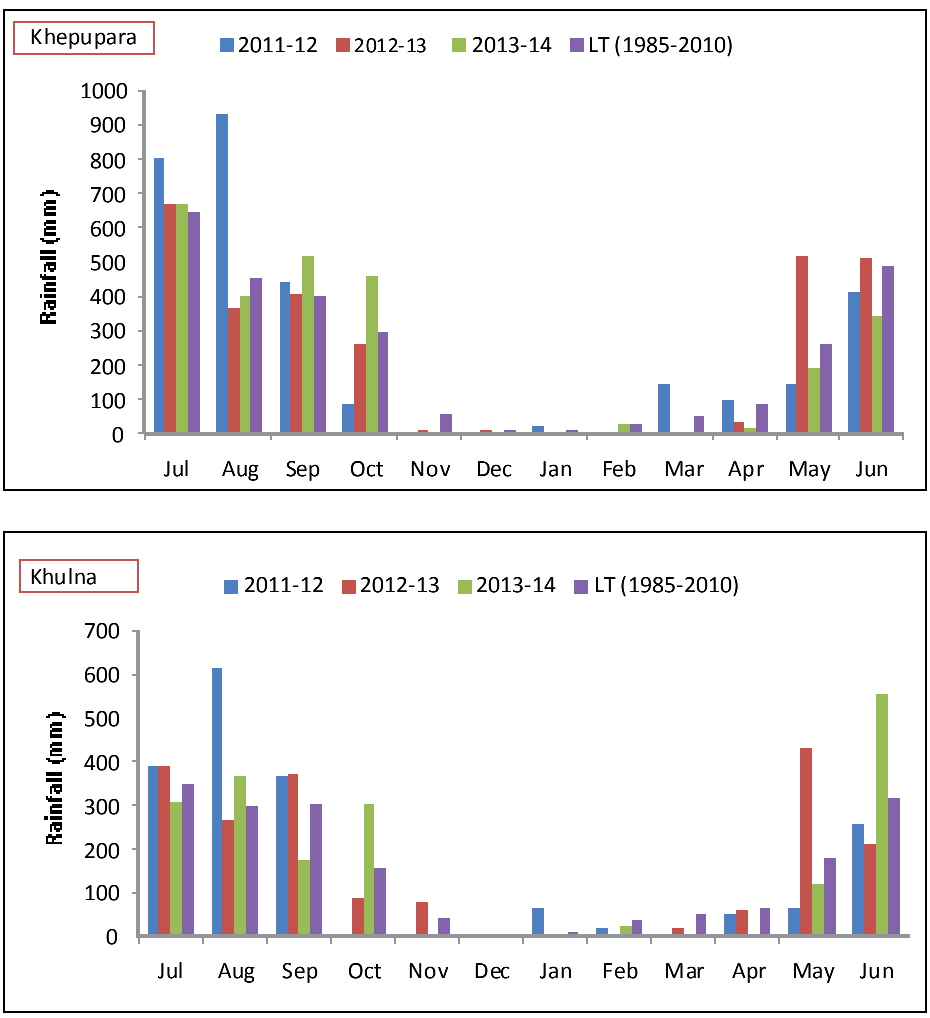
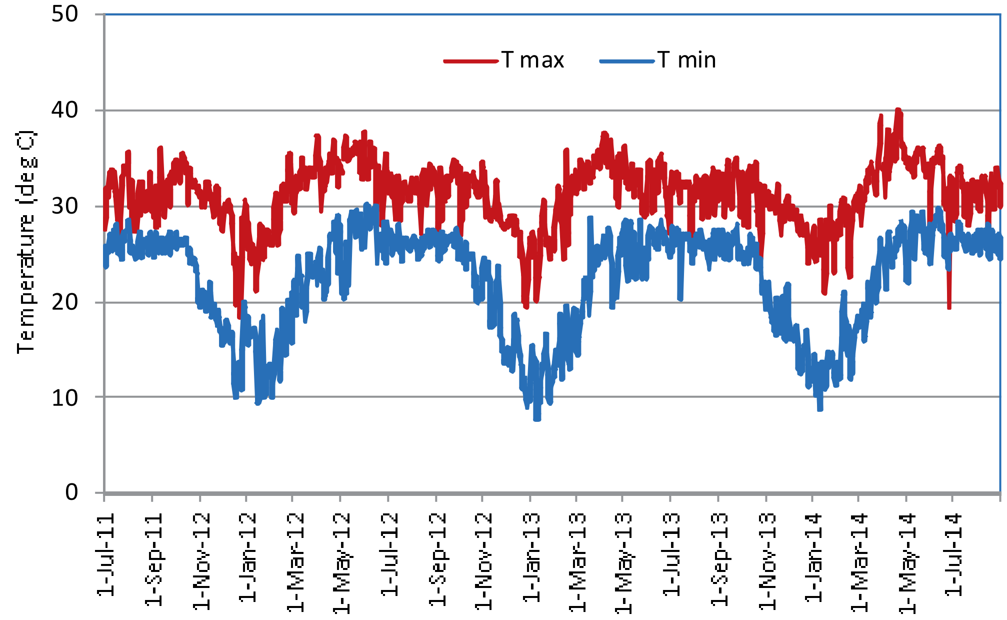


Fig. 1. Monthly rainfall at Khepupara (a) and Khulna (b) from July 2011 to June 2014 compared with the long-term average (1985-2010).

3.1.2 Temperature

Trends in temperature across the years were similar within and across sites (Figs 2a,b). Temperatures were generally favourable for growing rice throughout the year, apart from low minimum temperatures (around 10°C) in late December/early January each year and high temperatures (approaching 40°C in May). The mean monthly temperatures at Khepupara and Khulna during the study period were generally similar to the long-term average temperatures, except for higher than average temperatures in April 2014, in May 2012 and 2014, and in June 2012 (Figs 3a,b). Based on the long-term data, the temperature regime is slightly more extreme at Khulna than at Khepupara. Maximum temperature is higher at Khulna during summer and the rainy season, while minimum temperature is lower at Khulna in the winter (Fig. 4).

(a) Patuakhali



(b) Khulna

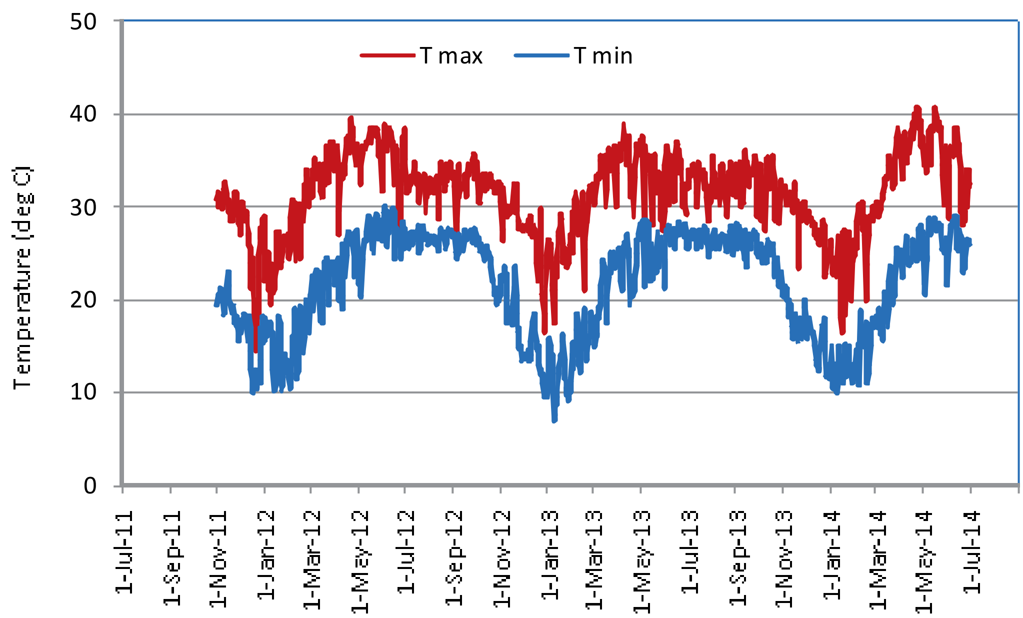


Fig. 2. Daily maximum and minimum temperatures at Khepupara (a) and Khulna (b) from July 2011 to June 2014.

(a) Khepupara

(b) Khulna

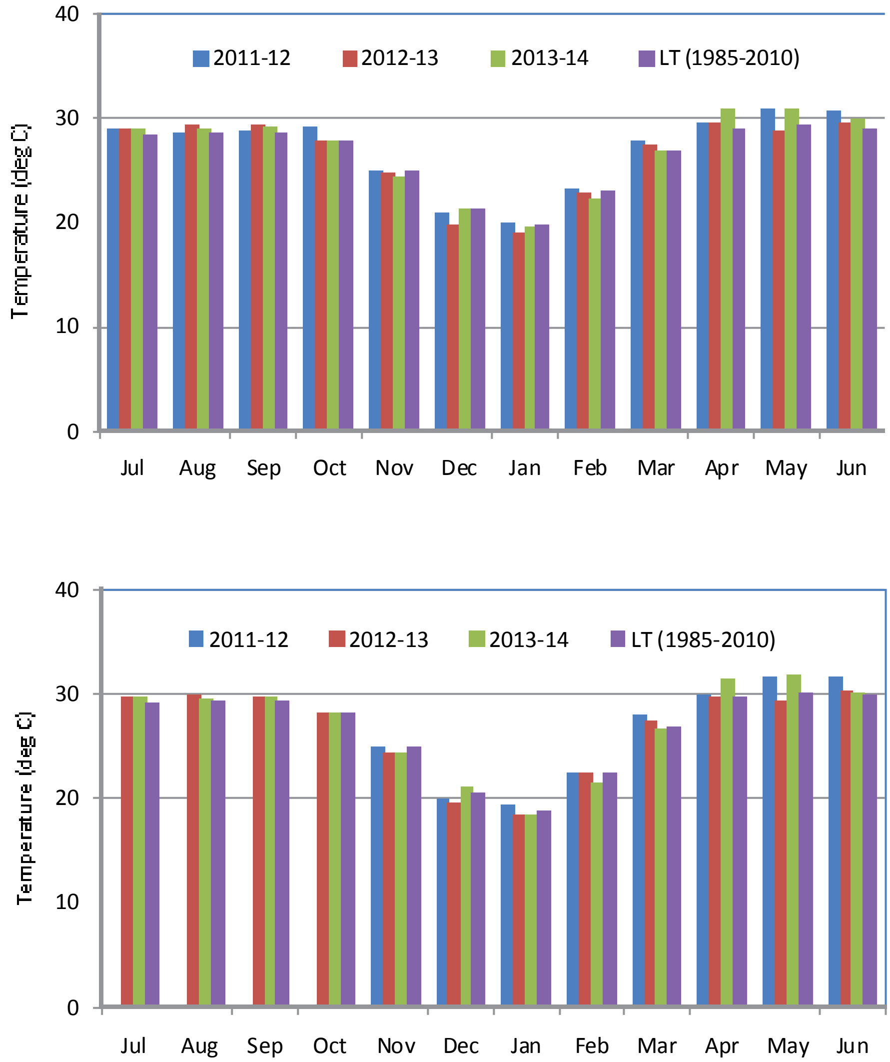


Fig. 3. Mean monthly temperature at Khepupara (a) and Khulna (b) from July 2011 to June 2014, and the long-term (1985-2010) averages.

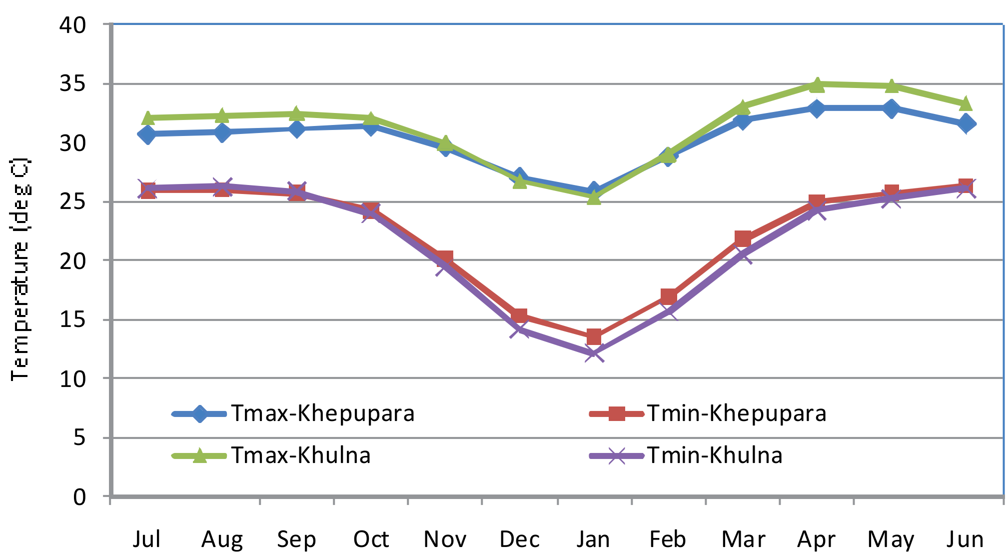
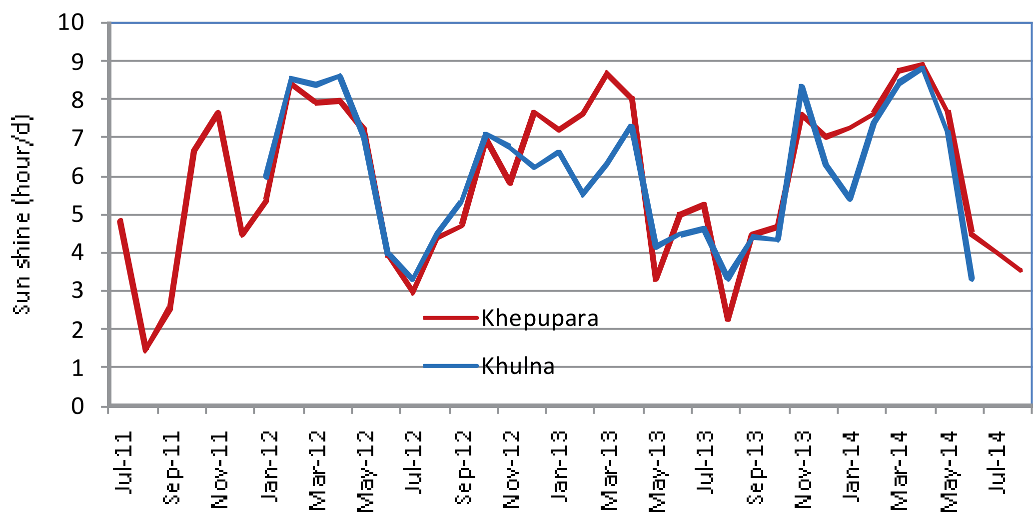


Fig. 4. Long-term (1985-2010) monthly average maximum and minimum temperatures at Khulna and Khepupara.

3.1.3 Sunshine hours

During the monsoon season (June to September) the amount of bright sunshine (3 to 5 h per day) was lower than at other times of the year (Fig. 5a). Daily sunshine hours were highest in November and February to May. The long-term data suggest that the amount of bright sunshine at Khulna is higher than at Khepupara throughout the year (Fig. 5b).

(a) Sunshine, 2011-2014



(b) Sunshine, 1985-2010

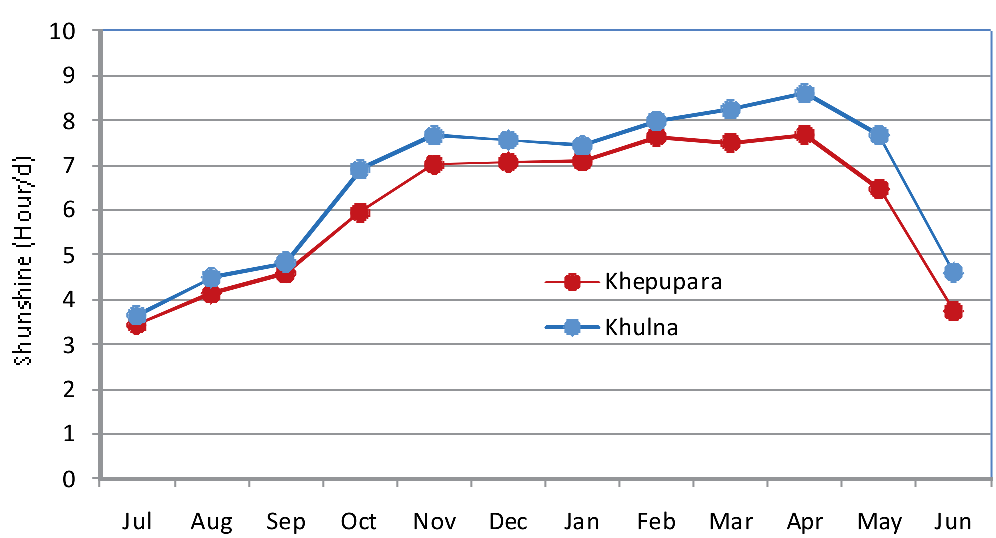


Fig. 5. Monthly average sunshine hour of Khulna and Khepupara during 2011-2014 (a) and long-term means (Khulna: 1985-2010 and Khepupara 1988-2010) (b).

3.2 Water depth in rice

Water depth in the paddy fields varied widely within and across seasons and years (Figs. 6-8), mainly depending on rainfall and management of the sluice gates during the rainy season.

3.2.1 Bazarkhali

Aman. Water depth in the *aman* crops was generally between 5 and 20 cm, except in early September 2012 (second or third week after transplanting) when it increased to 50 cm due to high rainfall (Fig. 6). The crops were thus submerged for about 5 d.

Boro. Water depth in the *boro* crops fluctuated between 1 and 5 cm throughout the season as a result of careful irrigation management (data not presented).

Aus. Water depth during the *aus* season generally fluctuated between 0 and 10 cm because the high tide river water level from May to July was only slightly higher than the land level (Fig. 7). However, in mid-May 2013, water depth increased rapidly to about 60 cm due to excessive rainfall from cyclone Mohasen. As a result, the crop was submerged for about one week, about two weeks after transplanting.

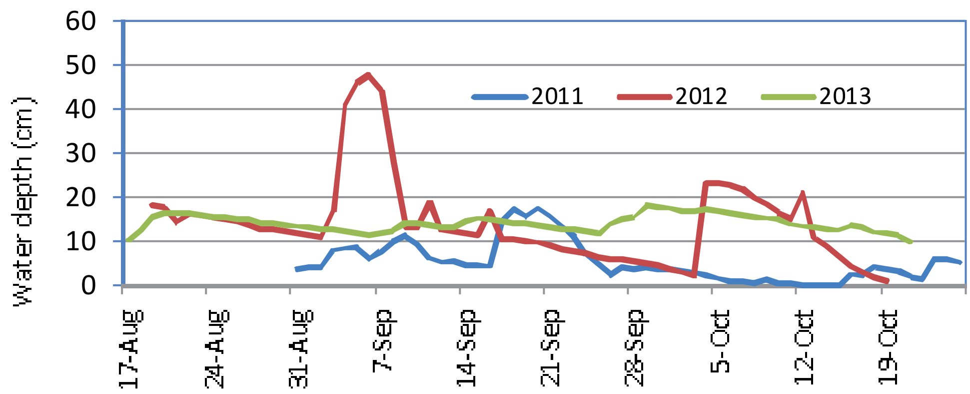


Fig. 6. Paddy water depth in *aman* 2011 to 2013 at Bazarkhali.

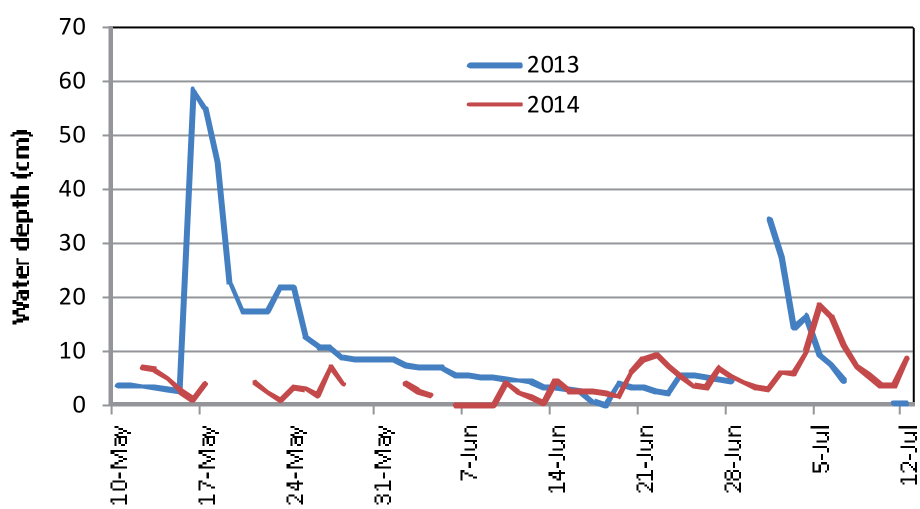


Fig. 7. Paddy water depth in *aus* 2013 and 2014 at Bazarkhali.

3.2.2 Kismatfultola/Hatbati

Aman. Water depth during the *aman* crops generally fluctuated between 5 and 25 cm (Fig. 8). However, in 2011, the crop at Hatbati was inundated for about a week starting two weeks after transplanting due to excessive rainfall coupled with the intake of water though the sluice gates by the community for land preparation and transplanting of the higher lands. The 2011 crop also experienced water stagnation throughout the grain filling period, from mid-October to maturity, as a result of further intake of water by the community to flood higher lands in the landscape. Water depth in 2012 and 2013 was within 5-20 cm during the *aman* season at Kismat Fultola.

Boro. Water depth during the *boro* crops fluctuated from 0 (saturated soil) to 6-10 cm throughout the season each year as a result of careful irrigation management (data not presented).

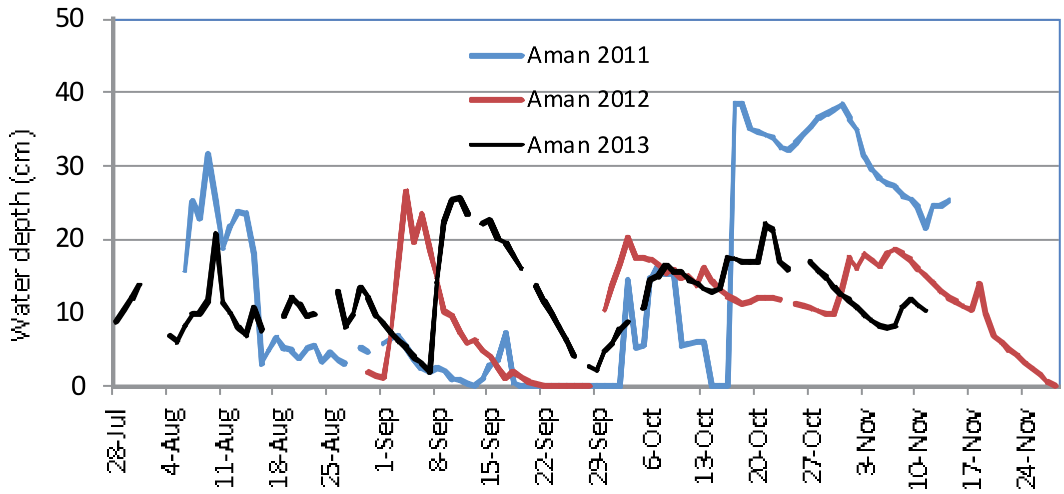


Fig. 8. Paddy water depth in the *aman* crops at Hatbati (2011) and Kismatfultola (2012, 2013).

3.3 Khal water salinity

3.3.1 Bazarkhali

Salinity of the water in the *khal* at Bazarkhali reached a maximum of about 0.6 dS/m towards the end of each dry season, and declined to about 0.1 dS/m during the rainy season (Fig. 9). Thus the water in the *khal* was always suitable for irrigation.

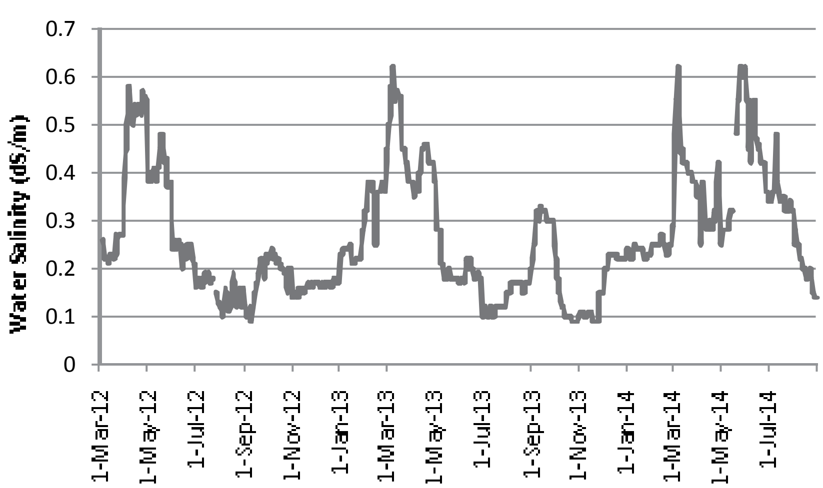


Fig. 9. *Khal* water salinity at Bazarkhali.

3.3.2 Kismat Fultola/Hatbati

Salinity of the water in the *khal* at Kismat Fultola was much higher than that at Bazarkhali, and increased as the dry season progressed (Fig. 10). Maximum EC ranged from 15 dS/m in 2012 to 21 dS/m in 2013. EC declined to about 0.2 dS/m during the rainy season. In the 2012 dry season, the *khal* was filled with river water by opening the sluice gate at high tide until first week of February, and the water was stored for irrigation by closing the sluice gate. The water remained suitable for irrigation (<4 dS/m) until early May 2012. But in 2013 and 2014 the Water Users' Organization kept the sluice gate partly open during the dry season to try and prevent siltation in the gate intake canal. Thus the *khal* water became unsuitable for irrigation by late February in 2013 and 2014.

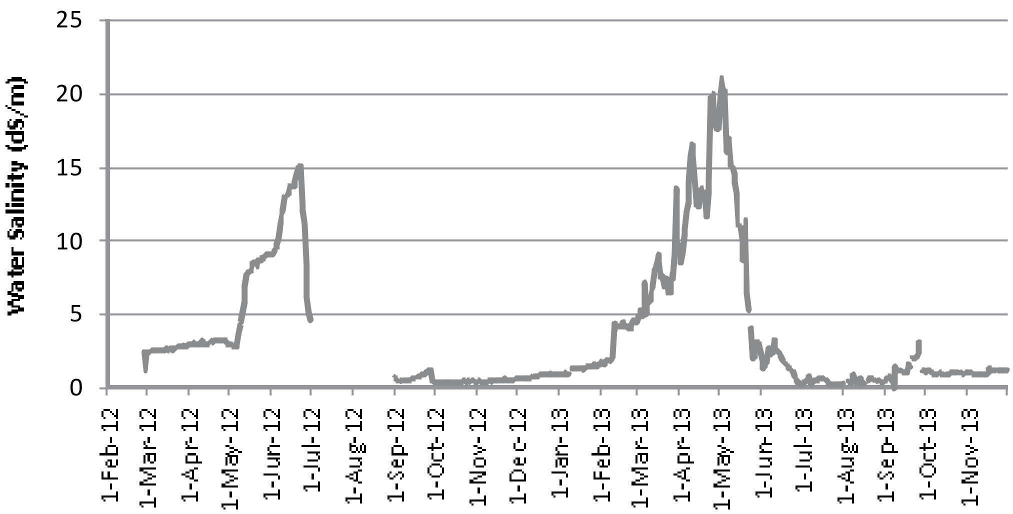


Fig. 10. *Khal* water salinity at Kismat Fultola.

3.4 Crop performance at Bazarkhali

3.4.1 Aman

BRRI dhan33 had the shortest duration each year (105 to 115 d), while BRRI dhan54 had the longest duration (120 to 125 d) (Table 9). Duration of all varieties other than BRRI dhan54 was 6 to 20 d longer in 2012 than in the other two years, probably due to inundation for about one week shortly after transplanting on 28 August 2012 (Fig. 6). BRRI dhan54 was transplanted 10 d earlier than the other varieties and is taller and thus more tolerant to water stagnation. The BINAdhan-7 was more heavily damaged because of its very short stature, hence its 20 d longer duration in 2012 than in 2013 due to delayed tillering.

Yield was always in excess of 4.1 t/ha except for BRRI dhan33 in 2011. Over the three years, average yield of BRRI dhan53, BRRI dhan54 and BINAdhan-7 was similar (4.6-4.7 t/ha), while BRRI dhan33 averaged 4.2 t/ha. The inundation in 2012 did not appear to affect yield.

Table 9. Duration, grain weight and yield (mean ± s.e.) of *aman* crops at Bazarkhali

Year	*Aus-aman-boro*	*Aus-aman-rabi*		
	BRRI dhan54	BRRI dhan33	BRRI dhan53	BINAdhan-7
Duration (d)				
2011	126	105	118	
2012	125	115	124	127
2013	120	107	112	107
Mean	*124*	*109*	*118*	*117*
Grain yield (t/ha)				
2011	4.1±0.1	3.8±0.1	4.3±0.1	
2012	4.8±0.1	4.3±0.1	4.5±0.1	4.6±0.1
2013	4.7±0.03	4.5±0.3	5.3±0.2	4.7±0.04
Mean	*4.6±0.2*	*4.2±0.2*	*4.7±0.3*	*4.6±0.02*

3.4.2 Boro

Duration of the *boro* crops ranged from 123 to 152 d (Table 10). There was a consistent trend for declining crop duration as sowing date was delayed, due to the warmer weather experienced by later sown crops. Grain yields ranged from 5.8 to 7.9 t/ha, except for the 30 December sowing in 2011 that yielded only 4.4 t/ha, probably due to leaf blight attack in the seed bed which led to poor growth and tillering after transplanting. In the first two seasons yield declined with delay in sowing, however in 2013-14, yield of the first sowing was lower than yield of later sowings, due to severe stem borer attack (est. 20% yield loss).

Table 10. Effect of sowing date on duration and yield (mean ±s.e.) of *boro* crops (BRRI dhan28) at Bazarkhali

Year	Sowing date		
	15 Nov	7 Dec	30 Dec
Duration (d)			
2011-12	148	138	123
2012-13	152	144	126
2013-14	149	139	126
Mean	*150*	*140*	*125*
Grain yield (t/ha)			
2011-12	7.9±0.1	6.7±0.2	4.4±0.2
2012-13	6.7±0.2	7.0±0.2	5.9±0.2
2013-14	5.8±0.2	6.6±0.3	6.1±0.2
Mean	*6.8±0.6*	*6.8±0.1*	*5.5±0.6*

3.4.3 Aus

Duration of all *aus* varieties was ~100 d except in 2013 when duration was longer (Table 11), probably because the crops were inundated for about a week shortly after transplanting (Fig. 7). Yield ranged from 4.6 to 5.2 t/ha in 2012, 3.8 to 4.3 t/ha in 2013 and 3.6 to 4.1 t/ha in 2014. The lower yield in 2014 may be due to lower solar radiation at flowering (data not presented) than in other years, as temperature was similar each *aus* season (data not presented).

Table 11. Duration, grain weight and yield (mean ± s.e.) of *aus* crops at Bazarkhali

	Aus-aman-boro	*Aus-aman-rabi*		
Year	*BRRI dhan 48*	*BRRI dhan 42*	*BRRI dhan 43*	*BRRI dhan65 (OM 1490)*
Duration (d)				
2012	*102*	*103*	*103*	*-*
2013	*117*	*108*	*108*	*108*
2014	*100*	*100*	*100*	*103*
Mean	*106*	*104*	*104*	*106*
Grain yield (t/ha)				
2012	*4.6±0.0*	*5.1±0.2*	*5.2±0.2*	*-*
2013	*4.3±0.1*	*4.2±0.2*	*4.0±0.2*	*3.8±0.1*
2014	*4.1±0.1*	*3.6±0.0*	*3.6±0.1*	*3.6±0.1*
Mean	*4.3±0.2*	*4.3±0.4*	*4.3±0.4*	*3.7±0.1*

3.4.4 Rabi

The maize and sunflower crops performed well each year, with maize yields ranging from 8.7 to 9.5 t/ha, and sunflower from 3.6 to 3.8 t/ha (Table 12). Yields of the mulched watermelon (42 and 63 t/ha) and chili (2.3 and 3.6 t/ha) were also good. The effects of mulch on maize and sunflower yield were inconsistent across crops and years. In all three years there was little effect of mulch on sunflower yield, and the same was true for maize in 2013-14. In 2011-12, mulching reduced maize yield by 0.8 t/ha, while the reverse occurred in 2012-13. The high yields and lack of effect of mulch on maize and sunflower suggests that soil moisture was adequate both with and without mulch as a result of timely flood irrigation. In contrast, at a nearby site (at Patuakhali), Bhattacharya et al. (2015) found a small (~0.5 t/ha) but significant increase in yield of maize with mulching in 2012-13 and 2013-13, but a significant decline (~0.5 t/ha) in yield of sunflower with mulching. There was a consistent trend for slightly higher yield of sesame and mungbean with mulch, and for much higher yield of watermelon with mulch. This may have been due to lower soil water availability in the non-mulched plots, as all these crops were only lightly irrigated by watering can or sprinkler. Yield of mungbean was disappointing, especially in the first and third years, due to poor germination for unknown reasons (possibly poor quality seed), and the chili crop stand was poor in the third year (many plants died after emergence).

Table 12. Yield of *rabi* crops at Bazarkhali

Crop Season	Mulching	Yield (t/ha)			
		2011-12[1]	2012-13	2013-14	Mean ± s.e.
Maize	Mulch	8.7	9.3	9.2	9.1±0.1
	No-Mulch	9.5	8.7	9.1	9.1±0.2
Sunflower	Mulch	3.6	3.6	3.8	3.7±0.1
	No-Mulch	3.7	3.8	3.7	3.8±0.1
Mungbean	Mulch	0.40	0.85	0.46	0.57±0.1
	No-Mulch	0.35	0.63	0.25	0.41±0.1
Sesame	Mulch		0.80	0.57	0.68±0.1
	No-Mulch		0.56	0.49	0.53±0.0
Watermelon	Mulch		63	42	52±11
	No-Mulch		33	12	23±10
Chili	Mulch		3.6[2]	2.3	2.9±0.7
	No-Mulch			2.0	

[1]Sesame crop damaged by 112 mm rainfall prior to harvest, yield of watermelon was not recorded

[2]Yield after the first harvest, combined for both mulched and non-mulched plots (only one harvest due to damage by 500 mm rainfall in May 2013)

The growth duration of the *rabi* crops varied from 68 to 140 d and there was no effect of mulch on crop duration (Table 13). The crops matured one to two weeks earlier in 2011-12 than in later years, probably because of late sowing (second half of January, two to three weeks later than in 2012-13 and 2013-14) and thus warmer growing conditions in 2011-12. All crops were harvested by the end of April, well before the beginning of the pre-monsoon and cyclone seasons (Table 14).

Table 13. Growth duration of *rabi* crops at Bazarkhali

Crop	Duration (d)			
	2011-12	2012-13	2013-14	Mean ± s.e.
Maize	125	132	132	130±2
Sunflower	106	115	114	112±3
Mungbean	68	86	92	82±7
Sesame	92	101	111	101±6
Watermelon	99	105	116	107±5
Chili		140	129	135±6

Table 14. Growth period (sowing-harvest) of rabi crops at Bazarkhali

Crop	2011-12	2012-13	2013-14
Maize	09 Jan 12 – 13 May 12	24 Dec 12 – 05 May 13	16 Dec 13 – 27 Apr 14
Sunflower	09 Jan 12 – 25 Apr 12	24 Dec 12 – 17 Apr 13	16 Dec 13 – 09 Apr 14
Mungbean	24 Jan 12 – 02 Apr 12	16 Jan 13 – 10 Apr 13	11 Jan 14 – 10 Apr 14
Sesame	24 Jan 12 – 25 Apr 12	17 Jan 13 – 28 Apr 13	12 Jan 14 – 03 May 14
Watermelon	30 Dec 11 – 06 Apr 12	30 Dec 12 – 15 Apr 13	13 Dec 13 – 10 Apr 14
Chili	17 Jan 12 – crop damage	22 Dec 12 – 10 May 13	10 Dec 13 – 18 Apr 14

3.5 Crop performance at Kismat Fultola/Hatbati

3.5.1 Aman

The duration of BRRI dhan49 ranged from 135 to 147 d, and that of BRRI dhan54 from 140 to 146 d (Table 15). Duration of BRRI dhan54 was longer than at Bazarkhali, where the crop was sown 24 d later, reflecting the fact that this variety is sensitive to photoperiod. Yields ranged from 4.2 to 4.7 t/ha except for BRRI dhan49 in 2013, which yielded 5.7 t/ha.

Table 15. Duration, grain weight and yield components of *aman* at Kismatfultola/Hatbati

Cropping Pattern	Variety	Year	Growth duration (d)	1000 grain wt (g)	Yield (t/ha)
Aman-Boro	BRRI dhan49	2011	135	20.2	4.2±0.1
		2012	139	19.9	4.7±0.2
		2013	140	22.4	5. 7±0.2
		Mean	*138*	*20.8*	*4.9±0.4*
Aman-Rabi	BRRI dhan54	2011	140	27.7	4.5±0.3
		2012	145	26.4	4.3±0.2
		2013	146	-	4.7±0.1
		Mean	*144*	*27.0*	*4.5±0.1*

3.5.2 Boro

Some of the seedlings of the 10 November 2011 sowing died after transplanting, presumably due to the combined stresses of low temperature and mild salinity. Gap filling was done using spare seedlings and tillers from surviving hills. In 2012-13 the 30 November and 20 December sowings died after transplanting, and likewise the 20 December sowing in 2013-14. There was a trend for decreased duration with delay in sowing, as at Bazarkhali (Table 16). Yield of the 10 November sowing was similar each year, at 4.6 to 4.9 t/ha. In 2011-12, yield increased with delay in sowing from 10 November to 20 December when the crop was irrigated with low salinity water (Fig. 10). The reason for low yield of the 10 November sowing is probably due to the seedling death and gap filling described above. In the next two years, there was no or very low yield for later sowings.

Yields at Kismat Fultola/Hatbati were much lower than at Bazarkhali (except for the last sowing in 2011-12 when the seedling nursery at Bazarkhali was affected by leaf blight). Temperatures in both regions were similar during the *boro* season (Figs 2a,b); therefore, we suspect that the cause of the generally much lower yields at Kismat Fultola/Hatbati was the combination of salinity and low temperature.

Table 16. Effect of sowing date on duration, yield components and yield of *boro* (BRRI dhan28) at Kismat Fultola/Hatbati

	Sowing date		
Year	10 Nov	30 Nov	20 Dec
Duration (d)			
2011-12	143	143	135
2012-13	166	Cold damage	Cold damage
2013-14	150	144	Cold damage
Mean	*153*	*144*	*135*
Grain yield (t/ha)			
2011-12	4.57	5.86	6.31
2012-13	4.89	0.00	0.00
2013-14	4.57	1.73	0.00
Mean	*4.68*	*2.53*	*2.10*

3.5.3 Rabi

In 2012 and 2014, maximum mungbean yields of 0.9 to 1 t/ha were achieved, but yields of sesame were generally poor (usually <0.5 t/ha). Mungbean yield tended to increase with improved management and highest yields were achieved with treatments M5 (line sowing plus fertilizer plus irrigation plus mulching plus improved variety BARI Mung 6) and M6 (as for M5 but without mulch) (Table 17). In 2012, yield was increased from 0.3 to 1.0 t/ha with line sowing, fertilizer and irrigation. However, in 2014 there was no benefit of line sowing and fertilizer, probably due to water deficit, as irrigation was not provided due to the high salinity of the *khal* water (Fig. 10). Mulching suppressed yield of sesame as the mulch impaired establishment, probably because the rows were covered by the straw. All *rabi* crops in 2013 were destroyed by waterlogging as a result of cyclone Mohasen in mid-May, which occurred shortly before crop maturity. In that year, sowing of the *rabi* crops did not take place until 8 February 2013.

Table 17. Yield of *rabi* crops Hatbati/Kismatfultola

Crop season[1]	Crop	Yield (t/ha)						
		M1[2]	M2	M3	M4[3]	M5	M6	Mean
2012	Mungbean	0.32	0.46	0.61	0.87	1.01	-	0.65±0.10
	Sesame	0.28	0.47	1.04	0.58	0.49	-	0.57±0.10
2014	Mungbean	0.67	0.69	0.81	0.65	0.9	0.88	0.77±0.04
	Sesame	0.44	0.3	0.39	-[3]	0.42	0.37	0.38±0.02

[1]All 2012-13 *rabi* crops destroyed by cyclone in May, due to late establishment

[2]M_1 = Farmer practice (farmers' variety, broadcast onto dry cultivated soil, no fertilizer, manual weeding)

M_2 = M_1 + line sowing

M_3 = M_2 + fertilizer + irrigation (no irrigation in 2013-14 due to fresh water scarcity)

M_4 = M_3 + mulch (5 t/ha of rice straw)

M_5 = M_4 + improved variety (BARI mung 6, BARI til4)

M_6 = M_5 no mulch (in 2012-13 and 2013-14 only)

[3]Sesame plants died due to excess soil moisture caused by seepage from the *boro* rice field

3.6 Total system production

3.6.1 Bazarkhali

Aus-aman-boro. Total system yield ranged from 13.2 to 16.6 t/ha over the three years and three *boro* sowing dates (Table 18). The lowest system yield was due to severe stem borer attack of the earliest *boro* sowing. All other systems yielded more than 14 t/ha.

Table 18. Annual *aman-boro-aus* system yield at Bazarkhali

Year	Aman (t/ha)	Boro (t/ha)			Aus (t/ha)	Total rice yield (t/ha/yr)			
		15 Nov[1]	7 Dec	20 Dec		15 Nov	7 Dec	20 Dec	Mean
2011-12	4.1	7.9	6.7	5.8	4.6	16.6±1.2	15.4±0.8	14.5±0.5	15.5±0.6
2012-13	4.8	6.7	7.0	6.6	4.3	15.8±0.7	16.1±0.8	15.8±0.7	15.9±0.1
2013-14	4.7	4.4[2]	5.9	6.1	4.1	13.2[2]±0.2	14.7±0.5	14.9±0.6	14.2±0.5
Mean	4.6	6.3	6.5	6.2	4.3	15.2[2]±0.5	15.4±0.1	15.1±0.1	15.2±0.4

[1]*Boro* sowing date

[2]Severe stem borer attack in 15 Nov sown *boro* crop

Aus-aman-rabi. Total system yield (REY) ranged from 8.5 to 30.7 t/ha over the three years with six rabi crops grown under mulched and no-mulch practices (Table 19). Inclusion of watermelon generally resulted in much higher REY than in the *aus-aman-boro* system, due to the high yield of watermelon. Inclusion of maize and sunflower gave comparable or slightly higher REY (16 to 19 t/ha) than the triple rice system, due to the higher yield of maize and the higher value of sunflower seed. System yield with mungbean, sesame and chili in the system (10 to 13 t/ha in years when the crops were planted on time) was always considerably lower than that of the triple rice system.

Mulching greatly increased system yield of watermelon, but yield variability across years was high in both mulched and non-mulched treatments. System yield with maize and sunflower was more stable over the three years than with the other *rabi* crops.

Table 19. Annual *aus-aman-rabi* system yield at Bazarkhali

Rabi crop	*Aman*[1] (t/ha)	*Rabi* (rice equivalent yield, t/ha)[2]		*Aus*[1] (t/ha)	Total system rice equivalent yield (t/ha)	
		Mulch	No mulch		Mulch	No mulch
2011-12						
Chili	4.0±0.2	0.0	0.0	5.2±0.04	9.2±0.8	9.2±0.8
Maize		8.7	9.5		17.9±2.4	18.7±2.9
Mungbean		2.0	1.8		11.2±1.6	11.0±1.7
Sesame		0.0	0.0		9.2±0.8	9.2±0.8
Sunflower		7.5	7.7		16.7±1.8	16.9±1.9
2012-13						
Chili	4.5±0.1	5.5	n/a	4.0±0.1	14.0±0.8	
Maize		9.3	8.7		17.8±2.9	17.2±2.6
Mungbean		4.3	3.2		12.8±0.3	11.7±0.7
Sesame		2.5	1.7		11.0±1.1	10.0±1.5
Sunflower		7.5	7.9		16.0±1.9	16.4±2.1
Watermelon		22.2	11.6		30.7±10.3	20.1±4.3
2013-14						
Chili	4.8±0.2	3.5	3.1	3.6±0.1	11.9±0.7	11.5±0.9
Maize		9.2	9.1		17.6±2.9	17.5±2.9
Mungbean		2.3	1.3		10.7±1.2	9.7±1.8
Sesame		1.8	1.5		10.2±1.5	9.9±1.7
Sunflower		7.9	7.7		16.3±2.2	16.1±2.1
Watermelon		14.8	4.2		23.3±6.1	12.6±0.6

[1]Mean of three varieties

[2] In 2011-12 chili and sesame were damaged due to excess rainfall; in 2012-13 chili yield in no-mulch plots was not recorded

3.6.2 Kismatfultola/Hatbati

Aman-boro. Annual system production ranged from 4.7 to 10.5 t/ha and was strongly affected by *boro* sowing date (Table 20). The most consistent system was with *boro* sown on 10 November, with system yield ranging from 8.8 to 10.2 t/ha over the three years.

Table 20. Annual *aman-boro-aus* system yield at Hatbati/Kismatfultola

Year	Aman (t/ha)	Boro (t/ha)			Total rice yield (t/ha/yr)			
		10-Nov[1]	30-Nov	20-Dec	10-Nov	30-Nov	20-Dec	Mean
2011-12	4.2	4.6	5.9	6.3	8.8±0.2	10.1±0.9	10.5±1.1	9.8±0.5
2012-13	4.7	4.9	0.0[2]	0.0[2]	9.6±0.1	4.7±2.4	4.7±2.4	6.3±1.6
2013-14	5.7	4.6	1.7[2]	0.0[2]	10.3±0.6	7.4±2.0	5.7±2.9	7.8±1.3
Mean	4.9	4.7	2.5	2.1	9.6±0.1	7.4±1.2	7.0±1.4	8.0±0.8

[1] *Boro* sowing date

[2] Crop seriously affected/destroyed due to low temperature and high irrigation water salinity

Aman-rabi. Annual system REY ranged from 5.2 to 8.9 t/ha, and systems with mungbean (5.9 to 8.9 t/ha) had slightly higher yield than with sesame (5.2 to 7.3 t/ha) (Table 21). Thus REY of the best *aman-rabi* systems was slightly lower than that of the best *aman-boro* systems.

Table 21. Annual *aus-aman-rabi* system yield at Hatbati/Kismatfultola

Rabi crop[1]	*Aman* (t/ha)	*Rabi* rice equivalent yield (t/ha)		Total system rice equivalent yield (t/ha)	
		Minimum	Maximum	Minimum	Maximum
2011-12					
Mungbean	4.5	1.4 (M1[2])	4.4 (M5)	5.9±1.5	8.9±0.03
Sesame		0.7 (M1)	2.8 (M3)	5.2±1.9	7.3±0.9
2013-14					
Mungbean	4.7	2.9 (M1,2,4)	4.0 (M5)	7.6±0.9	8.7±0.4
Sesame		0.8 (M2)	1.2 (M1,5)	5.5±2.0	5.9±1.8

[1]All 2012-13 *rabi* crops destroyed by cyclone in May, due to late establishment

[2]M_1 = Farmer practice (farmers' variety, broadcast onto dry cultivated soil, no fertilizer, manual weeding)

M_2 = M_1 + line sowing

M_3 = M_2 + fertilizer + irrigation (no irrigation in 2013-14 due to fresh water scarcity)

M_4 = M_3 + mulch (5 t/ha of rice straw)

M_5 = M_4 + improved variety (BARI mung 6, BARI til4)

M_6 = M_5 no mulch (in 2012-13 and 2013-14 only)

4. Discussion

Cropping system intensification in the coastal zone of Bangladesh has been limited by the misperception that the river water is too saline for irrigation throughout the coastal zone. In reality, most of the rivers in the south-central coastal zone (Barisal Division) remain non-saline throughout the year, while the rivers in Khulna District are suitable for irrigation from July to mid-February i.e., for the first couple of months of the dry season (Khan and Kamal 2015). Our findings on salinity in the *khals* in polders 43/2/F and 30 are consistent with this. There is also the misperception that modern, high yielding *aman* varieties (HYV) cannot be grown in the coastal zone, whereas there are significant areas of medium-high lands on which flooding depth is not too high for HYV. Furthermore, in the polders, systematic operation of the sluice gates to enable drainage of excess water at low tide and separation of lands of different elevation could enable the production of HYV *aman* over large areas (Mondal et al. 2015).

The results of the work presented above clearly demonstrate the feasibility of intensifying to high yielding *aus-aman-boro* and *aus-aman-rabi* cropping systems in the south-central coastal zone of Bangladesh. Here, triple rice cropping can produce about 15 t/ha/yr in comparison with current farmer production of 3 to 6 t/ha of rice, and 0-1 t/ha of *rabi* crops such as grass pea. Alternatively, high yielding or high value *rabi* crops such as maize and sunflower can be grown instead of *boro*, with total rice equivalent yield (REY) similar to or slightly higher than that of the triple rice system. Intensification and diversification to a wide range of *rabi* crops provides further more productive options than current practice.

The results also demonstrate the feasibility of adoption of high yielding *aman-boro* cropping systems in areas where fresh water is limited in the dry season (such as Khulna District). In such areas river water can be brought in through the sluice gates at high tide for irrigation directly from the river from November until early to mid-February. The final intake of river water should take place in early February, after which the gates should be closed to store the water for irrigation by pumping from the *khals*. In the medium salinity area, 'early' (10 Nov) sowing of *boro* was critical for consistently high *boro* yields and thus system yields of 9 to 10 t/ha, compared with current farmer production of about 3 t/ha of *aman* rice and 0-1 t/ha of sesame (or mungbean). Use of improved production techniques ('early' (timely) sowing, sowing in lines, and use of improved varieties, fertilizer, irrigation) increased the productivity of sesame and mungbean, but not beyond 1 t/ha. However, others (Rahman et al. 2015) have also shown the viability of high yielding or high value crops such as maize and sunflower in this medium salinity area, which would further increase rice equivalent system yield.

A key requisite to enable the cultivation of many high yielding and high value *rabi* crops is 'early' (timely, mid-November) harvest of the *aman* crop and drainage in early November if there is still water present. Early drainage is essential to allow suitable conditions for harvest of the *aman* crop and to allow the soil to dry sufficiently for timely *rabi* crop establishment. Early *aman* harvest means growing modern non-photoperiod sensitive short to medium duration *aman* varieties instead of the current practice of late maturing, photoperiod sensitive traditional varieties. This in turn means the need for drainage of water at low tide when field water depth is too high for HYV (following excessive rainfall), and prior to topdressing N fertilizer. Late establishment results in damage or destruction of the traditional *rabi* crops by pre-monsoon rainfall and cyclones in May, as happened in 2013. Similarly, impaired productivity and destruction of sunflower and maize can occur when establishment is delayed (Rahman et al. 2015).

Successful production of traditional *rabi* crops (sesame and mungbean) in medium salinity areas like Kismat Fultola currently depends very much on rainfall – too little, or too much at the wrong times—and thus production is highly risky and varies greatly from year to year. Better management to allow timely establishment and capitalize on stored soil moisture, and storage of fresh water for irrigation later on, would be beneficial.

5. Conclusions

The results show that it is possible to greatly increase cropping system productivity in low and medium salinity regions of the coastal zone, using improved rice and *rabi* varieties and good water management – in particular, drainage after excessive rainfall during the monsoon season to enable the cultivation of high yielding, early maturity *aman* varieties. In the south-central coastal zone where fresh water was available throughout the year, triple rice system productivity of 13 to 17 t/ha was achieved in farmers' fields using short duration, high yielding *aus* varieties followed by short to medium duration HYV *aman* and a medium duration *boro* variety sown in mid-November to mid-December. Similar or higher system rice equivalent yields were achieved by replacing the *boro* crop with maize, sunflower and watermelon sown in early December

In moderately saline areas in Khulna District, freshwater is limited to the first couple of months during the dry season. Here, 9 to 10 t/ha of rice were produced in an HYV *aman-boro* system with sowing of the *boro* crop in early November.

Since cropping intensity and productivity in other parts of Bangladesh are already high, the under-utilized agricultural lands of the coastal zone may well be the only region where significant gains in food production can be made to address future challenges to the food security of Bangladesh.

Acknowledgements

This paper presents findings from 'G2: Productive, profitable and resilient agriculture and aquaculture systems', a project of the CGIAR Challenge Program on Water and Food. The authors are grateful for high quality technical assistance from Swapan Bhadra, Amal Ray, Lincoln Ray, Tanmoy Ray and Mithun Ray.

References

Bangladesh Agricultural Research Council (BARC) 2008. Estimation of Fallow Land Area and Crop Production Plan for Barisal, Pirojpur, Jhalakati, Bhola, Patuakhali and Bagerhat Districts. A report submitted to the Ministry of Agriculture, Govt. of Bangladesh. May 2008. (In Bangla).

Bangladesh Agricultural Research Council (BARC) 2012. Climate and land resources information database. http://www.barcapps.gov.bd/dbs/index.php?t=ym_temphttp://www.barcapps.gov.bd/dbs/index.php?t=ym_temp (last accessed 28 December 2014)

Bangladesh Agricultural Research Institute (BARI) 2006. *Krishi projucti hatboi* (Handbook of Agro-Technology - in Bangla) 4th edition. BARi, Gazipur, Bangladesh

Bangladesh Bureau of Statistics (BBS) 2010.Census of agriculture 2008. Ministry of Planning, Dhaka, Bangladesh.

Bangladesh Bureau of Statistics (BBS) 2011. Statistical year book of Bangladesh 2012. Ministry of Planning, Dhaka, Bangladesh.

Bangladesh Rice Research Institute (BRRI) 2010. Adhunik dhaner chas (Modern rice cultivation - in Bangla). BRRI, Gazipur,Bangladesh.

Bangladesh Rice Research Institute (BRRI) 2013. Adhunik dhaner chas (Modern rice cultivation - in Bangla). BRRI, Gazipur,Bangladesh.

Bhattacharya, J., Mondal, M.K., Humphreys, E., Saha, N.K., Rashid, M.H., Paul, P.C. and Ritu, S.P. 2015.

Rice-rice-*rabi* cropping systems for increasing the productivity of low salinity regions of the coastal zone of Bangladesh. These proceedings.

BRAC 2011. Crop intensification for achieving food self-sufficiency in the coastal regions of Bangladesh. Final Narrative Report (January 2010-October 2011) submitted to the Eureopean Union (EU), December 2011.

Kabir, K. A., Karim, M., Shahrier, M.B., Saha, S.B., Chakraborty, S., Jharendu, P. and Phillips, M.J. 2014. Homestead farming systems in southwest Bangladesh: A survey. CPWF Working Paper Series (submitted).

Khan, Z.H. and Kamal, F.A. 2015. The Ganges coastal zone – current conditions, future projections. These proceedings.

Khan, Z.H., Kamal, F.A., Khan, M.S.H., Rahman, M., Khan, M.S.A., Khan, N.A.A.K. and Sharma, B.R. 2015. External drivers of change, strategies and future projection on surface water resources of the Ganges coastal zone of Bangladesh. These proceedings.

Ministry of Agriculture-Food and Agriculture Organization. 2013. Master Plan for agricultural development in the southern region of Bangladesh. Prepared by the Ministry of Agriculture of the Government of Bangladesh and Food and Agriculture Organization of the United Nations, Dhaka, Bangladesh, March 2013.

Mondal, M.K. 1997. Management of soil and water resources for higher productivity of coastal saline ricelands in Bangladesh. Unpublished PhD dissertation, University of the Philippines Los Baños, Philippines.

Mondal, M.K., Tuong, T.P., Ritu, S.P., Choudhury, M H.K., Chasi, A. M., Majumder, P.K., Islam, M.M. and Adhikary, S.K. 2006. Coastal water resource use for higher productivity: Participatory research for increasing cropping intensity in Bangladesh. In C. T. Hoanh, T. P. Tuong, J. W. Gowing and B. Hardy (Eds). Environmental and livelihoods in tropical coastal zones: Managing agriculture-fishery-aquaculture conflicts. Comprehensive Assessment of Water Management in Agriculture Series, no. 2. CABI Publishing p 72-85.

Mondal, M.K., Tuong, T.P., Sharifullah, A.K.M. and Sattar, M.A. 2010. Water supply and demand for dry-season rice in the coastal polders of Bangladesh. In C. T. Hoanh, B. W. Szuster, K. Suan-Pheng, A. M. Ismail and A. D. Noble (Eds.) Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land-Water Interface Comprehensive assessment of water management in agriculture series, no. 9. CABI publication: 264-278.

Mondal, M.K., Humphreys, E., Tuong, T.P., Rahman, M.N. and Islam, M.K. 2015. Community water management and cropping system synchronization: The key to unlocking the production potential of polder ecosystems in Bangladesh. These proceedings.

Rahman, M.N., Amin, M.G.A., Mondal, M.K. and Humphreys, E. 2015. Residual soil moisture utilization techniques for improving land productivity in the coastal zone of Bangladesh. These proceedings.

Ritu, S.P., Mondal, M.K., Tuong, T.P., Talukdar, S.U. and Humphreys, E. 2015. An a*us-aman* system for increasing the productivity of a moderately saline region of the coastal zone of Bangladesh. These proceedings.

Sharifullah, A., Tuong, T.P., Mondal, M.K. and D.T. Franco. 2009. Assessing water supply and demand for dry season rice in coastal polders of Bangladesh. In: Humphreys, E. and R.S. Bayot (eds). *Increasing the productivity and sustainability of rainfed cropping systems of poor smallholder farmers.* Proceedings of the CGIAR Challenge Program on Water and Food International Workshop on Rainfed Cropping Systems, Tamale, Ghana, 22-25 September 2008. The CGIAR Challenge Program on Water and Food, Colombo, Sri Lanka.

Available at:
http://r4d.dfid.gov.uk/PDF/Outputs/WaterfoodCP/CPWF_Proceedings_Rainfed_Workshop%5B1%5D.pdf (last accessed 31 December 2014)

Soil Resources Development Institute (SRDI). 2010. *Saline soils of Bangladesh*. SRMAF project, Ministry of Agriculture, Govt. of Bangladesh. Dhaka: SFSDP-SRDI Publication.

Tuong, T. P., Humphreys, E., Khan, Z.H., Nelson, A., Mondal, M., Buisson, M.C. and George, P. 2014. Messages from the Ganges basin development challenge: Unlocking the production potential of the polders of the coastal zone of Bangladesh through water management investment and reform. CPWF Research for Development Series 9. Available at:
https://cgspace.cgiar.org/bitstream/handle/10568/41708/CPWF%20Ganges%20basin%20messages%20Sept%2014.pdf?sequence=5 (last accessed 30 Dec 2014).

Optimizing use of fresh and saline water for irrigation of *boro* rice in salt affected areas of Bangladesh using the crop model ORYZA v3

A.M. Radanielson[1], O. Angeles[1], T. Li[1], A.K. Rahman[2] and D. Gaydon[3]

[1] International Rice Research Institute, Philippines a.radanielson@irri.org, o.angeles@irri.org, t.li@irri.org
[2] Bangladesh Agricultural Research Institute, Bangladesh atiksobari26@yahoo.com
[3]CSIRO Agriculture Flagship, Australia don.gaydon@csiro.au

Abstract

Salinity is estimated to affect more than 30% of the cultivated rice area in Bangladesh. With climate change, the salt-affected area is likely to expand with increasingly detrimental impact on the region's productivity. Adaptive strategies based on conjunctive use of fresh and saline water for irrigation were evaluated. Simulations of different crop management combinations were performed with a modified version of the rice crop model ORYZA v3, which included a crop salinity-response module. The model was calibrated and validated with field experimental data collected between 2012 and 2014 in Satkhira, Bangladesh and Infanta, Quezon, Philippines. The factors considered were timing and amount of fresh and saline irrigation water, date of sowing and crop growth duration. Climatic variability and changes in soil salinity were represented using historical data from 2000 to 2014 for Satkhira. ORYZA v3 demonstrated good accuracy in simulating observed rice yields. Weekly irrigation, alternating between the use of fresh and saline water (with prevailing dynamics of salinity at the experimental site in Satkhira), reduced soil salinity and increased yield in comparison with sole use of saline water. A sensitivity analysis of simulated yield suggested that: i) early sowing to escape higher salinity at flowering time resulted in higher yield; ii) using fresh water for irrigation for two weeks alternating with saline water for one week significantly reduced yield loss due to salinity compared with continuous irrigation with saline water; and iii) the use of an improved, salt-tolerant variety such as BRRI dhan47 with medium growth duration irrigated with alternate two weeks fresh water and one week saline water would result in similar yield to that of BRRI dhan47 irrigated with fresh water. Further simulations with future climate data and in other salt-affected rice growing regions would be desirable to explore the generality of the results. These could be valuable to inform the development of priorities for investment and research for effective strategies to increase rice production in salt-affected areas.

Key message: Irrigation with a mixture of fresh and saline water and the use of salt-tolerant varieties are feasible strategies to increase rice production in salt-affected areas with limited availability of fresh water.

Key words: modeling, phenology, rice, salinity, variety, water productivity

1. Introduction

Soil salinity is among the environmental factors limiting rice crop production. It affects land in coastal areas and causes loss of cultivated land of about 1.6 million ha per year worldwide (FAO, 2013). Salinity is currently estimated to affect more than 30% of the cultivated rice area in Bangladesh. With climate change, this is likely to expand with increasingly detrimental impact on the region's productivity (Wassmann et al. 2009). Improving rice productivity to address the challenge of meeting and maintaining food security for the country must effectively address the cropping systems management challenges in these areas. Among the technologies developed to alleviate the effect of salinity is the use of tolerant varieties, which could significantly increase productivity using suitable crop management (Ismail et al. 2007).

Soil salinity dynamics are among the biophysical factors driving the cropping calendar under salt-stressed conditions in Bangladesh (Gaydon et al. 2014). On one hand, the establishment of wet season rice depends on the availability of enough rain to flush the accumulated salt deeper into the soil, beyond crop roots. On the other hand, the start of dry season cropping must be as early as possible for the crop to avoid the high peak of soil salinity later in the dry season. Studies have reported that alternate use of fresh and saline water makes better use of resources under salt-stressed conditions (Beltran 1999; Flowers et al. 2005). Furthermore, with climate change, a shift in planting dates would be expected to improve rice productivity for regions such Bangladesh (Li et al., 2015). Temporal and spatial variability of salinity adds complexity in cropping management and needs suitable tools to assist in effective decision making.

Modeling provides a powerful tool for formulation of hypotheses and quantification of cropping system performance. It can provide quantitative descriptions and insights into agricultural systems. It helps to define areas where knowledge is lacking and to design more adequate and effective experiments (France and Thornley 1984). Physically-based mechanistic models or empirical models that account for meteorological conditions can give either unrealistic or realistic results, depending on the conditions under which they were developed (Eatherall 1997). Crop modeling with the ability to represent soil salinity dynamics and the variability of the rice crop response to salinity throughout its crop development could be a useful tool to efficiently study the problem of rice production in salt-affected areas and to identify optimized irrigation management.

Fresh water availability is the most limiting factor in leaching salt which has accumulated in the root zone and in maintaining soil salinity at levels suitable for crop production (Crescimanno and Garofalo 2006). Strategies for maximizing the productivity of the available fresh water would increase yield and/or allow for an increased area of land under cultivation. Such strategies require an appropriate cropping calendar and adapted cultivars, managed to avoid the high salinity peak that occurs in the later stages of crop growth during the dry season. Conventional field experiments are limited in their ability to explore different combinations of these factors.

In this work, we evaluate the conjunctive use of fresh and saline water for irrigation through modeling, aiming to reduce yield loss due to salinity and to increase fresh water productivity. The objectives are to: i) identify combinations of sowing date and irrigation water management (based on the use of alternate fresh and saline water) that maintain acceptable yield levels in salt-affected areas, and ii) evaluate the effects of growth duration of a salt-tolerant variety (with the strategies from (i)) on water productivity and rice production.

2. Materials and methods

2.1 Field experiments

2.1.1 Field experiment design

Four field experiments were performed with the genotype BRRI dhan47 during the dry seasons of 2013 and 2014, respectively. Experiments (Expts) 1 and 2 were conducted in Infanta, Quezon Philippines ($14^0 45'$N, $121^0 41'$E) and Expts 3 and 4 in Satkhira, Bangladesh ($24^0 12'$N', $90^0 12'$E) (Table 1). BRRI dhan47 is one of several recently released salt tolerant varieties used by farmers in Bangladesh, with high yield under stressed conditions (Islam et al. 2008). Each experiment had four irrigation water management treatments in a randomized block design with three replicates.

Table 1. Experiments for model calibration and validation

Experiment	Season	Site	Sowing date	Transplanting date	Flowering date[1]	Physiological maturity[1]
Expt 1	2013 Dry	Infanta	January 26 2013	February 16 2013	April 22 2013	May 21 2013
Expt 2	2014 Dry	Infanta	January 15 2014	February 4 2014	March 31 2014	April 22 2014
Expt 3	Boro 2013	Satkhira	December 20 2012	February 2 2013	April 13 2013	May 9 2013
Expt 4	Boro 2014	Satkhira	January 1 2014	2 February 2014	April 10 2014	May 6 2014

[1] Dates are for treatments irrigated with fresh water only

In Expts 1 and 2, the rice was grown under four different water management conditions: i) continuous irrigation with saline water (SW); (ii) continuous irrigation with fresh water (FW); (iii) weekly alternation between fresh and saline water (FW:SW); and two weeks fresh and then one week saline water (2FW:SW). Saline water was pumped from the river canal. The fresh water was pumped from groundwater. Bulk soil salinity at 15 cm depth from the soil surface was determined hourly using 5TE sensors (Decagon Devices, USA) installed in each plot and connected to an automatic data-logger.

In Expts 3 and 4, there were also four water management treatments. Treatments (i) and (ii) were the same as in Expts 1 and 2 (FW, SW). In treatments (iii) and (iv) fresh and saline water were mixed in different proportions, rather than alternating, as follows: (iii) equal volume of saline and fresh water (FW: SW), and (iv) 2:1 volume of fresh water and saline water (2FW:SW). Mixture of the saline and fresh water was achieved by irrigating the field with saline water the first half (or two thirds) of the duration of the irrigation and then with fresh water. Soil salinity was measured with a portable EC meter for one replicate per treatment.

In both experiments, the plots were irrigated regularly to maintain a ponded water depth of about 2 to 3 cm minimum and 10 cm maximum. The salinity of both fresh water (from farm dam) and saline water (from river or canal) varied throughout the season (Table 2). In Expts 1 and 2, water salinity was about 0.49 and 5.5 dS m^{-1} respectively for the fresh and saline water. In Expts 3 and 4, salinity of the fresh water ranged from 0.65 to 1.88 dS m^{-1} with no significant variation during the crop period. Salinity of the saline water ranged from 1.96 to 8.13 dS m^{-1} and increased with time, reaching a maximum around flowering time (Table 2).

Table 2. Salinity of the fresh and saline water in Expts 3 and 4

Water	Experiment	Sowing time	Transplanting	Panicle Initiation	Flowering
Fresh water	Expt3	0.65	0.82	1.36	1.88
	Expt4	0.85	0.92	1.17	1.48
Saline water	Expt3	1.36	2.12	5.03	8.13
	Expt4	1.96	2.02	4.24	6.43

2.1.2 Field experiment management

The fields were puddled prior to transplanting. The age of seedlings at the time of transplanting was 21, 35, 44 d for Expts 1 and 2, Expt 3, and Expt 4, respectively (Table 1). Two to three and three to five seedlings per hill were transplanted at a spacing of 20 cm x 20 cm in Expts 1 and 2 and in Expts 3 and 4, respectively. Fertilizers were applied at the recommended rates and times for each site. The plots were kept weed free and pests and diseases were well controlled in all experiments.

2.1.3 Field experiment monitoring

Water salinity and soil salinity were determined before and after each irrigation event, and otherwise weekly. An automated weather station was installed near the fields to record rainfall, air temperature, relative air humidity and solar radiation on an hourly basis.

Biomass sampling was performed at key stages according to the data requirement of ORYZA v3 for model calibration and validation (Bouman et al. 2001). Crop grain yield and total above-ground biomass (WAGT) were measured from two sampling locations (six hills per location, total sampled area about $0.48m^2$) in each plot. Grain yield was determined on an area of 5 m^2 harvested from the middle of each plot, and is reported at 14% moisture content.

2.2 Crop model calibration

A version of the rice crop model ORYZA v3 (IRRI 2014) that includes a new module to account for the effects of salinity on rice growth was used in this study (Radanielson et al. 2015). ORYZA v3 is a rice simulation model offering the potential to identify production constraints and optimal management regimes related to nitrogen application, water management and crop scheduling (Bouman et al. 2001). Parameters related to salinity responses are variety-specific as described in Radanielson et al. (2013). The two components of salinity effect (osmotic stress and ion toxicity stress) are considered in the model. Osmotic stress is taken into account through an equation converting soil salinity into soil osmotic potential, reducing water uptake by the crop. Responses to salt accumulation into the plant are represented through a stress factor described with a logistic function with two genotypic parameters (Radanielson et al. 2013). The factor is applied to the maximum plant photosynthesis rate and the transpiration rate of the plant.

The model parameters of BRRI dhan47 for crop phenological development rate were computed using the phenology recorded from each salinity treatment in all four experiments. Other crop parameters for the model were calibrated using data from the treatments continuously irrigated with fresh water for the two years using the auto-calibration application of ORYZA v3 (IRRI 2014), assuming non-limited environmental growth conditions at each site (Table 2).

Statistical criteria for the calibration were set aiming to minimize the deviation between the simulation outputs and the observed values for the variables “total above-ground biomass (WAGT)” and “grain yield” for the non-stressed (FW) conditions. As we assumed that salinity responses are variety specific, parameters related to salinity responses were not calibrated but given as inputs to the model. These parameters were estimated from greenhouse experiments characterizing the salinity responses of BRRI dhan47 (Radanielson et al., 2013). The auto-calibration tool for ORYZA v3 was set to calibrate parameters related to biomass partitioning and leaf area expansion.

Table 3. Data use for model validation

	Experiment	Treatment	Variety	Site	Years
Calibration	Expts 1, 2, 3, 4	FW	BRRI dhan 47	Infanta Satkhira	2013-2014
Validation	Expts 1, 2, 3, 4	SW, FW:SW, 2FW:SW	BRRI dhan 47	Infanta Satkhira	2013-2014
Simulation		FW, SW, FW:SW, 2FW:SW	BRRI dhan47 with Long duration growth, BRRI dhan47 with medium duration growth, BRRI dhan47 with short duration growth	Satkhira	2000-2014

Note: SW, irrigation with saline water; FW:SW, irrigation with alternate one week fresh and one week saline water in Expts 1 & 2 and irrigation with a mixture of 1:1 volume of fresh and saline water in Expts 3 & 4; 2FW:SW, irrigation with two weeks fresh water and one week saline water in Expts 1& 2 and a mixture of volume 2:1 of fresh and saline water in Expts 3 & 4.

2.3 Crop model validation

The ability of the model to represent the observed crop behavior in Expts 1 to 4 was evaluated by comparing the simulated and observed values of total above ground biomass (WAGT) and rice yield of the saline water treatments at all sites (Table 3). Input values of the model parameters for development rate were different for each simulated treatment to inform the simulation of the crop phenology variability under salt stress in ORYZA v3. Similarly, measured values of soil EC in all four experiments were used as input data in the model.

Linear regression was used to compare paired data points for measured and simulated above-ground biomass and grain yield. The slope (α), intercept (β), and coefficient of correlation (R^2) of the linear regression were computed using the ORYZA Analysis Tools (IRRI 2014). The model performance was assessed using the Student's t test of means assuming unequal variance P(t) and using the absolute square normalized root of the mean squared error, $RMSE_n$, which was calculated as follows:

$$RMSE_n = \frac{\sqrt{\sum_{i=1,n}(S_i - O_i)^2}}{n\mu} \quad (3)$$

where S_i and O_i are simulated and observed values, respectively, and n is the number of pairs; μ, the overall mean of the observed values. The index of model agreement (ID) was also used as a measure of the models performance, calculated as follows:

$$ID = 1 - \left[\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(|S'_i| - |O'_i|)^2}\right] \quad (4)$$

where S_i and O_i are simulated and observed values, respectively; S'_i and O'_i are the difference between the simulated and observed values with the overall mean of the observed values; n is the number of pairs.

2.4 Model simulation scenarios

Simulations of different crop management combinations were performed with the modified version of the rice crop Model ORYZA v3 integrating a salinity module (Radanielson et al. 2013). Eleven dates of sowing were imposed at seven-day intervals, from December 1 to February 8. The model validation was carried out with experiments established between the end December and early January. This window of cropping accounted for the usual late December harvesting of the preceding T. *Aman* rice and allowed sufficient drainage of the field. Six virtual varieties were used. They were characterized with the potential rice production of the variety BRRI dhan47, however each with different phenology parameters to create short, medium and long duration growth types with the salinity tolerance characteristics of BRRI dhan47. Irrigation was managed as per the field experiments. The impact of climatic variability was evaluated using historical climate data from 2000 to 2014 for Satkhira.

2.5 Data analysis

Simulation outputs considering virtual salt tolerant varieties, use of fresh and saline water, and date of sowing, were analysed with a general linear regression model using R software (R Development Core Team 2008). Mean and standard deviation values over the 15 years of simulation were computed to evaluate variability among factors.

WAGT, yield, transpired water productivity and irrigation water productivity were the variables considered. Transpired and irrigation water productivity were calculated as the ratio of grain yield to the amount of water transpired or applied, respectively (kg ha^{-1} mm^{-1}).

Table 4. Statistics for comparison of observed and simulated WAGT and yield for the two sites

	Sites	Variables (kg ha^{-1})	n	P(t*)	β	α	R2	RMSE	RMSEn %	ID
Calibration	Infanta	WAGT	10	0.93	-64.34	1.01	0.97	573	14.96	0.98
		Yield	4	0.17	454.07	0.97	0.95	527	20.19	0.91
	Satkhira	WAGT	12	0.88	-97.26	1.08	0.99	839	13.88	0.98
		Yield	6	0.54	-75.02	1.08	0.76	697	13.10	0.99
Validation	Infanta	WAGT	11	0.69	12.77	1.15	0.98	806	24.77	0.92
		Yield	3	0.82	1530	0.72	1	176	3.18	0.93
	Satkhira	WAGT	19	0.38	-233.48	0.89	0.81	1116	31.84	0.68
		Yield	9	0.79	158.66	0.97	0.85	265	11.85	0.79

Note: *n*, number of data pairs; P(t^*), significance of Student's paired t-test assuming non-equal variances; α, slope of linear regression between simulated and measured values; β, y-intercept of linear regression between simulated and measured values; R^2, square of linear correlation coefficient between simulated and measured values; RMSE, absolute root mean squared error; $RMSE_n$, RMSE normalized by X_{obs} as a percentage; ID, model index of agreement; WAGT, above-ground biomass.

3. Results and discussion

3.1 Model validation for crop growth

BRRI dhan47 was characterized with duration of 90 d after transplanting (DAT) of 29 d old seedlings, and a flowering time of 64 DAT. The crop duration in Expt 1 was longer than in Expt 2 (Table 1) due to uncontrolled flooding for 5 to 7 days starting the day after transplanting. In Expt 3, the total crop growth duration is the longest due to the use of old seedlings of about 44 d.

Crop growth duration was reduced by 4 to 6 d under the stressed conditions with salinity up to 8 dS m^{-1}, similar to the findings of Castillo et al. (2007).

Simulated and observed values for WAGT were generally in good agreement under continuous fresh water irrigation (Table 4). The model index of agreement was higher than 0.95 with RMSE ranging from 527 to 697 kg ha^{-1}.

Table 5. Analysis of variance for simulated yield by ORYZA v3 for the site in Satkhira.

Factors	Df	SSE	MSE	Fvalue
Sowing	10	1987544038	198754404	189.63 ***
Irrigation	E 3	2447742453	815914151	778.45 ***
Variety	2	867936955	433968478	414.04 ***
Year	13	334952216	25765555	24.58 ***
Sowing x Irrigation	30	181603652	6053455	5.77 ***
Variety x Irrigation	6	347892173	57982029	55.32 ***
Error	4816	5047780741	1048127	

Root mean square errors for yield (421 to 785 kg ha^{-1}) were in the range of the error of the observed values, suggesting acceptable performance of the model. A similar range of RMSE values was reported for the ORYZA2000 rice crop model in a broader analysis (Bouman and van Laar 2006). The model presented good accuracy in simulating the observed rice WAGT and yields for BRRI dhan47 after calibration of the model crop parameters related to leaf growth and biomass partitioning.

Model performance in simulating rice crop development and growth under saline conditions was also generally acceptable, with an RMSE of 806 to 1710 kg ha^{-1} for above-ground biomass and 176 to 286 kg ha^{-1} for yield. Over all sites and seasons, an $RMSE_n$ of 12.3% was obtained for yield. Simulated above-ground biomass in Expts 3 and 4 had a much higher $RMSE_n$ (31.8%) than at Infanta due to underestimation of the salt stress at this site. Initial soil salinity was not considered as the model was run under no salt stress during calibration. For irrigation with various amounts of saline water, the regression of simulated against observed grain yield had an r^2 of 0.61 (P<0.001). Overall, the results presented acceptable ability of the model to simulate rice growth and yield in response to water irrigation management options that affect soil salinity (Table 4, Fig.1). The results were comparable with the results of simulations in the Mekong delta using ORYZA2000 (Tuong et al. 2003), in which the authors represented the effect of salinity by reducing water availability for the crop. By considering the effect of salinity on water availability and crop biomass production a significant improvement in model accuracy was obtained.

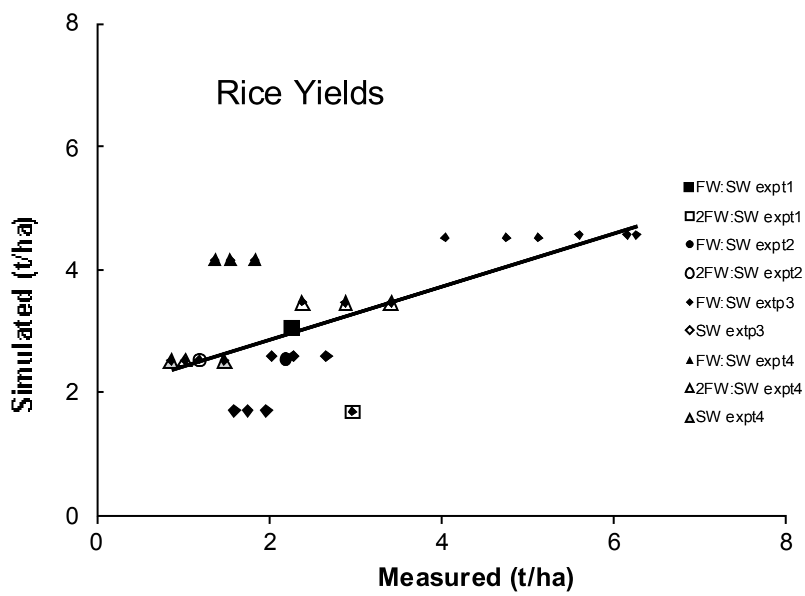


Fig. 1. Simulated and observed rice biomass under salt stress. Each point represents measured and simulated values from irrigation treatments in Expts 1 to 4. The line represents the regressed linear relationship between observed and simulated values. SW, irrigation with saline water; FW:SW, irrigation with alternate one week fresh and one week saline water in Expts 1 and 2 and irrigation with a 1:1 mixture of fresh and saline water in Expts 3 and 4; 2FW:SW, irrigation for two weeks with fresh water and one week with saline water in Expts 1 and 2 and a mixture (by volume) of 2:1 of fresh:saline water in Expts 3 and 4.

3.2 Effect of irrigation management on soil salinity and yield reduction

Yields were highest with continuous irrigation with fresh water, and least with continuous irrigation with saline water (Fig. 3). The use of alternate irrigation with fresh and saline water had a significant effect on soil salinity at each site in comparison with irrigation with fresh or saline water alone. Alternating one week each of fresh and saline water reduced soil salinity by 30% to 40% compared with irrigation only with saline water at Infanta (Figs 2a,b). At Satkhira, a 2:1 mixture of fresh and saline water reduced salinity by 45% and delayed the occurrence of salinity >4 dS m^{-1} by 4 to 5 d compared to the use of continuously saline water (Figs 2c,d). Using a combination of fresh and saline water has previously been shown to mitigate the build-up in soil salinity in crop production (Malash et al., 2005; Rezaei et al., 2011). In Satkhira, the continuously increasing soil salinity was a result of the increasing salinity of the river water as the dry season progress.

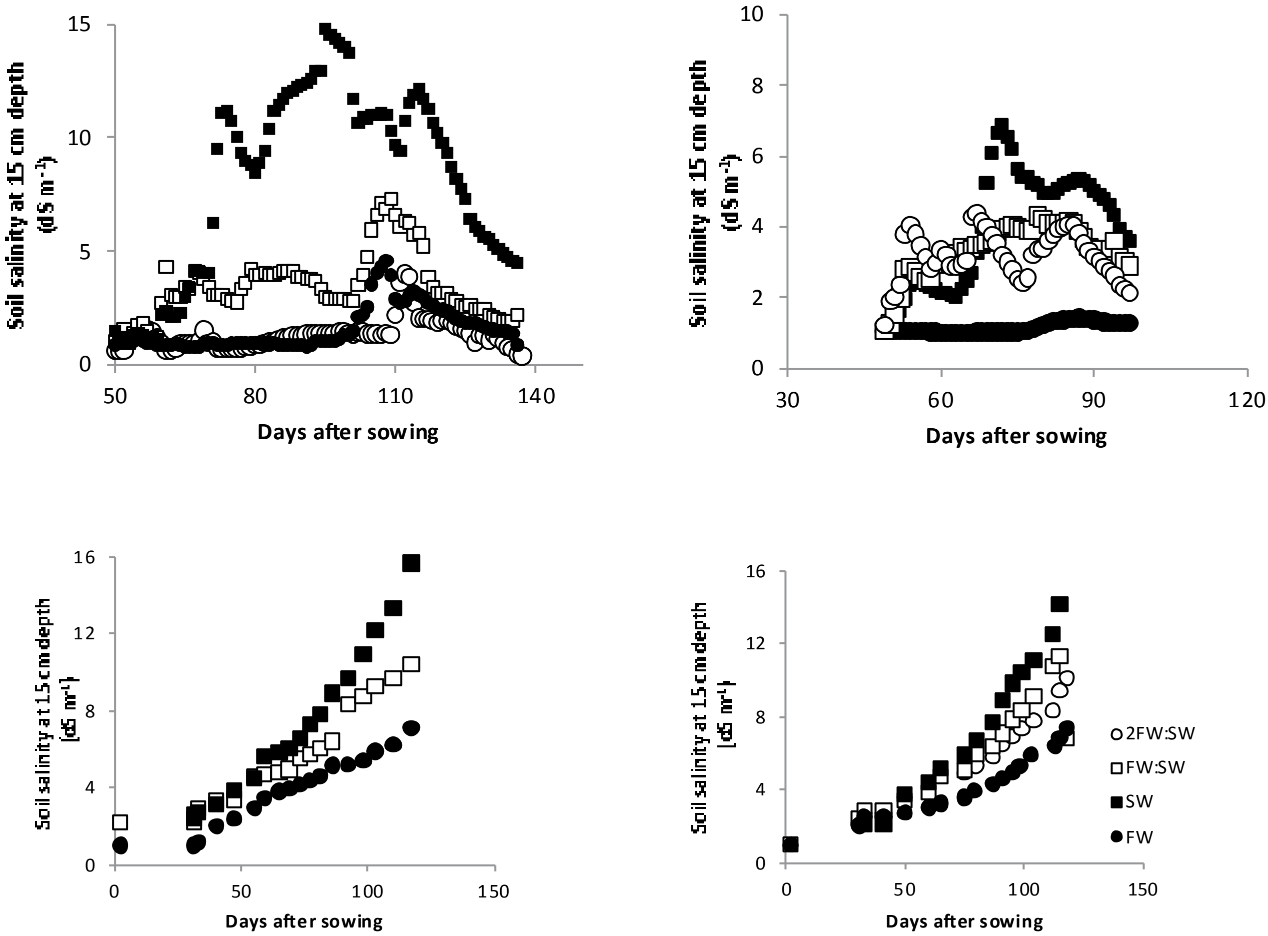


Fig. 2. Soil salinity dynamics measured at 15 cm of soil depth. Each point represents the mean value of three measurements taken at different points from the plots of the field in Expt 1 (a), Expt 2 (b), Expt3 (c) and Expt 4 (d). FW, irrigation with fresh water; SW, irrigation with saline water; FW:SW, irrigation with alternate one week fresh and one week saline water in Expts 1 and 2 and irrigation with a mixture of 1:1 volume of fresh and saline water in Expts 3 and 4; 2FW:SW, irrigation with two weeks fresh water and one week saline water in Expts 1 and 2 and a mixture of volume of 2:1 of fresh and saline water in Expts 3 and 4.

The mean observed yield over the two seasons was about 3500 kg ha^{-1} and significant differences were observed between seasons and the sites. Yield variability was driven by variability in both soil salinity and weather condition (data not presented).

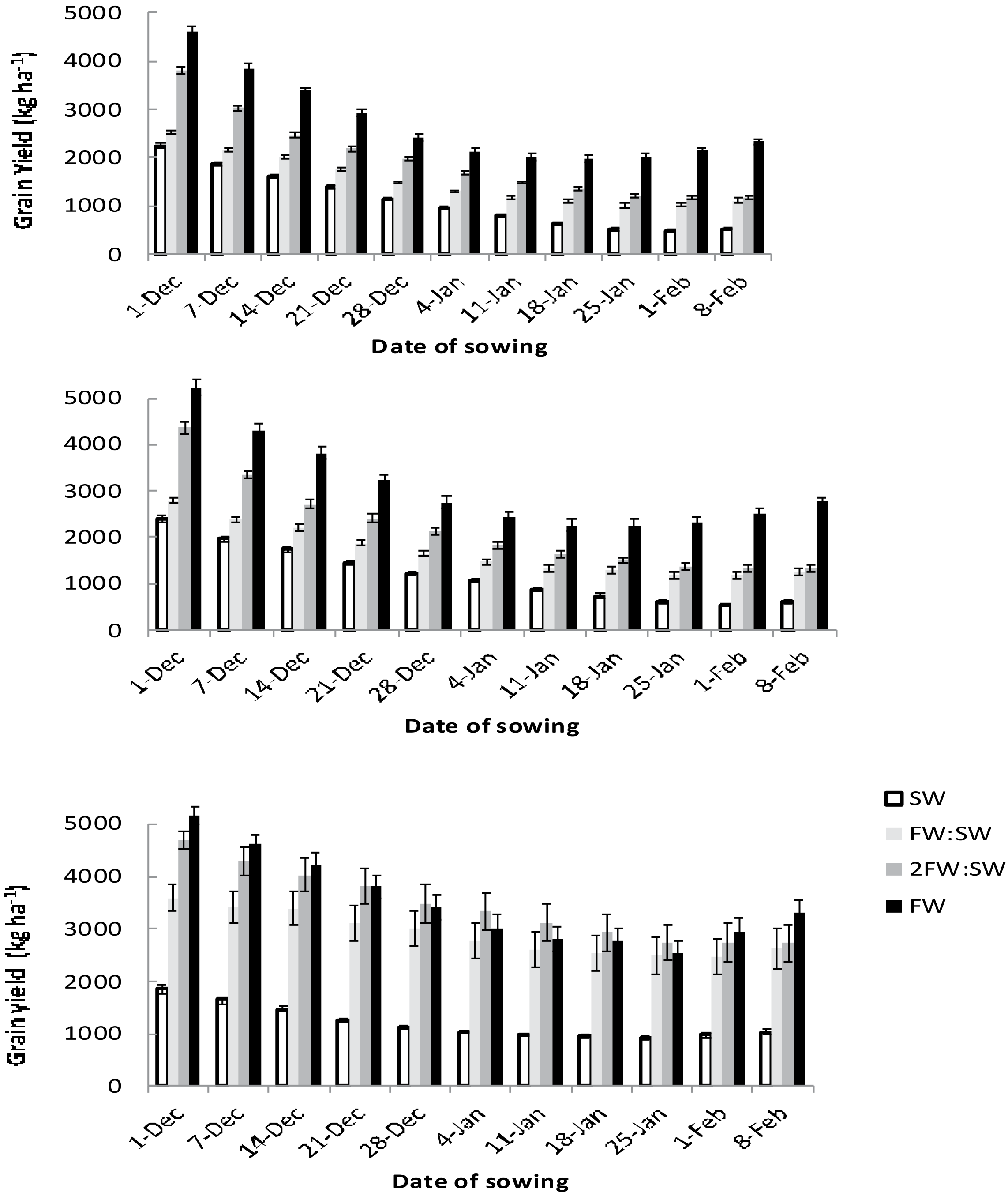


Fig. 3. Variability (2000-2014) of simulated yield among varieties, date of sowing and water irrigation management for Satkhira, Bangladesh. Each bar represents an average value of the outputs simulated by ORYZA v3 over the 15 years under the 11 sowing dates and three groups of virtual varieties: a) variety with short growth duration; b) variety with medium growth duration; c) variety with long growth duration; SW, irrigated with saline water; FW, irrigated with fresh water; FW:SW, irrigated with alternate one week fresh water to one week saline water; 2FW:SW, irrigated with alternate two weeks fresh water to one week saline water.

3.3 Optimized cropping calendar and irrigation management for yield improvement at Satkhira

Simulated grain yield from 2000 to 2014 at Satkhira presented large variability with an o-efficient of variation of about 67% over the 15 years of simulation and the factors considered (Fig. 1). The effects of irrigation management, date of sowing and variety (crop growth duration) on simulated yield were significant (Table 4). The interaction between irrigation management, date of sowing and variety was also significant, suggesting that a combination of these factors to optimize rice productivity would be possible. Minimum and maximum mean yields were 492 kg ha^{-1} and 5228 kg ha^{-1} respectively, corresponding to a short duration variety sown on February 1 and irrigated with saline water, and a medium duration variety sown on December 1 and irrigated with fresh water (Fig. 3).

With December 1 sowing and irrigation with fresh water (FW), simulated yields of all varieties were similar (Fig 3). Yield of the long duration variety sown on this date and irrigated with a 2:1 mixture of fresh and saline water (2FW:SW) was also similar to yield of the former group. The combination of December 1 sowing x long duration variety x irrigation with 2FW:SW could be an option to minimize yield loss under shortage of fresh water in salt affected areas. The highest simulated yield with continuous irrigation with saline water (SW) occurred with a medium duration variety sown on the same date (Fig. 3). The recommended date for higher yield for *boro* rice in the coastal zone is earlier than this date considering the *boro* crop alone (Mondal et al. 2010, 2015). However, the feasibility of earlier sowing would depend on harvest date of the previous crop. Further simulation in cropping sequence would be needed to confirm the earliest date in optimizing annual system rice production.

Earlier times of sowing allowed avoidance of high soil salinity and cold temperature stress at flowering time, which resulted in higher grain yield. The use of alternating fresh and saline water for irrigation (two weeks to one week) or the 2:1 mixture reduced the yield loss due to salinity significantly. The use of a tolerant variety with medium growth duration in this condition would result in similar yield as the non-stressed condition with a long duration crop while reducing the use of fresh water for irrigation by 50%.

Yield increased with crop duration within sowing date x irrigation management combinations (Fig.3).

3.4 Water productivity

In term of transpired water productivity (WP), the medium duration variety performed the best, with a value of 16.26 kg $ha^{-1}mm^{-1}$ for crops sown on February 8 and irrigated continuously with fresh water (Fig. 4). Under irrigation with continuously saline water, transpired WP of the long duration variety sown on the same date presented a higher value of 28.37 kg $ha^{-1}mm^{-1}$. Under salt stress, plant responses to the stress corresponded firstly to a reduction in transpiration rate occurring at a lower level of salinity. Plant photosynthesis rate decreases secondly after accumulation of salt in the plant and at higher salinity (Munns et al. 1995). This conservation strategy increased the productivity of the transpired water by the crop under stress and would explain the simulated higher values of transpired WP under irrigation with continuously saline water.

Crops growing under fresh water had the highest value of water productivity due to higher yield, particularly for crops sown after January 11 (Fig. 4). Lowest transpired water productivity was observed for the short duration variety sown on January 25 and continuously irrigated with saline water (4.72 kg $ha^{-1}mm^{-1}$). This combination also had the lowest grain yield due to increasing soil salinity between the end of February and early March. This period corresponds to the panicle initiation stage. Soil salinity during this period exceeded 4 dS m^{-1}, the threshold salinity above which rice growth and yield are impaired (Zeng and Shannon 2000; Gaydon et al. 2014). Continuous irrigation with fresh water resulted in much lower soil salinity during this period, preventing yield loss. Yield of the crops irrigated with a mixture of fresh and saline water was significantly lower as soil salinity remained moderate to high, affecting the crop growth during the sensitive reproductive stage. In our simulation the use of older seedlings reduced the sensitivity of the crops to salinity during early stages. Crops sown after January 11 were exposed to higher salinity during seedling stage.

Late sowing (after January 25) reduced irrigation requirement by about 30% compared to early sowing (before December 8) with, respectively, means of 1051 mm and 730 mm over all irrigation water management, varieties and years. This was associated with an increase in in-season rainfall as sowing was delayed. Crop duration and irrigation treatment also had significant effects on the amount of irrigation water applied. The long duration crop irrigated continuously with fresh water had the highest irrigation requirement (1024 mm). The lowest value was observed for the same variety under irrigation with continuously saline water (790 mm).

These values are in the range of amounts reported for rice under non-stressed and stressed conditions (Zwart and Bastiaanssen 2004; Yadav et al., 2012).

The three factors had significant effect on the variability of irrigation water productivity. There was no significant interaction between crop duration and irrigation management on irrigation water productivity. Irrigation water productivity of the short duration variety was highest with saline water irrigation and sowing on February 8. Irrigation water productivity considering the amount of fresh water applied has presented the same trends with a mean value of 2.67 kg ha^{-1} mm^{-1}. Higher irrigation water productivity was observed for long duration crop sown on and after January 25 and irrigated with a mixture of 1:1 ratio of saline and fresh water, with the maximum value of 6.31 kg $ha^{-1}mm^{-1}$ (fig. 5). The minimum value, observed for the short growth duration variety irrigated with a mixture volume of 2:1 of fresh and saline water, was about 0.95 kg $ha^{-1}mm^{-1}$ sown on January 25 (Fig. 5).

This strategy of minimizing salinity effect through the use of fresh water and saline water in irrigation could represent an opportunity to expand the cropped area in salt-affected regions. Production of cropping systems in these conditions could be raised by 30 to 40% as observed in the experiments with better use of fresh water.

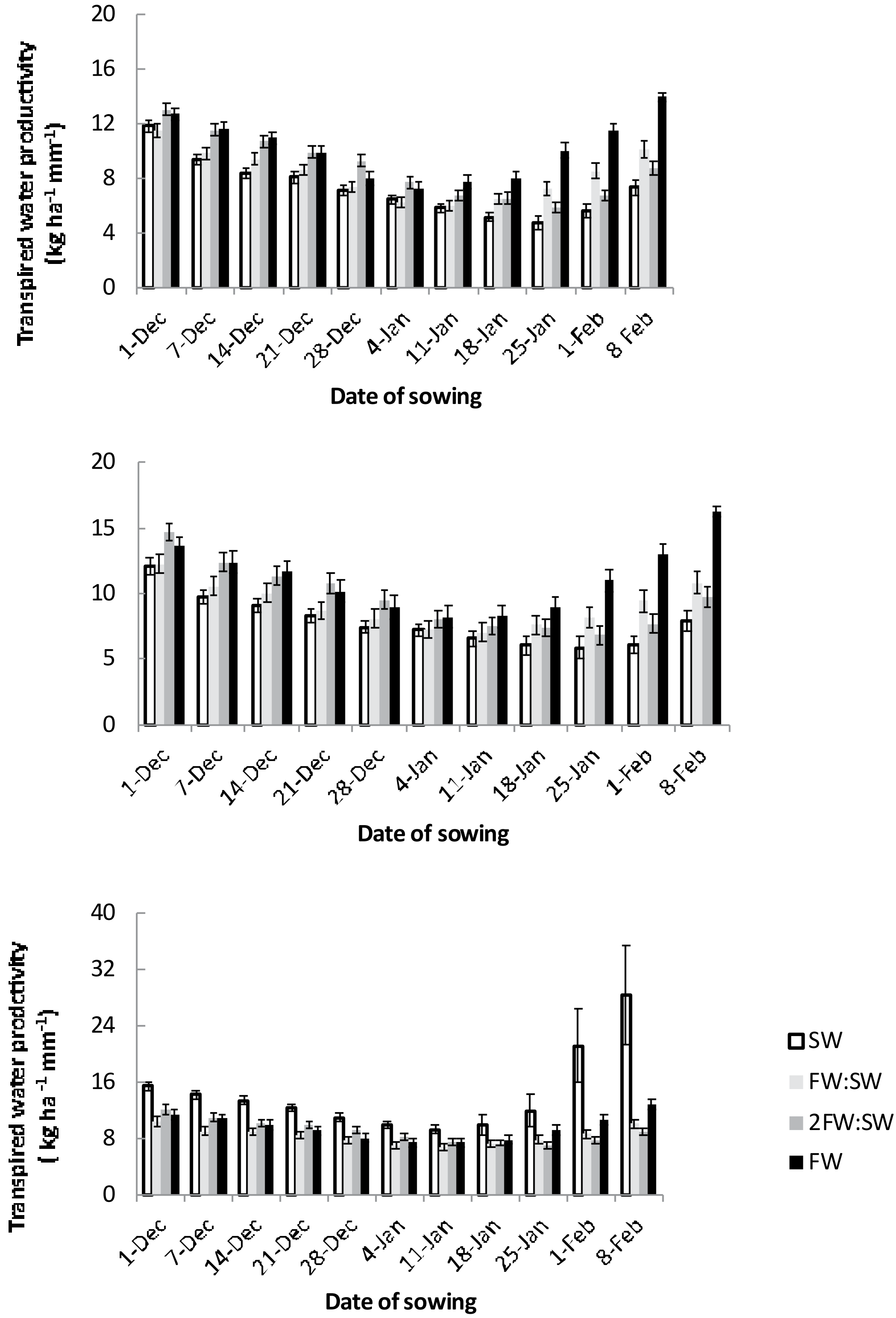


Fig. 4. Variability (2000-2014) of transpired water productivity among varieties, date of sowing and water irrigation management for Satkhira, Bangladesh. Each bar represents an average value of the outputs simulated by ORYZA v3 over the 15 years under the 11 sowing date and three groups of virtual varieties: a) variety with short growth duration; b) variety with medium growth duration; and c) variety with long growth duration; SW, irrigated with saline water; FW, irrigated with fresh water; FW:SW, irrigated with alternate one week fresh water to one week saline water; 2FW:SW, irrigated with alternate two weeks fresh water to one week saline water.

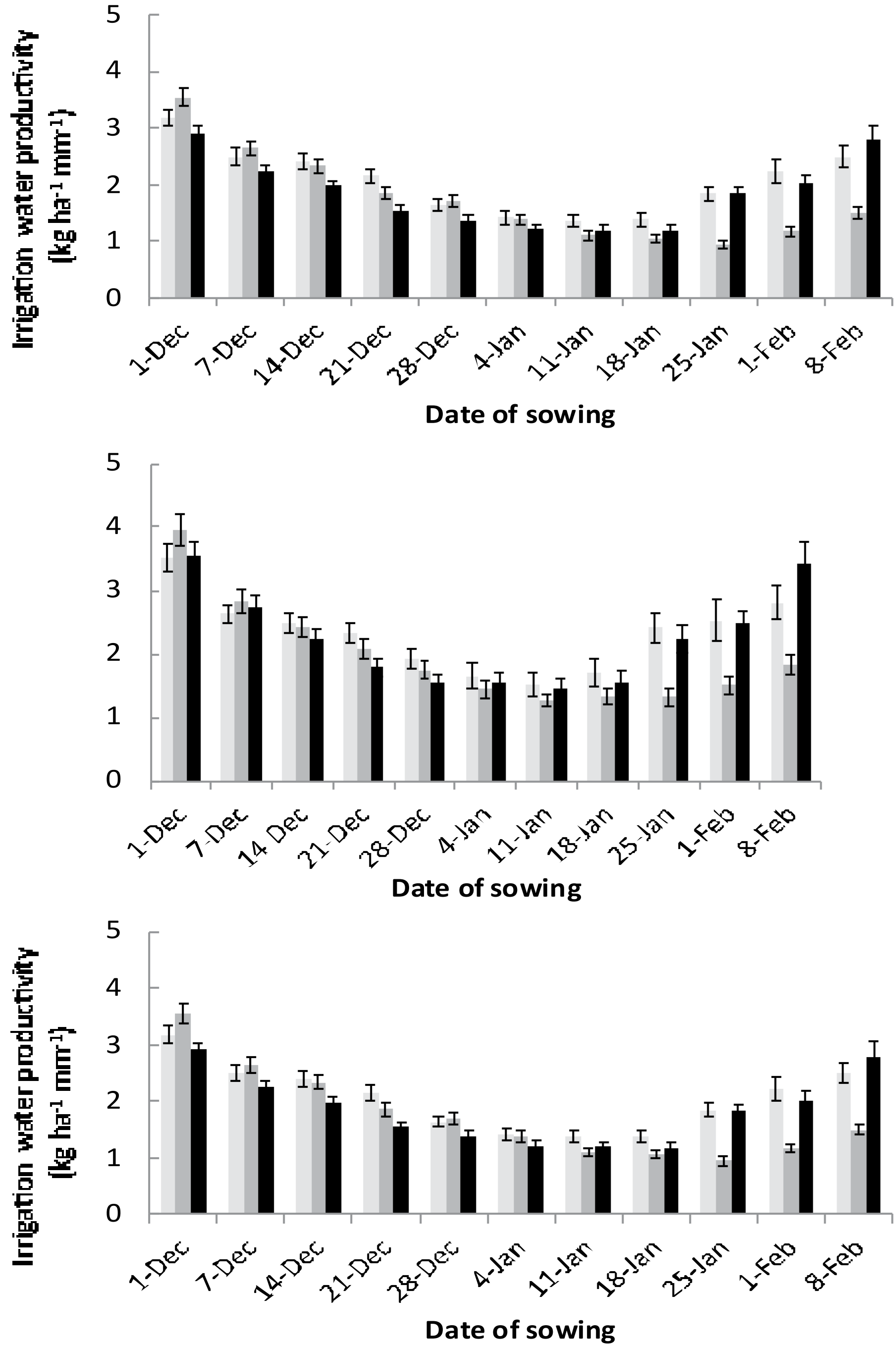


Fig. 5. Variability (2000-2014) of simulated irrigation water productivity, among date of sowing and irrigation management for Satkhira, Bangladesh. Each bar represents an average value of the outputs simulated by ORYZA v3 over the 15 years under the 11 sowing date and three groups of virtual varieties: a) variety with short growth duration; b) variety with medium growth duration; and c) variety with long growth duration; FW, irrigated with fresh water; FW:SW, irrigated with alternate one week fresh water to one week saline water; 2FW:SW, irrigated with alternate two weeks fresh water to one week saline water.

4. Conclusion

The modified version of ORYZA v3, accounting for rice salt stress response, demonstrated acceptable performance in simulating the growth and yield of the rice cultivar BRRI dhan47. The model was able to capture the variability observed in different seasons and sites under a range of salt-affected conditions.

The subsequent scenario analysis has highlighted the opportunity of alternating fresh and saline water use in irrigation to make better use of available fresh water. For sowing from late December to early January, higher yields were obtained with a long duration variety with the salt-tolerance characteristics of BRRI dhan47. However, with the medium duration variety, higher irrigation water productivity was obtained considering the fresh water applied with acceptable yield. Soil salinity increased continuously during the crop season in Satkhira. This must be considered in evaluating the sustainability of the system, particularly the effect of the saline water on soil degradation and salinization of the ground water. The study would need to then incorporate historical soil salinity trends to capture the actual growing conditions and also the common practices of farmers. Further simulations with future climate data and in different salt-affected rice growing regions would also be desirable to confirm the study findings and its perspective in climate change adaptation. These could be valuable to establish priorities for investments and research orientation for effective strategies to increase rice production.

Acknowledgments

This work was supported in part by the Global Rice Science Partnership (GRiSP), Stress Tolerant Rice Varieties for Africa and South Asia (STRASA), and the Australian Centre for International Agricultural Research (ACIAR – via project LWR/2008/019 "Developing multi-scale climate change adaptation strategies for farming communities in Cambodia, Laos, Bangladesh and India (ACCA)").

References

Beltrán, J.M.1999. Irrigation with saline water: benefits and environmental impact. Agricultural Water Management 40, 183-194.

Bouman, B.A.M., and H.H. van Laar. 2006. Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions, Agricultural Systems 87, 249–273.

Bouman, B.A.M., M.J. Kropff, T.P. Tuong, M.C.S. Wopereis, H.F.M. ten Berge, and H.H. van Laar. 2001. ORYZA2000: modeling lowland rice. International Rice Research Institute, Los Baños, Philippines, and Wageningen University and Research Centre, Wageningen, Netherlands.

Castillo, E.G., T.P. Tuong, A.M. Ismail and K. Inubushi. 2007. Response to salinity in rice: Comparative effects of osmotic and ionic stresses. Plant Production Science 10, 159–170.

Crescimanno, G. and P. Garofalo. 2006. Management of irrigation with saline water in cracking clay soils. Soil Science Society of America Journal 70, 1774-1787.

Eatherall, A. 1997. Modelling climate change impacts on ecosystems using linked models and a GIS. Climatic Change 35, 17-34.

FAO. 2013. Land and Water Management h ttp:// http://www.fao.org/nr/aboutnr/nrl/en/ Accessed 24 May 2013.

Flowers, T.J., R. Ragab, N. Malash, G. Abdel Gawad, J. Cuartero and A. Arslan. 2005. Sustainable strategies for irrigation in salt-prone Mediterranean: SALTMED. Agricultural Water Management 78, 3-14.

France J. and J.H.M., Thornley.1984. Mathematical models in Agriculture, Butterworths, London press.

Gaydon, D.S., A.M. Radanielson, O. Angeles, M.M.R. Khan, A.K. Chaki, M.A. Rahman and T. Li. 2014. Investigating options to increase fresh water productivity in Boro rice for salt affected areas of Bangladesh, using crop modeling, Paper presented at the IRC International Rice Congress 2014, October 26-30, in Bangkok, Thailand.

IRRI, 2014. ORYZA2000 : A crop growth simulation model for rice. https://sites.google.com/a/irri.org/oryza2000/scientific-documentation. Accessed September 2014.

Islam, M.R., M.A. Salam, M.A.R. Bhuiyan, M.A. Rahman, R. Yasmeen, M.S. Rahman, M.K. Uddin, G.B. Gregorio and A.M. Ismail. 2008. BRRI dhan 47: A salt tolerant rice variety for Boro season isolated through participatory variety selection. International Journal of Biological Research 5, 1: 1-6.

Ismail, A. M., S. Heuer, M. Thomson and M. Wissuwa. 2007. Genetic and genomic approaches to develop rice germplasm for problem soils. Plant Molecular Biology 65, 547–570.

Li., T., O. Angeles, A.M. Radanielson, M. Marcaida III and E. Manalo. 2015. Drought stress impacts of climate change on rainfed rice in South Asia. Climate Change. Under review.

Malash N., T.J. Flowers, R. Ragab. 2005. Effect of irrigation systems and water management practices using saline and non-saline water on tomato production. Agricultural Water Management 78, 25-38.

Mondal, M.K., T.P. Tuong, A.K.M. Shariffulah and M.A. Sattar. 2010. Water supply and demand for dry-season rice in the coastal polders of Bangladesh. In C. T. Hoanh, B. W. Szuster, K. Suan-Pheng, A. M. Ismail and A. D. Noble (Eds.) Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land-Water Interface (CABI publication): 264-278.

Mondal, M.K, N.K. Saha, S.P. Ritu, P.L.C. Paul, A.K.M. Sharifullah, E. Humphreys, T.P. Tuong, and M.A Rashid. 2015. Optimum sowing window for boro cultivation in the coastal zone of Bangladesh. These proceedings

Munns, R., Schachtman, D. P., and A. G. Condon, 1995: The signifiance of a 2 phase growth-response to salinity in wheat and barley. Australian Journal of Plant Physiology 22, 561-569.

R Development Core Team, 2008. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Radanielson, M. A., O. Angeles, T. Li. 2013. Salinity effect on rice biomass: seasonal and transient modelling of plant responses. Paper presented at the International Society for Ecological Modelling Conference 2013, October 27-31 in Toulouse, France.

Radanielson, M.A, D.S.Gaydon, T.Li and O. Angeles. 2015. Modeling salinity effect on rice growth and rice yield with ORYZA v3 and APSIM-Oryza. Ecological Modelling. In preparation.

Rezaei, M., N. Davatgar, A. Ashrafzad, N. Pirmoradian, M.R. Khaledian, M. Kavosi, E. Amiri and M. Vazifedost.2011. Intermittent irrigation: a procedure to use saline water in rice cultivation. Paper presented at the ICID 21st International Congress on Irrigation and Drainage, October 15-23, in Tehran, Iran.

Sudhir-Yadav, E. Humphreys, T. Li, G. Gill, and S.S. Kukal.2012. Evaluation of tradeoffs in land and water productivity of dry seeded rice as affected by irrigation schedule. Field Crops Research 128, 180-190.

Tuong, T. P., N.D. Phong, and B.A.M. Bouman. 2003. Assessing rice yield in rice–shrimp systems in the Mekong Delta, Vietnam: a modeling approach. In Rice–shrimp farming in the Mekong Delta: biophysical and socioeconomic issues. ACIAR Technical Reports 52e,102-110.

Wassmann, R., S. V. K. Jagadish, K. Sumfleth, H. Pathak, G. Howell, A. Ismail, R. Serraj, E. Redona, R. K. Singh, and S. Heuer. 2009. Regional vulnerability of climate change impacts on asian rice production and scope for adaptation. Advances in Agronomy, 102, 91-133.

Zwart, S.J. and, W.G.M. Bastiaanssen. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management 69, 2: 115–133.

Zeng, L. and M. C. Shannon. 2000. Salinity effects on the seedling growth and yield components of rice. Crop Science 40,4 :996–1003.

Response of wheat, mustard and watermelon to irrigation in saline soils

A.R. Akanda[1], S.K. Biswas[1], K.K. Sarker[1], M.S. Mondal[2], A.F. Saleh[2], M.M. Rahman[2] and A.Z.M. Mosleuddin[3]

[1]Bangladesh Agricultural Research Institute, Bangladesh razzaquebari@gmail.com, sujitbari@yahoo.com, ksarkerwrc@gmail.com
[2]Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Bangladesh mshahjahanmondal@iwm.buet.ac.bd, saleh@iwfm.buet.ac.bd, mmrahman@iwfm.buet.ac.bd
[3]Bangladesh Agricultural University, Bangladesh abunajia@yahoo.com

Abstract

Proper water management is necessary to sustain irrigated agriculture in areas with saline soil and saline water in Bangladesh. Therefore, a study was carried out to investigate the effects of irrigation on wheat, mustard and watermelon in saline soils of coastal areas. The experiments were conducted in farmers' fields in Debhata, Satkhira District and Amtali, Barguna District during the *rabi* season of 2013-2014. The experiments were laid out in a randomized block design with four irrigation treatments of wheat (BARI Gom 25), mustard (BARI Sarisha 14) and watermelon (Hybrid-Big family), replicated three times. Soil salinity (*in situ* electrical conductivity) increased from 2 to 5 dS/m at the time of sowing to 8 to 10 dS/m at the time of harvest with farmers' practice irrigation management. Increasing irrigation frequency from one to two or three in wheat and mustard did not affect soil salinity at any stage throughout the season. However, increasing irrigation frequency from one to two had significant positive effects on the growth, yield contributing characters and yield of wheat, but little effect on mustard yield or yield components. Wheat yield increased from about 3 t/ha with one irrigation during the vegetative stage to 3.9 t/ha with irrigation at the crown root initiation (CRI) and booting stages. Providing a third irrigation at grain filling did not increase yield further. Increasing irrigation frequency of watermelon from 25 to 15, 10 and 5 d intervals greatly reduced the build up in soil salinity during the second half of the season, and increased watermelon yield by more than 50%. The highest fruit yield of watermelon was around 35 t/ha achieved using 5 and 10 d irrigation intervals, while the farmers' practice produced the lowest yield (20.7 t/ha) at a 25 d irrigation interval. The highest total water productivity of wheat (2.6 kg/m^3) and mustard (1.45 kg/m^3) occurred with a single irrigation at the CRI and preflowering stages, respectively. Water productivity of watermelon was the highest (8.9 kg/m^3) at 10 and 15 d irrigation intervals and lowest (7.8 kg/m^3) at 25 d intervals. The results show that high yields of wheat (~4 t/ha), mustard (~1.5 t/ha) and watermelon (~35 t/ha) can be achieved on moderately saline soils of the coastal zone using moderately salt tolerant varieties and proper irrigation management, similar to achievable yields in non-saline regions.

Key message: Proper irrigation practices can increase the yield of *rabi* crops by avoiding water deficit stress and suppressing the build up of soil salinity in coastal areas of Bangladesh.

Keywords: water productivity, soil salinity, coastal zone, Bangladesh

1. Introduction

Soil salinity is one of the serious abiotic stresses that reduces plant growth, development and productivity worldwide (Siringam et al. 2011). More than 800 Mha of land throughout the world are affected by varying degrees of salinity (FAO 2008). About 33% of all irrigated lands worldwide are affected by salinity and sodicity. The coastal areas of Bangladesh cover about 20% of the country and comprise more than 30% of the cultivable lands of the country. About 53% of the lands of the coastal areas are affected by varying degrees of salinity. Agricultural land use in these areas is very poor compared to the country's average cropping intensity of 191% (Haque 2006; BBS 2011). The factors that contribute significantly to the development of saline soil are tidal flooding during the wet season (June to October), direct inundation by saline water and the upward or lateral movement of saline groundwater during the dry season (November to May). The severity of the salinity problem in Bangladesh increases with the desiccation of the soil. The effects of salinity depend on the degree of salinity at the critical stages of crop growth, which reduces yield, in severe cases to zero.

The dominant crop grown in the saline areas is transplanted *aman* rice which is grown during the rainy season using traditional, low yielding varieties. The cropping patterns followed in the coastal areas are mainly Fallow-Fallow-Transplanted *aman*. But recently the cultivation of a wide range of crops such as wheat, mustard, sunflower and vegetables after the *aman* harvest has been expanding around some surface water sources and shallow wells with low salinity water (e.g. electrical conductivity (EC) ranging from 1.7 to 3^+ dS/m). The global production of watermelon is greater than that of any other cucurbits (Robinson and Decker-Walters 1997), and world production has expanded from 2.9 to 3.7 x 10^6 tons in the period from 1999 to 2004 (FAOSTAT 2004). In Bangladesh too, watermelon production is increasing every year as farmers are getting good returns. A major share of this crop is cultivated in coastal districts like Bhola, Barguna, Cox's bazar and Patuakhali. It is also a major economic crop in coastal areas of Bangladesh.

However, the sustainability of production systems based on crops that are not specifically tolerant to salinity requires proper management of both water and salt. With careful water management it is possible to sustain irrigated agriculture in areas with saline soil and saline groundwater with and without subsurface drainage. Many studies have reported substantial increases in crop yields as a result of suitable irrigation management, including studies under saline conditions (Batra 1990; Ayars et al. 1991; Minhas 1996; Zhang et al. 2004; Malash et al. 2005; Jalota et al. 2006; Ali et al. 2007). In the absence of sufficient rainfall for natural leaching, irrigated farming in arid lands is exposed to accumulation of salts in the soils. Both the quantity and quality of irrigation water used and their effects on farm productivity need to be precisely known. Considerable research has been directed towards defining the effects of salinity on crop growth and development (Maas 1990; Shalhevet 1994; Shannon and Grieve 1999). The impact of irrigation with slightly saline water on crops (wheat, mustard and watermelon) and soil has not been studied in coastal regions of Bangladesh. The present study was therefore carried out to identify the best irrigation strategy for the cultivation of wheat, mustard and watermelon in coastal saline soils irrigated with low salininity water. The specific objectives were: (i) to generate physiological data at different growth stages, (ii) to find out the critical growth stages for salinity stress, (iii) to find out the effect of salinity on crop yield, and (iv) to develop guidelines for irrigation of *rabi* crops in the coastal zone of Bangladesh.

2. Materials and methods

2.1 Study area

Three experiments were conducted in farmers' fields in Satkhira and Barguna Districts in Bangladesh during the *rabi* season of 2013-2014. Field experiments on wheat and mustard were carried out in farmers' fields in Kulia village, Debhata *Upazila*, Satkhira District. An experiment on watermelon was conducted in a farmer's field in Kalibiri village, Amtali *Upazila*, Barguna District. The soils were clay loam with an average field capacity of 27% (gravimetric water content) and mean bulk density of 1.34 g/cm over the 0-60 cm soil profile (15 cm layers).

2.2 Experimental design

Three field experiments were laid out in a randomized complete block design with four irrigation treatments for wheat, mustard and watermelon, and replicated three times. Each experiment was conducted in a farmers' field. The unit plot size for wheat, mustard and watermelon was 4 m × 3 m, 5 m × 3m and 3.5 m × 3.5 m, respectively**.** The irrigation treatments were as follows:

Wheat

T_1 = Farmers' practice (irrigation during early vegetative stage at 35-40 d DAS)
T_2 = One irrigation at the crown root initiation (CRI) stage (17-21 DAS)
T_3 = Two irrigations, at CRI and booting stages (55-60 DAS)
T_4 = Three irrigations, at CRI, booting and grain filling stages (75-80 DAS)

Mustard

T_1 = Farmers' practice (irrigation during early vegetative stage (20–25 DAS)
T_2 = One irrigation at preflowering stage (30-35 DAS)
T_3 = One irrigation at siliqua filling stage (45-50 DAS)
T_4 = Two irrigations at preflowering and siliqua filling stages

Watermelon

T_1 = Irrigation at 5 d intervals from emergence to fruit setting
T_2 = Irrigation at 10 d intervals from emergence to fruit setting
T_3 = Irrigation at 15 d intervals from emergence to fruit setting
T_4 = Three irrigations, at 25, 50 and 75 d after emergence (DAE) (farmers' practice)

The experimental blocks were separated by a distance of 2 m and the plots in each block were separated by a buffer of 1 m to prevent lateral movement of water from one plot to another plot.

2.3 Crop management

2.3.1 Wheat and mustard

Wheat (BARI Gom 25), a medium salt tolerant variety (no yield penalty up to 6-7 dS/m of soil salinity), was sown at 140 kg/ha on 28 November 2013 with a row spacing of 20 cm. Mustard (BARI Sarisha 14), a low salt tolerant variety (no yield penalty up to 3.5-6.5 dS/m of soil salinity), was sown at 7 kg/ha on 15 December 2013 with a row spacing of 30 cm (BARI 2011). Fertilizer ($N_{120}P_{30}K_{50}S_{20}B_1Zn_{4.5}$ kg/ha) was applied in the forms of urea, triple super phosphate, muriate of potash, gypsum, borax, and zinc sulphate, respectively. Cow dung at the rate of 5 t/ha was applied before final land preparation. Two-thirds of the urea and all other fertilizers were applied at the time of final land preparation, while the remaining urea was applied before the first irrigation. One manual weeding was done for wheat and mustard at 30 and 33 DAS, respectively. The mustard crops were sprayed with Rovral-50wp at 0.2% at 30 DAS for prevention against diseases. Wheat and mustard were harvested on 11 and 3 March 2014, respectively. There was no significant weed, pest or disease infestation in the experimental plots.

2.3.2 Watermelon

Watermelon (Hybrid-Big family: no yield penalty up to 7-8.5 dS/m) was planted in pits spaced at 1.5 m x 1.5 m on 17 January 2014, one seed per pit (AHT 2011). Fertilizer ($N_{83}P_{24}K_{40}S_{16}$kg/ha) was applied in the forms of urea, triple super phosphate, muriate of potash and gypsum, respectively. Decomposed cow dung was applied at 5 t/ha. Half of the P and K, and the full dose of S and cowdung were applied during pit preparation. The remaining P and K was applied at the branching stage (30 DAE). The N was applied into four equal splits at 15, 30, 45 and 60 DAE. There were two manual weedings at 23 and 40 DAE. Watermelons were harvested from 15-25 April 2014 as the fruits matured.

2.4 Monitoring

2.4.1 Wheat

The number of spikes, number of grains per spike, 1000 grain weight, and grain and straw yield of wheat were determined at harvest. Harvest index was calculated as the ratio of dry grain yield to total dry grain plus straw yield. The sample size of the harvested area was one square meter for determining grain and straw yield. Sub-samples (30 plants) from each plot were randomly selected to detemine yield contributing characters.

2.4.2 Mustard

Plant population, number of siliqua per plant, seed per siliqua, 1000 seed weight, and grain and straw yield of wheat were determined at harvest. Harvest index was calculated as the ratio of dry grain yield to total dry grain plus straw yield. The size of the harvested area was one square meter for determining grain and straw yield. Sub-samples (10 plants) from each of the plots were randomly selected to determine yield contributing characters.

2.4.3 Watermelon

The number of watermelon fruits per plot, average weight of fruit, fruit yield and above-ground biomass (except fruit) were determined at harvest. The number of days to flower initiation, fruit setting and days to fruit maturity were also recorded.

2.4.4 Soil water content and irrigation water

Soil moisture before each irrigation was monitored by the researchers. Gravimetric soil water content was determined at the times of sowing and harvesting and before each irrigation. The soil samples were collected considering a root zone depth of 30 cm (initial stage), 45 cm (vegetative stage) and 60 cm (flowering and grain filling stage). The soil was sampled in 15 cm increments, well-mixed, subsampled, weighed, dried at 105°C, and reweighed to determine gravimetric moisture content. The irrigation water requirement was calculated by the following formula (Mandal and Dutta 1992; Michael 1978):

$$d = \frac{PwAsD}{100}$$

$$P_w = FC - RL$$

where, d = depth of irrigation water to be applied (cm)

As = apparent specific gravity of soil

D = depth of soil profile to be irrigated (cm)

FC = soil moisture content at field capacity (%, g water/100 g soil)

RL = residual soil moisture level before each irrigation (%, g water/100 g soil)

The amount of applied irrigation water was the depth of water needed to refill the soil profile (0-30, 45 or 60 cm depending on growth stage) to field capacity. Field capacity was determined by ponding water method on the soil surface as suggested by Michael (1978). Total water use (TWU) was calculated as the sum of irrigation input, rainfall and soil water contribution (SWC) between sowing and harvest. The amount of irrigation water was determined by volumetric measurement and supplied to the experimental plots using a polythene hose pipe. The plots were irrigated with shallow tubewell water with electrical conductivity (EC) ranging from 1.7 to 3.4 dS/m using groundwater for wheat and mustard, and medium salinity canal water with EC ranging from 4.5 to 6.5 dS/m for watermelon. The rate of outflow of the shallow tubewell was also calculated by volumetric measurement.

2.4.5 Soil salinity

The soil salinity was monitored *in situ* at different growth stages of wheat and mustard and at 10 d intervals in watermelon using a portable HI 993310 (Hanna Instruments, Woonsocket, R.I.) water conductivity and soil salinity meter with steel probes (HI 76305) that can be inserted directly into the soil. The HI 76305 is an amperometric steel probe that measures the total conductivity of the soil, that is, the combined conductivity of air, water and soil. Soil salinity was measured from 0-15 and 15-30 cm at at least three spots in each plot.

2.5 Data analysis

Crops data were analyzed by ANOVA using MSTAT-C. The least significant difference (LSD) at 5% probability was used to identify significant differences between treatments.

3. Results and discussion

3.1 Soil salinity

At the time of sowing, soil salinity ranged from about 2.3 dS/m in watermelon to about 4.9 dS/m in wheat. Salinity increased as the dry season progressed in all treatments in all crops, to maximum values at harvest of around 10 and 8 dS/m in wheat (Fig.1a) and mustard (Fig.1b), respectively, and to around 7 dS/m in watermelon. There was a consistent trend for lower salinity with higher irrigation frequency, but the differences were small and not significant in wheat and mustard throughout the season, and in watermelon until about half-way through the season. The effect of irrigation treatment on soil salinity in watermelon increased during the latter half of the season, and at the time of harvest salinity ranged from about 8.5 dS/m with farmer practice to about 5.5 dS/m with irrigation at 5 d intervals (Fig.1c). Based on observed data, the soils can be classified as moderately saline soils (S_2) that can be used for moderately salt-sensitive crops using proper irrigation management (Majumdar 2004).

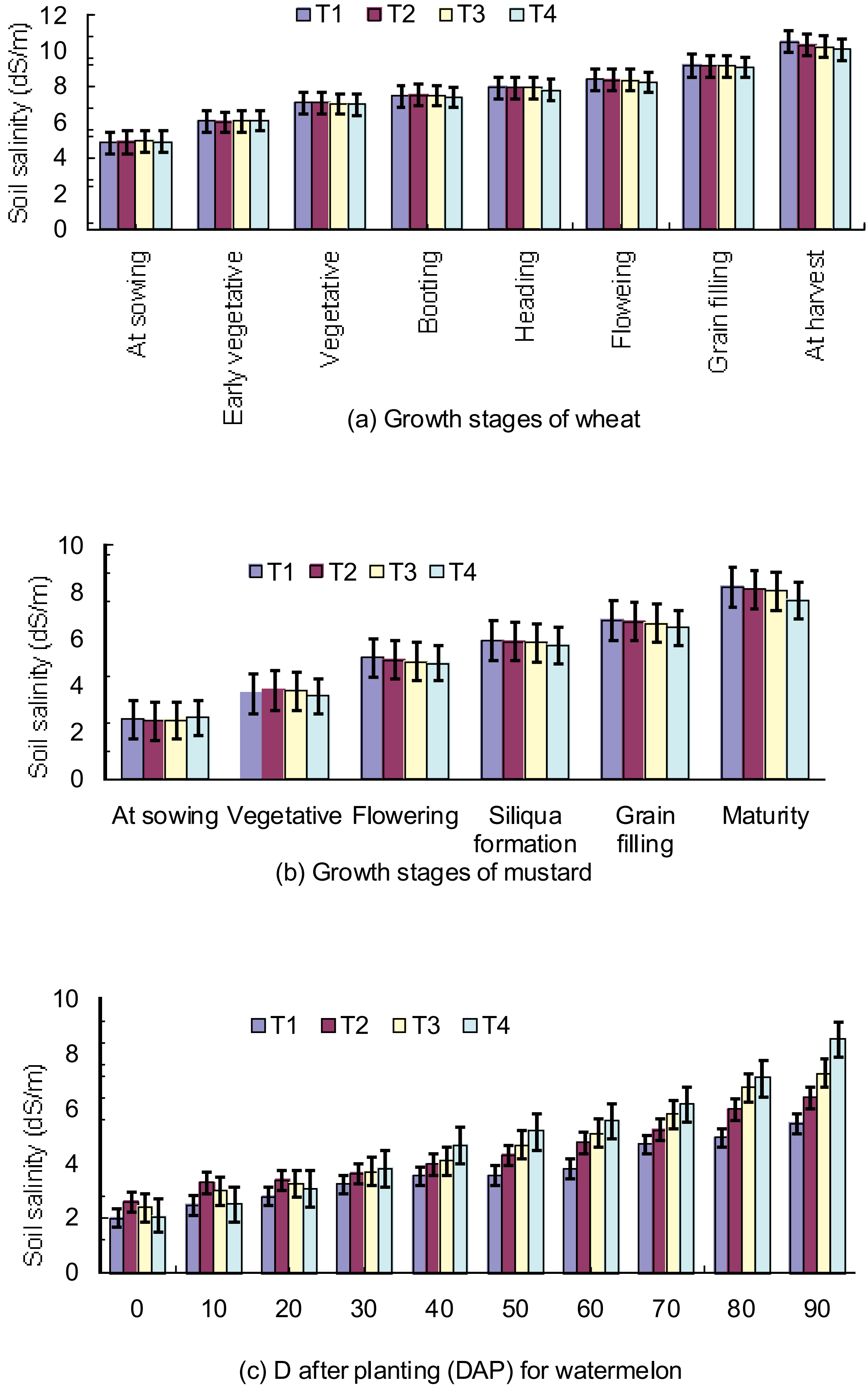


Fig. 1. Soil salinity at different growth stages of wheat (a), mustard (b) and at 10 d intervals for watermelon (c) as affected by irrigation treatment. Error bars indicate the standard error of the means.

3.2 Response of wheat, mustard and watermelon to irrigation

3.2.1 Growth, yield and yield contributing parameters of wheat

Irrigation had a significant positive effect on the growth, yield and yield contributing parameters of wheat (Table 1). One irrigation at CRI did not significantly increase grain or straw yield compared with one irrigation about 20 d later (farmers' practice). Increasing the number of irrigations from one to two significantly increased grain yield by increasing spike density and grain weight. However, there was no further increase in grain yield (nor in any yield components) by applying a third irrigation during grain filling. However, the third irrigation resulted in a significant increase in straw yield over all other treatments. Applying two or three irrigations produced a grain yield of around 4 t/ha, which is a good yield in non-saline environments. The effects of the irrigation treatments on soil salinity were small, suggesting that responses to irrigation were the result of reduced water deficit, and not due to differential effects of the irrigation treatments on soil salinity. Mridha et al. (2001) reported that optimum wheat yield (3-4.5 t/ha) requires three to four irrigations for a range of soil types and agroclimatic conditions across Bangladesh.

Table 1. Yield and yield contributing parameters of wheat under different irrigation levels

[a]Treat-ment	Spike/m^2 (no.)	Grains/spike (no.)	1000 grain weight (g)	[b]Grain yield (t/ha)	Straw yield (t/ha)	[c]HI
T_1	438	18.0	54.3	3.02	5.24	0.37
T_2	478	21.3	55.3	3.35	5.28	0.41
T_3	502	22.3	57.4	3.90	5.42	0.42
T_4	508	22.7	57. 6	4.08	6.06	0.40
[d]$LSD_{0.05}$	30	[e]ns	2.4	0.52	0.71	ns
[f]CV(%)	10.1	9.5	5.6	7.9	8.3	5.4

[a]Treatments: T_1 = Farmers' practice (irrigation at initial vegetative stage); T_2 = One irrigation at CRI; T_3 = Two irrigations, at CRI and booting; T_4 = Three irrigations, at CRI, booting and grain filling

[b]Grain yield at 12% moisture content

[c]HI harvest index

[d]LSD least significant difference at 5% level

[e]ns non-significant

[f]CV coefficient of variation

3.2.2 Yield and yield contributing parameters of mustard

There were very few effects of irrigation treatment on the performance of mustard, with yield of all treatments around 1.4 to 1.5 t/ha (Table 2). The results are supported by the findings of Sardar et al. (2014) who reported similar mustard yields in moderately saline (1 to 1.6 t/ha) and non-saline (1.4-1.6 t/ha) areas of Bangladesh. There were no effects on plant density, number of seeds/siliqua, seed yield or harvest index (HI). However, plant height, and the number of siliqua/plant was lower with farmers' irrigation management than for other treatments. Farmers' practice straw yield was significantly lower than yield with two irrigations.

Table 2. Growth, yield and yield contributing parameters of mustard under different irrigation levels in saline soil

[a]Treat-ment	Plant /m^2	Siliqua/ plant	Seed/ siliqua	1000 seed weight (g)	Seed yield (t/ha)	Straw yield (t/ha)	HI
T_1	82	75.0	36	3.53	1.42	9.63	0.16
T_2	79	93.0	38	3.58	1.49	9.94	0.16
T_3	81	87.7	37	3.58	1.44	10.2	0.15
T_4	92	97.0	40	3.59	1.52	10.5	0.15
[b]$LSD_{0.05}$	[c]ns	13.3	ns	ns	ns	0.76	ns
[d]CV(%)	9.3	7.8	8.1	5.5	7.5	11.0	11.1

[a]Treatments: T_1 = Farmers' practice (Irrigation at initial vegetative stage); T_2 = One irrigation at preflowering stage; T_3 = One irrigation at siliqua filling stage; T_4 = Two irrigations each at preflowering and siliqua filling stages

[b]LSD least significant difference at 5% level

[c]ns non-significant

[d]CV coefficient of variation

3.2.3 Yield and yield contributing parameters of watermelon

There were consistent trends for faster plant development with reduced irrigation frequency, but the differences were small (maximum 5 d at maturity) and never significant. Highest yield was around 35 t/ha with 5 and 10 d irrigation frequency (Table 3). Sadar et al. (2013) reported that yields of 52 t/ha were possible through proper irrigation in coastal saline areas. There were large effects of irrigation frequency on fruit yield, with significantly lower yield of farmers' practice than all other treatments. Yield with 5 d irrigation interval was significantly higher than with 15 d irrigation interval. Unit fruit weight also increased with irrigation frequency, with significantly higher values for 5 and 10 d intervals than with less frequent irrigation.

Table 3. Yield components, yield and biomass of watermelon under different irrigation regimes

[a]Treatment	Flowering Initiation (DAS)	Days to 80% flowering	Days to fruit setting	Days to maturity	Unit fruit weight (kg)	Yield (t/ha)	ADM (except fruit)
T_1	58	65	72	98	3.32	37.7	2.40
T_2	58	65	72	98	3.12	33.7	2.21
T_3	55	63	70	96	2.62	28.4	1.81
T_4	54	63	68	93	2.16	20.5	1.61
[b]$LSD_{0.05}$	[c]ns	ns	ns	ns	0.63	6.1	0.47
[d]CV(%)	9.1	7.4	8.0	10.1	5. 7	5.9	5.1

[a]Treatments: T_1 = Irrigation at 5 d interval after emergence up to fruit setting; T_2 = Irrigation at 10 d interval after emergence up to fruit setting; T_3 = Irrigation at 15 d interval after emergence up to fruit setting; T_4 = Three irrigations each at 25, 50 and 75 d after emergence

[b]LSD least significant difference at 5% level

[c]ns non-significant

[d]CV coefficient of variation

3.3 Water input and water productivity of wheat, mustard and watermelon

3.3.1 Water use and water productivity of wheat

Total water use was similar for farmers' practice and one irrigation at CRI (~134 mm) and increased as the number of irrigations increased (Table 4). Soil water depletion at harvest decreased slightly as the frequency of irrigation increased. The highest water productivity (2.60 kg/m^3) was obtained with one irrigation at CRI while the lowest (1.93 kg/m^3) was obtained with three irrigations.

Table 4. Water use and water productivity of wheat under different irrigation water regimes

[a]Treatment	Total irrigation water applied (mm)	Rainfall (mm)	[b]SMC (mm)	[c]TWU (mm)	Grain yield (t/ha)	Water productivity (kg/m^3)
T_1	53	32	54	139	3.02	2.17
T_2	41	32	56	129	3.35	2.60
T_3	92	32	48	172	3.90	2.27
T_4	138	32	41	211	4.08	1.93

Note: [a]Treatments: T_1 = Farmers practice (Irrigation at initial vegetative stage); T_2 = One irrigation at CRI stage; T_3 = Two irrigations each at CRI and booting stages; T_4 = Three irrigations each at CRI, booting and grain filling stages

[b]SMC soil moisture contribution

[c]TWU total water use

3.3.2 Water use and water productivity of mustard

As with wheat, soil water depletion in mustard decreased as irrigation frequency increased (Table 5). As a result, there was little variation in total water use across the four treatments. Water productivity was highest with a single preflowering irrigation.

Table 5. Irrigation water applied and irrigation water productivity of mustard grown underdifferent irrigation regimes

[a]Treatment	Total irrigation water applied (mm)	Rainfall (mm)	SMC (mm)	TWU (mm)	Seed yield (t/ha)	Water productivity (kg/m^3)
T_1	60	-	54	114	1.42	1.25
T_2	42	-	61	103	1.49	1.45
T_3	56	-	46	112	1.44	1.29
T_4	89	-	39	128	1.52	1.19

[a]Treatments: T_1 = Farmers practice (Irrigation at initial vegetative stage); T_2 = One irrigation at preflowering stage; T_3 = One irrigation at siliqua filling stage; T_4 = Two irrigations each at preflowering and siliqua filling stages

3.3.3 Water use and water productivity of watermelon

Total water use varied greatly across the four treatments, from 261 mm with farmers' practice to 455 mm with a 5 d irrigation interval (Table 6). The variation in total water use was due to the large variation in irrigation input, from 187 to 391 mm. The seasonal use of water by the highest yielding treatment was 455 mm, which is within the range of 400-600 mm reported by Doorenboss and Kassam (1979) for watermelon cultivation. Water productivity was highest with 10 and 15-d irrigation intervals, at around 8.8 kg/m^3.

Table 6. Water use and water productivity of watermelon under different irrigation water regimes

[a]Treatment	Total water applied (mm)	Rainfall (mm)	SMC (mm)	TWU (mm)	Yield (t/ha)	Water productivity (kg/m^3)
T_1	391	21	43	455	37.70	8.29
T_2	311	21	48	380	33.67	8.86
T_3	250	21	52	323	28.41	8.79
T_4	187	21	53	261	20.47	7.84

[a]Treatments: T_1 = Irrigation at 5 d interval after emergence up to fruit setting; T_2 = Irrigation at 10 d interval after emergence up to fruit setting; T_3 = Irrigation at 15 d interval after emergence up to fruit setting; T_4 = Three irrigations each at 25, 50 and 75 DAE (farmers' practice)

4. Conclusions and recommendations

Increasing the irrigation frequency of wheat from one to three, and of mustard from one to two, had only a small effect on the development of soil salinity at two sites with initial salinities of about 5 and 2.5 dS/m, respectively. With one irrigation, soil salinity in wheat and mustard increased to 10 and 8 dS/m at harvest. Yield of wheat increased from around 3 t/ha with one irrigation to around 4 t/ha with two or three irrigations. The results suggest that the yield response to increased irrigation frequency from one to two was due to increased water availability, and demonstrate the good tolerance of BARI Gom 25 to soil salinity. Similarly, there was little effect of increasing irrigation frequency from one to two on soil salinity in the mustard, nor on crop performance. However, increasing irrigation frequency of watermelon from 25 to 15, 10 and 5 d intervals greatly reduced the buildup in soil salinity during the second half of the season and increased watermelon yield by more than 50%. The highest fruit yield of watermelon was around 35 t/ha at 5 and 10 d irrigation intervals, while the farmers' practice (25 d intervals) produced the lowest yield (20.7 t/ha). The reduction in yield at lower irrigation frequency may have been due to higher salinity and/or water deficit. The results demonstrate that good yields of *rabi* crops can be achieved on moderately saline soils of the coastal zone with the standard irrigation management for salinity tolerant varieties of wheat and mustard. For watermelon, 10 d irrigation intervals also give high water productivity, which might be recommended for irrigation management on moderately saline soils in coastal areas of Bangladesh.

Acknowledgements

The paper is based on the project research of ESPA funded by DFID. The authors would like to acknowledge DFID, BARI, Gazipur, BUET, Dhaka for providing all facilities and sharing knowledge for sustaining irrigated agriculture in coastal areas of Bangladesh. Finally, we acknowledge the CGIAR Challenge Program on Water and Food for inviting us to present the findings of this paper at the Revitalizing the Ganges Coastal Zone Conference held on 21 to 23 October 2014, Dhaka, Bangladesh.

References

Ali, M.H., M.R. Hoque, ,A. A. Hassan, , M.A. Khair. 2007. Effects of deficit irrigation on yield, water productivity, and economic returns of wheat. Agric. Water Manage. 92: 151–161.

Ayars, J.E., Hutmacher, R.B., Steiner, J.J., Mantel, A.B., Vail, S.S. 1991. Irrigation of carrots on a sandy loam soil. Irrig. Sci. 12: 193–198.

Akanda, M.A.R., Islam, M.S., Khan, B.R., Mondal, M.R.I.1994. Response of mustard to irrigation at different stages of growth. Annual Research Report 1994, IWM Division, Bangladesh Agricultural Research Instittue, Gazipur-1701.

ATH, 2011. Agriculture Technology Handbook (ATH): Part 1, Published by Bangladesh

Agricultural Research Institute (BARI), Joydebpur, Gazipur.

Batra, B.R. 1990. Effect of different levels of irrigation and fertilization on growth and yield of carrot (Daucuscarota L.) for root production. Vegetable Sci. 17 (2): 127–139.

BBS (Bangladesh Bureau of Statistics). 2011. Statistical year book of Bangladesh. Bangladesh

Bureau of statistics, Statistics Division, Ministry of planning. Government of the people's Republic of Bangladesh.

BARI, 2011. BARI Annual Report 2010-2011, Published by Bangladesh Agricultural

Research Institute (BARI), Joydebpur, Gazipur.

Doorenboss, J. and Kassam, A.H. 1979. Yield response to water. FAO Irrigation and Drainage Paper No. 33, Rome.

FAO, 2008. Land and Plant Nutrition Management Service. Retrieved from:http://www.fao.org/ag b/agl /agll/spush/.

FAOSTAT, 2004. FAO Statistical Yearbooks, World Food and Agriculture Organization of the United Nations. Statistic Database, Production Statistics, www.fao.org

Haque, A.A. 2006. Salinity Problems and Crop Production in Coastal Regions of Bangladesh.Pak. J. Bot., 38(5): 1359-1365.Jalota, S.K., Sood, A., Chahal, G.B.S., Choudhury, B.U., 2006. Crop water productivity of cotton-wheat system as influenced by deficit irrigation, soil texture and precipitation. Agric. Water Manage. 84: 137–146.

Maas, E.V. 1990. Crop salt tolerance. In: Tanji, K.K. (Ed.), Agricultural Salinity Assessment and Management, ASCE Manuals and Reports on Engineering Practice No. 71. American Society of Civil Engineers, New York, pp. 262–304.

Malash, N. Flowers, T.J., Ragab, R., 2005. Effect of irrigation systems and water management practices using saline and nonsaline water on tomato production. Agric. Water Manage. 78: 25–38.

Mandal, M.A.S. and Dutta, S.C. 1995. Crop Diversification: Findings from a field research programme. Published by The University Press Limited, Red Crescent Building, 114 Motijheel C.A., Dhaka 1000.

Minhas, P.S. 1996. Saline water management for irrigation in India. Agric. Water Manage. 30: 1–24.

Michael, A.M. 1978. Irrigation: Theory and Practice. 1st Edition. Vikash Publishing House Pvt. Ltd. New Delhi. 801 p.

Mridha, M.A.K., Rashid, M.H., Islam, M.S., and Alam, M.S. 2001. Irrigation requirement of wheat under different soil types and agro-climatic conditions, Annual Research Report 2001, IWM Division, Bangladesh Agricultural Research Instittue, Gazipur.

Majumdar, D.K. 2004. Irrigation water management: Principles and Practice, 3rd printing, Practice Hill Company of India Private Limited, New Delhi 11001, India.

Pasternak, D., De Malach, Y., 1995. Crop irrigation with saline water. In: Pessarakli, M. (Ed.), Handbook of Plant and Crop Stress. Marcel Dekker, Inc., NY, pp. 599–622.

Robinson, R.W. and Decker-Walters, D.S. 1997. Curbits (Crop Production Science in Horticulture), CABI, ISBN 0851991335. www.cuke.hort.ncsu.edu/curbit/wmelon.

Siringam, K., Juntawong, N., Cha-um, S. and Kirdmanee C.2011. Salt stress induced ion accumulation, ion homeostasis, membrane injury and sugar contents in salt-sensitive rice (*Oryza sativa* L. spp. indica) roots under isoosmotic conditions. Afr. J. Biotech 10: 1340-1346.

Shalhevet, J. 1994. Using water of marginal quality for crop production: major issues. Agric. Water Manage. 25: 233–269.

Shannon, M.C., Grieve, C.M. 1999. Tolerance of vegetable crops to salinity. Sci. Hort. 78: 5–38.

Sardar, P.K., Hossain, M.M. and Howlader, M.M. 2013. Production of high value curbit crops. A way of adaptation to the coastal saline areas of Khulna. On Farm Division, Bangladesh Agricultural Research Institute, Daulatpur, Khulna.

Sardar, P.K., Hossain, M.M. and Howlader, M.M. 2013.OFRD Khulna: Activities and Achievements, Bangladesh Agricultural Research Institute, Daulatpur, Khulna.

Yesim, E., Yuksel,A.N. and Orta,A.H. 2001. The Effects of Deficit Irrigation on Watermelon Yield, Water Use and Quality Characteristics. Pakistan Journal of Biological Sciences, 4: 785-789.

Zhang, Y., Kendy, E., Qiang, Y., Changming, L., Yanjun, S., Hongyong, S. 2004. Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in NorthChina Plain. Agric. Water Manage. 64: 107–122.

Rabi crop establishment methods for increasing land productivity in the coastal zone of Bangladesh

M.N. Rahman[1], M.G.M. Amin[1], M.K. Mondal[2] and E. Humphreys[2]

[1]Bangladesh Agricultural University, Bangladesh, nefaur25@gmail.com, maminbau@yahoo.com
[2]International Rice Research Institute, Bangladesh and Philippines, m.mondal@irri.org, e.humphreys@irri.org

Abstract

Cropping intensity in the coastal zone of Bangladesh is low, with much land lying fallow during the dry season. While many farmers cultivate *rabi* crops such as sesame, mungbean and grass pea, yields are low (0.5-1 t/ha). Furthermore, sesame and mungbean are not sown until mid-February to early March and as a result early kharif rains and cyclonic storms often cause crop damage. Early establishment (December) of *rabi* crops would reduce the risk of damage by rains and cyclones, and allow for the growth of high yielding and high value crops such as sunflower and maize. However, soil moisture content in December is often too high for tillage. Therefore, no till methods of crop establishment are needed. Traditional practice for crops such as maize and sunflower is to sow into cultivated soil, and to hill up the crops to prevent lodging. An experiment was therefore conducted from December 2013 to May 2014 in Khulna District to evaluate crop establishment methods for sunflower and maize. Dibbling shortly after *aman* harvest (in early December) was compared with sowing after tillage (after the soil had dried sufficiently for use of a two-wheel tractor operated power tiller (farmers' practice, T1)). There were three dibbled treatments: T2: dibbling in non-tilled, almost saturated soil with 5 t ha^{-1} of rice straw mulch applied immediately after sowing; T3: as for T2 but without mulch; and T4: as for T3 but with tillage (soil spading) and earthing 30 d after sowing. The dibbled treatments were sown on 10 December 2013, while the tilled treatment was sown on 4 February 2014. Early sown sunflower and maize produced grain yields of about 2 and 6 t ha^{-1}, respectively, despite the lack of irrigation (one irrigation of only 9 mm after urea topdressing 55 d after emergence). Delaying sowing to 4 February reduced sunflower yield to 2.2 t ha^{-1}, while the late sown maize was destroyed by the early *kharif* rains. The results demonstrate the high potential for increasing crop production in the coastal zone by early establishment of *rabi* crops such as maize and sunflower.

Key message: Sunflower and maize can be established by dibbling several weeks earlier than farmers' practice (tillage), with greatly reduced risk of damage from early *kharif* rains and cyclones.

Keywords: dibbling, mulch, sunflower, maize, soil cracks

1. Introduction

The coastal zone of Bangladesh, the most vulnerable area of the eastern Ganges basin, occupies about 30% of the country's land area and is home to some of the world's poorest people. The livelihoods of the people of the coastal zone depend primarily on agriculture. Of the 2.86 Mha of coastal and offshore lands of Bangladesh, about 1.06 Mha of arable land are affected by varying degrees (0.3 to 70 dS m^{-1}) of salinity (SRDI 2012). Cropping intensity in the coastal area is low due to soil salinity, unavailability of quality irrigation water in the dry season (Rahman and Ahsan 2011) and the late harvest of the *aman* crop, which prevents timely establishment of *rabi* crops (Mondal et al. 2015). Peak salinity of the river water during the dry season exceeds 5 dS m^{-1} across about 59% of the coastal zone, while river water salinity is less than 2 dS m^{-1} in about 39% of the region (SRDI 2012). Other challenges to agricultural productivity include excessive flooding during the rainy season, severe cyclonic storms, and tidal surges throughout the year.

The major cropping patterns in medium salinity areas of southwest Bangladesh are *aman-rabi* and *aman*-fallow. The predominant cropping practice in the study area, polder 30 in Batiaghata *Upazila*, is traditional rainy season *aman* rice (July to December), followed by sesame (on about 80% of the land area). The sesame is not planted until mid-February to early March because the soil is too wet for tillage prior to this (Ritu and Mondal 2006). As a result, the sesame crops are often damaged and sometimes completely destroyed by early rainfall in March and April and by cyclonic events in May (Mondal et al. 2015). The soil is too wet for tillage until February because the farmers grow photoperiod sensitive local rice varieties that are not harvested until December, by which time the weather is cold and foggy, with little or no soil evaporation until the weather starts to warm up at the end of January. Furthermore, water drains very slowly from the silty clay soils that predominate in the region.

Replacement of the local *aman* varieties with modern high yielding *aman* varieties (HYV) with earlier maturity would allow for drainage of the fields in early November, harvest in mid- to late November, and thus vacant fields for *rabi* crop establishment in December. However, excessive water depth during the rainy season is a major constraint to the use of HYV. Several recent studies have shown that, given the ability to drain excess water, HYV can be successfully grown during the rainy season with yields of 4 to 5 t ha^{-1} (Bhattacharya et al. 2015; Mondal et al. 2015; Saha et al. 2015). Furthermore, Mondal et al. (2015) showed that it is possible to manipulate the sluice gate in a sub-polder to enable effective drainage, and to harvest HYV before the end of November. The early *aman* harvest then creates the opportunity to grow high yielding and high value crops such as maize and sunflower. Early planting of these crops is desirable for many reasons including: (i) to make better use of residual soil moisture, (ii) to avoid exposing the crop to high soil salinity, which increases as the dry season progresses, (iii) to avoid damage from the early *kharif* rains and cyclones in May, and (iv) to avoid grain filling during the hottest time of the year. However, soil moisture may be too high for tillage shortly after rice harvest, especially on the heavy textured soils of the coastal zone. Therefore, no or reduced till methods of crop establishment are needed. The present study was therefore undertaken to evaluate crop establishment techniques for maize and sunflower in a medium salinity region of the coastal zone.

2. Materials and methods

2.1 Site

A field experiment evaluating establishment methods of sunflower and maize was conducted from December 2013 to May 2014 in polder 30 at Kismat Fultola village (22.7263°N, 89.5163°E) in Batiaghata *Upazila*, Khulna District. The area belongs to the agro-ecological zone of the Ganges tidal floodplain. The climate is subtropical, with average annual rainfall of 1,850 mm, a cool short winter from December to February with monthly mean minimum temperatures of 12–15˚C, and a hot summer in April to June (monthly mean maximum temperatures of 37–38°C).

The soil in the experimental field was a silty clay with a bulk density of 1.45 g cm^{-3} at 15 cm (Mondal et al. 2006). Salinity of the topsoil (0–15 cm) varies from 4.0 to 12.5 dS m^{-1} (electrical conductivity of the saturation extract) in the dry season and remains below 4.0 dS m^{-1} in the wet season (Mondal et al. 2006). River water salinity remains below 1 dS m^{-1} from July to December and gradually increases from January to a peak of around 20 dS m^{-1} in April or May (Mondal et al. 2006). The salinity of the groundwater at 40 m depth at the study site is about 4 dS m^{-1} throughout the year. The experimental site has a long history of transplanted *aman* using traditional varieties, followed by *rabi* crops, usually sesame. In the two years preceding the experiment high yielding varieties of *aman* were grown.

2.2 Experimental design

The experiment compared two *rabi* crops (sunflower, maize) and four establishment methods (see below) in a randomized complete block design with five replicates. Plot size was 5 m × 10 m and there was a buffer of 0.5 m between plots. The establishment methods were:

T1: dibbling after plowing with a power tiller powered by a two-wheel tractor (farmers' practice)

T2: dibbling in non-tilled, saturated soil with 5 t ha^{-1} (~100 mm thick) of rice straw mulch applied immediately after sowing, between the rows

T3: as for T2 but no mulch

T4: as for T3 but with tillage (using a spade) to loosen the soil followed by earthing up of the plants once soil moisture had decreased to field capacity (30 d after sowing, DAS)

2.3 Crop management

The *aman* crop was drained in early November 2013 and harvested in the third week of November, with the straw removed at ground level. The non-tilled treatments (T2-4) were sown by dibbling into the saturated soil on 10 December, while sowing of T1 was delayed until the soil was dry enough for tillage using a tiller powered by a two-wheel tractor on 2 February followed by sowing on 4 February.

Crop management was according to BARI recommendations (Hossain et al. 2006). Maize (Pacific-984; duration 125–135 d) and sunflower (Hysun-33; duration 110–120 d) were sown on a rectangular grid with two seeds per intersect ("hill") at a depth of 2 cm. Hill spacing of sunflower and maize was 60 cm x 45 cm (3.7 hills m^{-2}) and 45 cm x 30 cm (7.1 hills m^{-2}), respectively. Plants were thinned to one plant per hill 15 d after emergence (DAE).

The dose of N-P-K-S-Zn-B was 258-58-140-33-4-2 kg ha^{-1} for maize, and 55-26-25-20-1-2 kg ha^{-1} for sunflower, as per BARI recommendations (Hossain et al. 2006). All the fertilizer except for 50% of the urea was applied immediately after sowing by removing a chunk (15 cm x 10 cm x 10 cm, LxWxD) of soil about 7 cm to the side of each seed position, applying the correct amount of fertilizer to the hole using a calibrated dispenser, and replacing the soil. The rest of the urea was broadcast 55 d after DAE followed by a light irrigation (~9 mm, using a hand held hose) to wash the urea into the soil. There were no other irrigations because of the increasing salinity (from February onwards) of the water in the *khal* adjacent to the experimental site (Mondal et al. 2015).

Disease and insect pests were effectively controlled when necessary as per BARI recommendations (BARI 2011). Leaf blight of sunflower was controlled by applying Altima Plus 40 WP (emamectin benzoate + thiamethoxam) at 75 g/ha on 5 March 2014. Hairy caterpillar of sunflower was controlled by applying Knowine 50 WG (carbendazim 50%) on 11 March 2014 at 1.0 kg/ha. Preventative spraying of the insecticide Virtako 40 WG (chlorantraniliprole 20% + thiamethoxam 20%) was done at 75 g/ha on 26 January and 9 February 2014.

2.4 Crop monitoring

Seven randomly selected (non-border) plants in each plot were tagged and monitored from 45 DAS to harvest to monitor crop development, height (every 15 to 18 d) and yield components at maturity. Crop development stages were taken as the date when four of the seven tagged plants had reached each stage.

The start of flower bud initiation in sunflower was taken as the date when the terminal buds formed a miniature floral head at the apex of the stem. The start of flowering was determined as the date when all disk florets were open. The date when 80% of the seeds had become hard in each flower head was also recorded. Physiological maturity was taken as the date when all the seeds had turned black and shiny. At maturity, sunflower head diameter, the number of seeds and empty florets per head, and the weight of 1000 seeds were determined. Head diameter was measured with a 30 cm stainless steel scale then the heads were sun dried for three days and threshed manually prior to counting and weighing 1000 seeds.

In maize, tasseling was taken as the stage when all branches of the tassel were visible, and silking when the silks were visible outside the husks. The milky stage was the date when all the kernels were yellow and filled with white (“milky”) fluid. Physiological maturity was defined as the date when the kernels had turned shiny and golden. At maturity, plant density, the number of cobs per plant, cob length, cob circumference at the widest part, the number of kernels cob^{-1} and 1000-kernel weight were determined from the seven tagged plants.

Seed/grain yield of both crops was determined by harvesting and manually threshing all the plants in each plot for both crops. The sunflower of T2, T3 and T4 were harvested on 10 April 2014, while T1 was harvested on 25 May 2014. Treatments 2-4 of maize were harvested on 5 May 2014. Most of the maize plants in T1 were destroyed by heavy rainfall on 2 May 2014, when this treatment was at the silking stage. The sunflower heads and cobs were sun dried for 3 d prior to manual threshing and weighing of the grain. Grain moisture content at the time of weighing was not determined.

The crop data were analyzed for significance of difference between the treatment means at 95% probability using the Statistical Tool for Agricultural Research (STAR) software (STAR 2014).

2.5 Water monitoring

2.5.1 Irrigation

Irrigation amount was determined from the pump discharge rate and the time taken to irrigate. The discharge rate was determined by measuring the time taken to fill a 50 L drum (average of three determinations).

2.5.2 Soil water tension

Soil water tension was measured daily using tensiometers installed at 37.5 cm depth in one replicate of T2, T3 and T4 in both the maize and sunflower. The tensiometers were installed on 21 January 2014 and monitored until the soil became too dry for their use (late March).

2.6 Weather

A standard rain gauge and a USWB Class A evaporation pan were installed about 200 m from the experimental field and monitored each morning at 9 am. Daily maximum and minimum temperature were collected from the Khulna meteorological station, about 8 km north of the experimental site.

3. Results and discussion

3.1 Weather

Rainfall was low throughout the growth period of all crops (Fig. 1). There was a timely fall of 23 mm on 16-17 February, just before flower bud initiation of the sunflower, and 13 mm on 23-25 March during the latter part of seed filling of the sunflower. No other rain was received during the growth period of T2-4 of both crops. The late sown sunflower (T1) received 40 mm of rain on 2-4 May at the beginning of seed development.

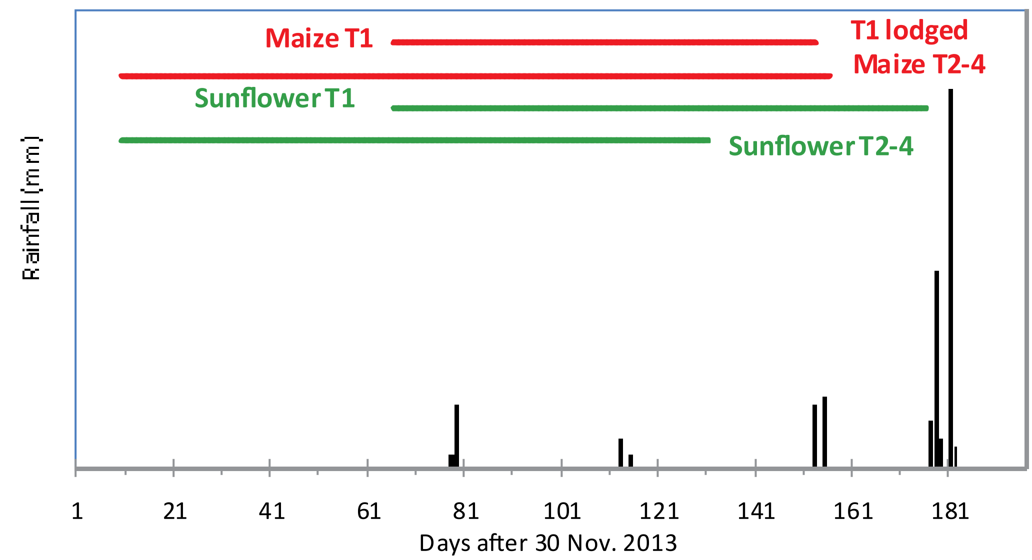


Fig. 1 Daily rainfall throughout the cropping period (horizontal lines show the cropping period from sowing to harvest for each treatment; maize T1 was destroyed by a storm at silking, which caused lodging).

Monthly pan evaporation increased from 60 to 80 mm from December to February, and then increased more rapidly to a peak of 199 mm in April (Fig. 2). Monthly mean daily maximum temperature varied from 26˚C (January) to 36˚C (April), while mean minimum temperature varied from 15˚C (in January) to 26˚C (in May). Mean daily sunshine hours were least in January (5.4 h) and highest in April (8.8 h).

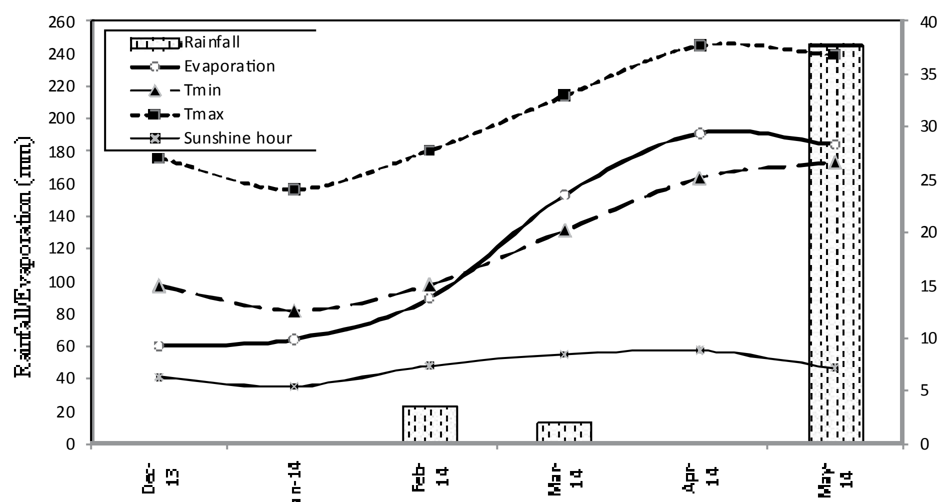


Fig. 2. Monthly total rainfall and evaporation at the study site, and monthly means of daily sunshine hours, and maximum (Tmax) and minimum (Tmin) temperatures at Khulna weather station, from December 2013 to May 2014.

3.2 Soil water tension

Soil water tension at 37.5 cm increased after sowing until a light irrigation was applied on 7 February (Fig. 3). This small amount of irrigation decreased soil tension in the non-mulched treatments because the soil was cracked (2-4 cm wide cracks to a depth of 20 to 35 cm) and the irrigation water flowed down the cracks and wet the soil at depth. The irrigation did not affect soil water tension in the mulched treatments as, while there were also large soil cracks, the width and depth of cracking was less in these treatments at this stage. Soil water tension at 37.5 cm was much lower in the mulched treatment (T2) than in the non-mulched treatments (T3 and T4) during the first three months in the sunflower, and during the first two months in the maize (Fig.

3). The slower soil drying in the mulched treatments was probably due to reduced soil evaporation – it is well established that mulch reduces soil evaporation, more so when the plant canopy is small (Bond and Willis 1969). As the season progressed, soil drying in the mulched treatments increased so that soil water tension became similar to that in the non-mulched treatments in early March (maize) and in late March (sunflower). As there was still a cover of mulch on the soil surface up to maturity, the greater drying in the mulched treatments at 37.5 cm as the season progressed probably reflects extraction of soil water by the roots. The more rapid soil drying during the first two months in the mulched maize than in the mulched sunflower suggests faster water uptake by the maize at that depth during the vegetative stage.

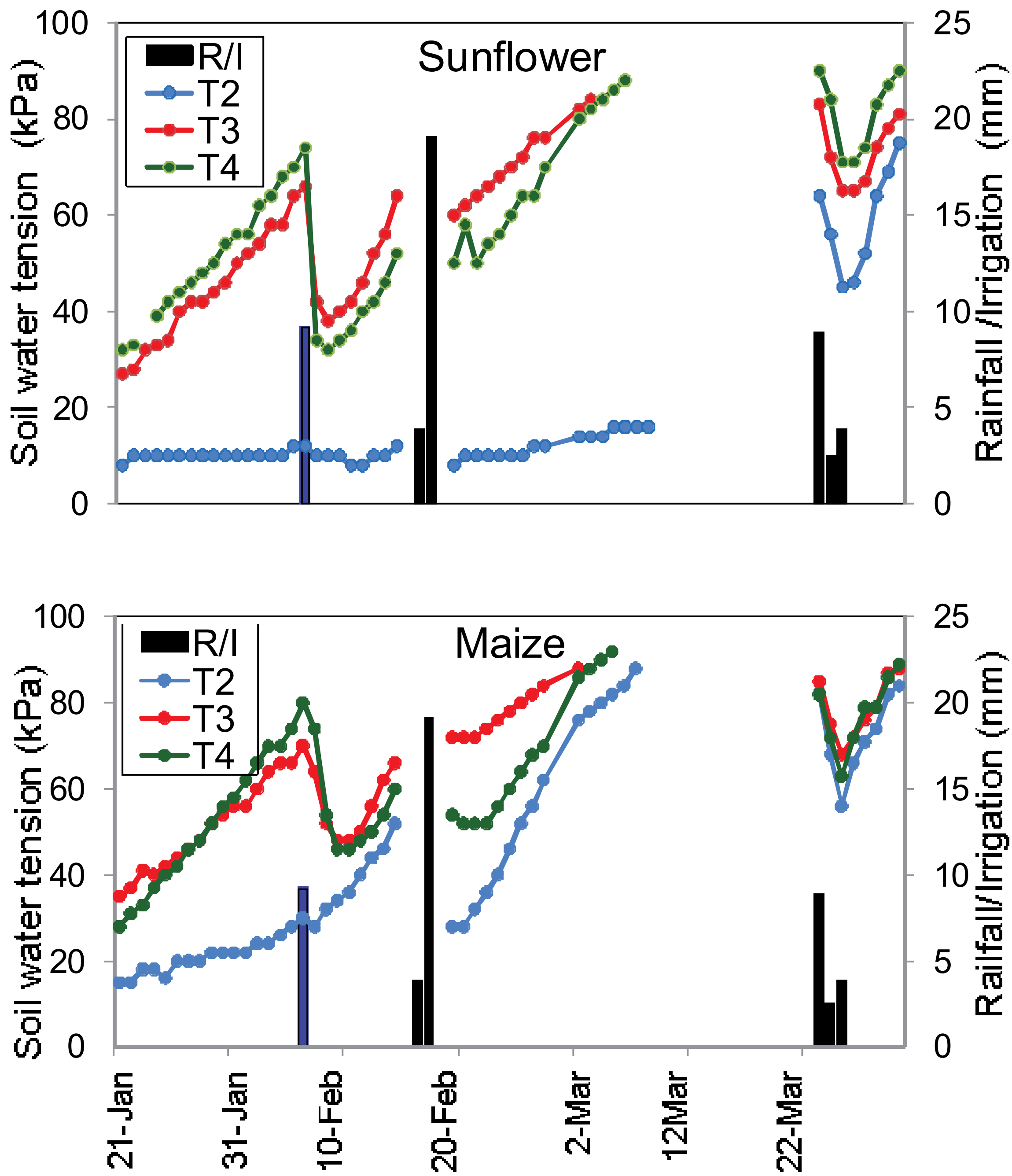


Fig. 3. Soil water tension at 37.5 cm depth for different establishment methods of sunflower and maize (R: rainfall, black bars; I: irrigation, blue bar).

3.3 Performance of sunflower

3.3.1 Sunflower development

Growth duration of the early sown sunflower (T2-4) was 117-121 d, compared with 110 d for the late sown sunflower (T1) (Table 1). Flower bud initiation and physiological maturity of T2-4 occurred 68-70 and 109-113 DAS, respectively. There was a small but consistent trend for mulch to delay development (by 3-4 d at physiological maturity, PM). Crop duration of the later sown sunflower (T1) was about 10 d less than that of T2-4, due to a shorter vegetative phase (shorter time from sowing to the start of flower bud initiation). In the same year, Bhattacharya et al. (2015) also found a reduction in duration of sunflower with delay in sowing from mid-December (from 113-115 d) to mid-January (107-108 d), and a small delay (1-4 d) in maturity with mulching, at Patuakhali.

Table 1. Development stages of sunflower (DAS)

Treatment	Start of flower bud initiation	Start of flowering	80% seeds hard	Physiol. maturity
T1 – cultivated, sown 4 Feb	58	74	89	104
T2 – ZT, mulch, sown 10 Dec	70	84	102	113
T3 – ZT, no-mulch, sown 10 Dec	68	82	100	109
T4 – ZT, no-mulch, sown 10 Dec, spading & earthing up 30 DAS	70	83	100	110

3.3.2 Growth parameters of sunflower

There was a consistent trend for mulch to increase plant height in comparison with all other treatments, with significant differences at maturity (Fig. 4, Table 2). Plant height at maturity with conventional practice (T1) and in the spaded treatment (T4) was significantly lower than in both the mulched and non-mulched zero tillage treatments, by around 10 cm. The mulched sunflower also had significantly larger head diameter than in all other treatments, while head diameter with conventional practice was significantly lower than in all other treatments.

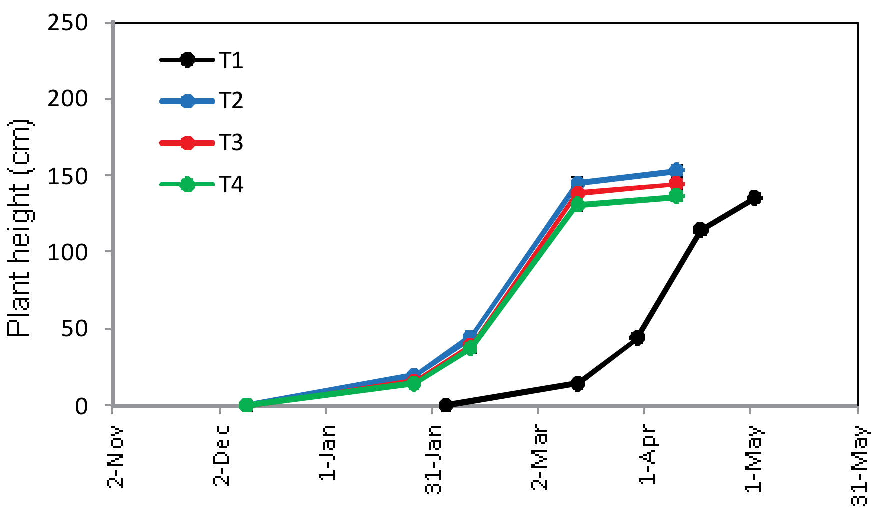


Fig. 4. Plant height of sunflower during the growing period as affected by establishment method. Vertical bars (barely visible) are standard errors of the means.

3.3.3 Yield and yield components of sunflower

The number of heads per m^2 was the same in all treatments (3.7 m^{-2}). The number of florets per head in the early sown treatments (1400-1480) was significantly higher than in the late sown treatment T1 (1200) (Table 1). Floret fertility was slightly but significantly higher in the late sown treatment than in all other treatments except T3 (dibbled, no mulch), and significantly lower in the mulched treatment than in all other treatments. Average seed weight was significantly lower with late sowing (by about 20%) than in the early sown treatments. There appears to be a systematic error in seed weight, as the 1000 seed weight of Hi-Sun33 is typically 59-69 g observed by Rahman (2012) in the coastal region of Bangladesh and 52-57 g recorded by Nasim et al. (2012) in Pakistan, however, the relative seed weight of the treatments appears sensible. The high 1000 seed weight is probably due to lack of proper drying of the seed.

Seed yield of all early planted treatments was similar (2.9-3.2 t ha^{-1}) and about 50% higher than that of the late sown treatment, mainly due to lower seed weight, and partly due to fewer florets per head (Table 2). The poorer performance of the late sown crop is probably due to a combination of factors: lower residual soil water content at the time of sowing, higher evaporative demand throughout the crop growth period and higher soil salinity. The lower seed weight indicates stress during the grain filling period, most likely water deficit stress due to the lack of rainfall and the higher evaporative demand experienced by this treatment. Yields of 3 t ha^{-1} of the early sown treatments were very good given the lack of irrigation, reflecting the ability of the crop to make use of residual soil water to depth, and the timely rain at flower bud initiation. It is likely that the yields are overestimated by about 50% due to insufficient drying. BRAC (2010) reported an average yield of 3 t ha^{-1} of sunflower in the region during the *rabi* season using two to three irrigations. Rashid et al. (2014) reported a yield of 3.1 t ha^{-1} for 14 January planting and 2.5 t ha^{-1} for late planting (5 March) in the coastal zone. Rashid et al. (2015) showed that yield declined by 22 kg ha^{-1} for every day delay in sowing after 5 December.

Table 2**.** Plant height at maturity, yield and yield attributes of sunflower as affected by establishment method (the number of heads per m^2 was 3.7 in all treatments)

Treatment	Plant height (cm)	Head diameter (cm)	No of florets[1] per head	Floret fertility (%)	1000-seed wt (g)	Seed yield (t ha^{-1})
T1	135	17.8	1200	97.4	69.6	2.2
T2	148	23.5	1480	90.7	93.7	3.2
T3	144	21.1	1460	94.9	87.3	2.9
T4	136	21.9	1400	93.9	87.6	3.1
$LSD_{0.05}$	7.6	1.2	92	2.6	6.8	0.4
CV %	11.4	12.5	14.1	5.8	17.09	9.4

[1]Disk flowers

3.4 Performance of maize

3.4.1 Maize development

The early sown maize (T2-4) reached the tasselling stage 91-94 DAS, and physiological maturity at 139-143 DAS (Table 3). Tasseling of the late sown maize (T1) occurred 7-10 d earlier and silking occurred 7-11 d earlier than of the earlier sowing crops. However, the late sown maize was destroyed by lodging as a result of strong winds and 35 mm rain in early May (Fig. 1) when the crop was at the silking stage. There was a small but consistent trend for mulch to delay tasseling (by 2-3 d), silking stage (by 3-4 d), the milky stage (by 3-6 d), and physiological maturity (by 3-4 d).

Table 3. Development stages of maize (DAS)

Treatment	Tasseling	Silking	Milky kernel stage	Physiol. maturity
T1 – cultivated, sown 4 Feb	84	87	destroyed[1]	destroyed
T2 – ZT, mulch, sown 10 Dec	94	98	119	143
T3 – ZT, no-mulch, sown 10 Dec	91	94	113	139
T4 – ZT, no-mulch, sown 10 Dec, spading & earthing up 30 DAS	92	95	116	140

[1]Crop lodged as a result of rain and wind at the silking stage

3.4.2 Maize growth parameters

There was a consistent trend for significantly taller maize plants in the mulched treatment than in other treatments sown at the same time, with significant differences during the second half of the season (Fig. 5, Table 4). At maturity, the mulched plants were significantly taller than the other early sown treatments, by 30-40 cm. But spading and earthing up gave the longest cobs (19.8 cm).

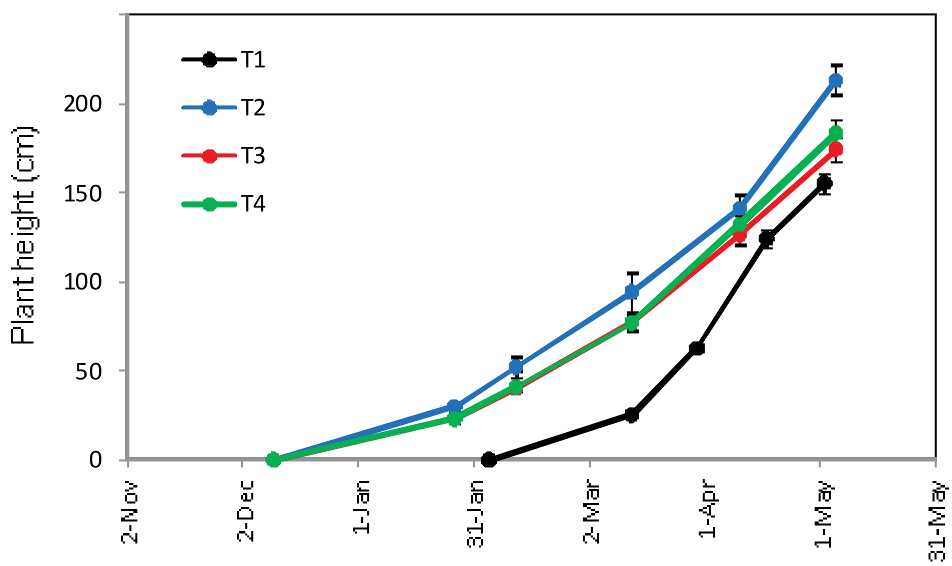


Fig. 5. Plant height of maize during the growing period as affected by establishment method (T4 lodged in early May as a result of rain and strong wind). Vertical bars are standard errors of the means.

3.4.3 Yield and yield attributes of maize

Plant density was 7.1 m^{-2} in all plots and very few plants had more than one harvestable cob per plant. There were no significant treatment effects on the number of kernels per cob (mean 385) (Table 4). Average kernel weight was significantly higher with spading and earthing up than in the no till treatments. Maize yield ranged from 5.7 to 6.2 t ha^{-1}, with no significant differences between treatments. In well-irrigated maize at Patuakhali, Bhattacharya et al. (2015) achieved higher yields (about 9 t ha^{-1}) in the same season, with 500 to 600 kernels per cob and 1000 kernel weight of 350 to 370 g (J. Bhattacharya pers. comm.). In the same region, BRAC (2010) obtained maize yield of 8 t ha^{-1} using two to four irrigations.

Table 4. Growth, yield and yield attributes of maize as affected by establishment method (the number of cobs m^{-2} was 7.1 in all treatments)

Treatment	Plant height (cm)	Cob length (cm)	Cob perimeter (cm)	No of kernels cob^{-1}	1000 kernel wt (g)	Seed yield (t ha^{-1})
T2	213	17.6	12.4	395	237	5.7
T3	174	14.8	12	373	248	5.7
T4	183	19.8	12.9	388	282	6.2
$LSD_{0.05}$	10	1.7	ns	ns	27	ns
CV %	11	20.5	12.9	37.5	22.7	12.

4. General discussion

Dibbling of sunflower and maize into moist soil (close to saturated) on 10 December, shortly after *aman* harvest, produced yields of around 3 and 6 t ha^{-1}, respectively. These yields were achieved in the absence of irrigation (apart from 9 mm applied after urea topdressing), making use of residual soil moisture and a small amount of in-season rainfall (36 mm in two events). There was a 50% reduction in yield of the late sown sunflower following conventional tillage once the soil had dried sufficiently. Conventional tillage delayed crop establishment by almost two months, and the reduction in yield was probably partly due to soil water deficit during the latter part of the season, resulting in fewer florets per head and lower seed weight. However, there is also evidence that delaying sowing of sunflower beyond mid-December also reduces yield of well-irrigated crops (Rashid et al. 2015). The late sown maize was destroyed by wind and rain at the silking stage, which caused lodging. If it had not been destroyed at that stage, it would probably have been damaged by the 204 mm of rain that fell in the last week of May. The late sown sunflower matured just before this rain and thus serious damage was avoided.

The work demonstrates that early establishment of sunflower and maize is possible and can produce good yields even in the absence of tillage and irrigation. Furthermore, early sowing greatly reduces the risk of crop damage as a result of strong wind and rain that occur in April in some years, and the risk of damage from cyclonic storms that tend to occur in May. The shorter duration of sunflower is also an advantage in terms of crop water requirement and risk of damage from early rains.

Mulch was effective in conserving soil moisture during the vegetative stage of the crops (as evidenced by the soil tension data, and the better growth and visual appearance of the mulched crops), but this did not translate into yield. In the case of sunflower, yields of the early sown sunflower were similar to those expected of well-irrigated crops, suggesting that these crops did not suffer from water deficit stress, despite the lack of irrigation. This may have been because of three main factors: (i) the high plant available water on the silty clay soil (~200 mm in the top 60 cm, Michael 1985), which was saturated to depth at the time of seeding, (ii) the strong tap root in sunflower and its ability to extract residual soil water to about 1 m depth (Jensen, undated: http://homeguides.sfgate.com/kinds-roots-sunflowers-have-60427.html), and (iii) the low evaporative demand during the first two months after sowing (Fig. 2). In the case of maize, yields were about two-thirds of those of a well-irrigated maize crop in the region, suggesting increasing soil water deficit stress as the maize season progressed, as evidenced by fewer kernels per cob and lower kernel weight than in high yielding crops of this variety. The lack of effect of mulch in the maize may have been due to the fact that the soil in all treatments ultimately dried to the degree that T2-4 experienced similar levels of water deficit stress during the second half of the maize season.

5. Conclusions

This study shows the feasibility of growing sunflower and maize in a medium salinity region of the coastal zone, with crop establishment in almost saturated soil shortly after *aman* harvest. Early establishment (early December) by dibbling in non-tilled soil gave much higher yield than late establishment after the soil had dried sufficiently for tillage to take place. Late establishment resulted in destruction of the maize crop by early rains. On the silty clay soil at this location, respectable yields of sunflower (est. 2 t/ha) and maize (6 t/ha) were achieved with only one light irrigation. Mulching conserved soil moisture, reduced soil cracking and improved crop growth, but did not increase yield, probably because all crops eventually ran out of water. Further studies on the use of mulch and standing stubble, soil water dynamics and establishment method are needed across a range of situations (soil type, land elevation) to fine tune the guidelines for the production of high yielding *rabi* crops in the polders of the coastal zone of Bangladesh, and to determine the profitability of production.

Acknowledgements

This paper presents findings from G2 'Productive, profitable, and resilient agriculture and aquaculture systems', a project of the CGIAR Challenge Program on Water and Food. The authors are grateful for high quality technical assistance from Amal Ray, Lincoln Ray, Tanmoy Ray and Mithun Ray.

References

Agele, S.O., Olaore, J.B. and Kinbode, F.A.A. 2010. Effect of some mulch materials on soil physical properties, growth and yield of sunflower (*Helianthus annuus, L*). Advan. Environ. Biol., 4(3):368–375.

BARI (Bangladesh Agricultural Research Institute). 2011. Regional yield trial of sunflower varieties/lines. Regional review paper. Jessore. pp.136–138.

Bhattacharya, J., Mondal, M.K., Humphreys, E., Saha, N.K., Rashid, M.H., Paul, P.C. and Ritu, S.P. 2015. Rice-rice-*rabi* cropping systems for increasing the productivity of low salinity regions of the coastal zone of Bangladesh. These proceedings.

Bond, J.J. and Willis, W.O. 1969. Soil water evaporation – surface residue rate and placement effects. *Soil Sci. Soc. Am. Proc.* 33: 445–448.

BRAC. 2010. Crop intensification for achieving food self-sufficiency in the coastal regions of Bangladesh. Dhaka. Bangladesh.

Hansen, V.E., Israelsen, O.W. and Stringham, G.E. 1980. Irrigation principles and practices. John Willey and Sons Inc. USA, p 44.

Haque, S.A. 2006. Salinity problems and crop production in coastal regions of Bangladesh. Review article. Pak. J. Bot., 38(5):1359–1365.

Hossain, M.H, M.M. Rahman, M.H. Rashid, A.T.M. Farid, M.A. Quyum, M. Ahmed, M.S. Alam, and K.M. Sahahuddin. 2006. Krishi Projukti Hatboi (Handbook on agro-technology), fourth edition, Bangladesh Agricultural Research Institute, Gazipur 1701, Bangladesh.

Jensen, L. What kind of roots do sunflower have? Available at: http://homeguides.sfgate.com/kinds-roots-sunflowers-have-60427.html

Michael, A.M. 1985. Irrigation theory and practice. Vikash Publishing House Pvt. Ltd, New Delhi, India. pp. 478-482.

Mondal, M.K. 1997. Management of soil and water resources for higher productivity of the coastal saline rice lands of Bangladesh. PhD thesis, University of the Philippines LosBanos, Philippines.

Mondal, M.K., S.P. Ritu, M.H.K. Choudhury, A.M. Chasi, M.A. Mannan, P.K. Majumder, M.M. Islam, and S.K. Adhikary. 2004a. Appropriate water management strategy for boro rice cultivation in the coastal saline environment. In proceedings of the workshop on Coastal water management and uptake technologies held at Hotel Castle Salam, Khulna, Bangladesh on 26 June 2004. pp.28–37.

Mondal, M.K., T.P. Tuong, S.P. Ritu, M.H.K. Choudhury, A.M. Chasi, P.K. Majumder, M.M. Islam, and S.K. Adhikary. 2006. Coastal water resource use for higher productivity: participatory research for increasing cropping intensity in Bangladesh. CAB International 2006. Environment and Livelihoods in Tropical 72 Coastal Zones, pp.72–85 (eds C.T. Hoanh, T.P. Tuong, J.W. Gowing and B. Hardy).

Mondal, M.K., Humphreys, E., Tuong, T.P., Rahman, M.N. and Islam. M.K. 2015. Community water management and cropping system synchronization: The keys to unlocking the production potential of the polder ecosystems in Bangladesh. These proceedings.

Nasim, W., A. Ahmad, A. Bano, R. Olatinwo, M. Usman, T. Khaliq, A. Wajid, H.M. Hammad, M. Mubeen and M. Hussain. 2012. Effect of nitrogen on yield and oil quality of sunflower (Helianthus annuuas L) hybrids under sub humid conditions of Pakistan. American J. Plant Science (3):243-251.

Rahman, M.M. 2012. Enhancement of resilience of coastal community in Bangladesh through crop diversification in adaptation to climate change impacts. Unpublished thesis of Masters in Disaster Management, BRAC University, Dhaka, Bangladesh.

Rahman, M.M. and M. Ahsan. 2011. Salinity constraints and agricultural productivity in coastal saline area of Bangladesh. Soil Resources in Bangladesh: Assessment and Utilization.

Rashid, M.H., S. Nasrin, and D. Mahalder. 2014. Zero tilled dibbled sunflower enables planting earlier and harvests more in the coastal saline area of Bangladesh. Int. J. Environ. Sci. Develop., 5(3):260–264.

Rashid, M.H., Hossain, F., Nath, D.K., Sarker, P.C., Ferdous, A.K. M. and Russel, T. 2015. Oil seed crops in rice based cropping systems in southern Bangladesh. These proceedings.

Ritu, S.P. and M.K. Mondal. 2006. Soil and water salinity relations in the southwest coastal region of Bangladesh. J. Progres. Agric., 17(1):249–256.

SRDI (Soil Resources Development Institute). 2012. Saline soils of Bangladesh. Soil fertility assessment, soil degradation and its impact on agriculture program of SRDI, Mrittika Bhaban, Krishikhamar Sarak, Farmgate, Dhaka 1215.

Saha, N.K., Mondal, M.K., Humphreys, E., Bhattacharya, J., Rashid, M.H., Paul, P.L.C. and Ritu, S.P. 2015. Triple rice in a year: Is it a feasible option for the low salinity areas of the coastal zone of Bangladesh? These proceedings.

STAR. 2014. Biometrics and Breeding Informatics, PBGB Division, International Rice Research Institute, Los Baños, Laguna. Available at http://bbi.irri.org/

Screening of watermelon varieties for the coastal area of Khulna

M.M. Hossain, S.M. Zaman, P.K. Sardar and M.M. Howlader

Bangladesh Agricultural Research Institute, Bangladesh mosharraf74@yahoo.com, sm_zaman60@yahoo.com, dr.proshanta74@yahoo.com, mohsinhawlader@yahoo.com

Abstract

A field experiment was conducted at a multi-location trial site, Dacope, during the 2011-12 and 2012-13 *rabi* seasons. The aim of the study was to evaluate the performance of watermelon varieties in a moderately saline area of the coastal zone. The design of the field experiment was a randomized complete block with four replicates. Four commercial watermelon varieties viz. World Queen, Field Master, Hunter and Winner, were evaluated. Significant variation was found in yield and yield contributing characters among the varieties. In both years Hunter (52.2 t/ha) and Winner (49.2 t/ha) had the highest fruit yield, while the lowest fruit yield (44.7 t/ha) was from Field Master.

Key message: Hunter was the best performing watermelon variety at Khulna in terms of both yield and sweetness.

Keywords: yield, brix, salinity

1. Introduction

Watermelon originates from the Middle East to the Mediterranean and belongs to the family *Cucurbitaceae* (Maynard et al. 2001). There is remarkable diversity of watermelons, each having unique flavor, texture and appearance (Norman 1992). According to FAOSTAT (2009), melon is grown on 1.3 million ha producing 26.7 million tons. China is the leading country in production of melon (51%), followed by Turkey (6%) and the United States of America and Spain (4%). Melons are consumed as dessert, fresh-cut fruit and juice (Saftner and Lester 2009). The refreshing pulp, high nutritional value, sweet pleasant aroma, bright color, firm fresh texture, high sugar content (>10%) and good shape are important traits that make melons unique and a refreshing treat in Japan (Gusmimi and Whener 2005; De Melo et al. 2000; Long 2005; Seko 2004) with high profitability (Best 2001). Watermelon is now one of the popular summer fruits and an important labor-intensive cash crop in Bangladesh. Generally, it is grown in Chittagong, Comilla, Jessore, Faridpur, Rajshahi, Pabna and Natore districts. The total production area is 12,000 ha and total production is 100,000 tons (BBS 2005). Recently, commercially cultivation has taken place in the coastal areas of Khulna. But the yield of watermelon in the southern belt is less than that of other areas in Bangladesh. Suitable varieties, soil, climate, fertilization and other management practices are important for achieving potential yield of any crop. Among them, variety selection is one of the most important factors for obtaining higher yield. Suitable varieties are needed for the coastal region. Therefore, an experiment was undertaken to evaluate watermelon varieties in Khulna region.

2. Materials and methods

The experiment was conducted at the BARI multi-location site at Dacope during the 2011-12 and 2012-13 *rabi* seasons. The experiment was laid out in a randomized complete block design with four replicates and a unit plot size of 6 m × 6 m. The treatments were four watermelon varieties viz. World Queen, Field Master, Hunter and Winner. The land was fertilized with 92-35-125-18-1-1 kg/ha of N-P-K-S-Zn-B in the forms of urea, triple superphosphate, muriate of potash, gypsum, zinc sulphate and boric acid. Half of the nitrogen and all the phosphorus, potassium, sulphur, zinc and boron were applied during final land preparation. The remaining nitrogen was applied 30 d after sowing as a side dressing about 20 to 30 cm from the base the plants. Seeds were sown on 4 February 2012 and 8 February 2013 with a spacing of 2 m x 2 m. A 12 cm-thick straw mulch cover was applied immediately after sowing. Irrigation, weeding and other intercultural operations were done as and when required. The crop was harvested from 3 April to 15 May 2012 and 12 April to 20 May 2013. Fruit yield and yield contributing characters were determined on ten randomly selected plants from each plot, and the data were analyzed statistically. Mean differences were calculated by Duncan's Multiple Range Test (Gomez and Gomez 1984). Soil salinity of the experimental plot and rainfall were recorded during the crop growing period.

2.1 Soil salinity

Soil samples were collected and air dried, crushed and ground with a hammer and foreign matters and plant materials were removed. Then a soil solution was made by adding one part soil with five parts distilled water. The soil solution was shaken well for 30 minutes and then allowed to settle for one minute. EC was determined using a HANNA Model HI 8033 EC meter, which was calibrated with 0.01M KCl at 25^{o} C (Peterson 2002).

3. Results and discussion

3.1 Soil salinity

Soil salinity increased as the season progressed to maximum values of 8 to 10 dS/m (Fig. 1).

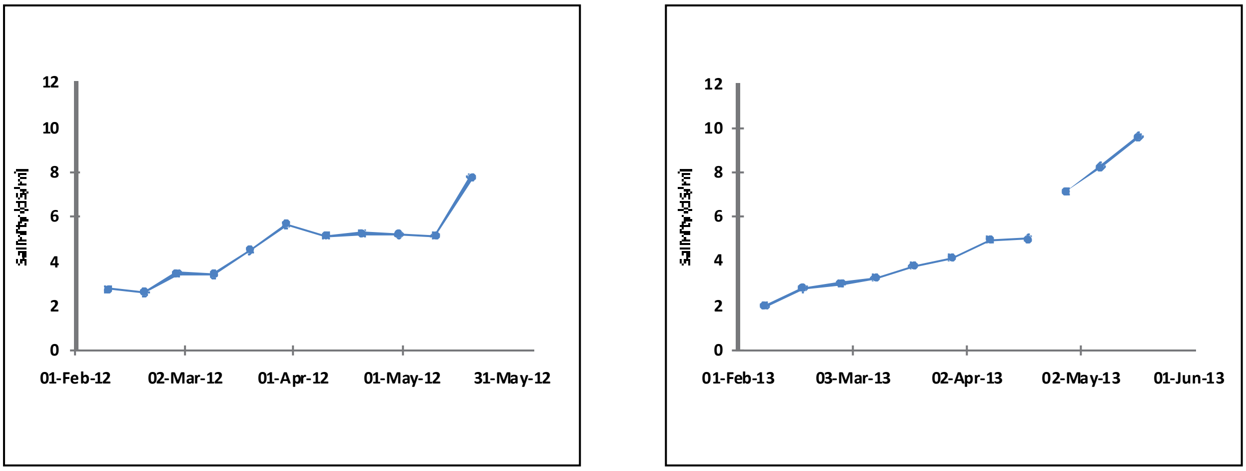


Fig. 1. Soil salinity during the watermelon season in 2012 (a) and 2013 (b).

3.2 Crop performance

Length and diameter of fruit, number of fruits per plant, individual fruit weight and fruit yield differed significantly among the varieties. Days to maturity varied slightly and ranged from 60 to 62 d for World Queen to 64 to 68 d for Hunter. Adelberg et al. (1997) stated that some cultivars were early while others were intermediate or late due to genetic and varietal differences. Mortality ranged from 23.9% (World Queen) to 11.6% (Hunter). No significant differences were found in the number of fruit per plant. Field Master and World Queen had the longest fruit length (~22 cm) and highest fruit diameter (~18.5 cm). No significant variation was observed in individual fruit weight. Hunter and Winner had the highest yield (49-52 t/ha) due to lower mortality. The findings of significant differences in fruit yield were consistent with the observations of other researchers (Izge et al. 2007; Sana et al. 2003; Tsegaye et al. 2007).

Table 1. Yield and yield attributes of watermelon varieties at the MLT site, Dacope, Khulna during 2011-12 and 2012-13 (pooled data)

Variety	Days to maturity	Mortality (%)	Fruit/plant (no.)	Fruit length (cm)	Fruit diameter (cm)	Individual fruit wt. (kg)	Fruit yield (t/ha)
World Queen	60-62	23.9	1.30	31.3	18.5	3.87	45.9
Field Master	60-63	19.2	1.25	32.3	18.4	3.69	44.7
Hunter	64-68	11.6	1.34	28.6	17.2	3.68	52.2
Winner	60-64	14.5	1.30	30.8	18.2	3.70	49.2
LSD (0.05)	-	3.5	NS	1.7	0.2	0.24	3.8
CV (%)	-	10.2	3.80	2.7	0.6	NS	3.9

Brix (%) also varied between the watermelon varieties. Highest Brix (12.5%) was measured in Hunter and the lowest (6%) from Winner (Fig. 2). According to Hosoki et al. (1990), sugar content in melon can be categorized into three classes. Fruit with Brix below 10 can be classified as class 1; 10-12, class; and above 12, class 3.

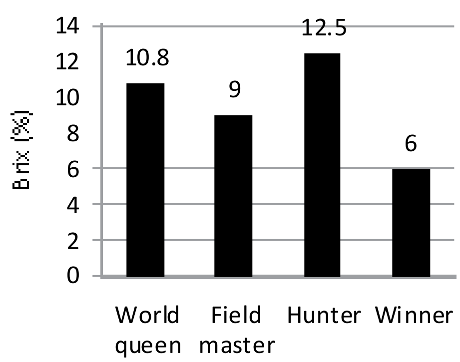


Fig. 2. Brix of the watermelon varieties.

4. Conclusions and recommendations

Out of four watermelon varieties, Hunter had the longest field duration (64-68 d), highest yield (52.2 t/ha), and highest Brix (12.5%). So Hunter may be recommended for fresh cut fruit and supplied to the local market due to its sweet taste as well as its high yield.

Acknowledgements

Thankful appreciation is due to the authority of the Sponsored Public Goods Resources (SPGR) project for support in terms of funds and support of officers and SPGR staff. Thanks is extended to Dr. Jalal Uddin Sarker, Chief Scientific Officer (former), On-Farm Research Division, Bangladesh Agricultural Research Institute, Joydebpur, Gazipur who gave us valuable suggestions and instruction. The authors are also grateful to all officers, Scientific Assistant (SA) and field staff for their cordial cooperation and inspiration to complete the project successfully.

References

Adelberg, J.W.; X.P Zhang and B.B. Rhodes. 1997. Micro Propagation of Water melon (*Citrullus lanatus*). In Biotechnology in Agriculture and Forestry 39. HighTech and Micropropagation V, Bajaj, Y.P.S. (Eds.). Springer Publication, New Delhi, Pages. 60.

Bangladesh Bureau of Statistics (BBS). 2005. Statistical yearbook of Bangladesh. Statistical division, Ministry of Planing, Dhaka 1000, Bangladesh.

Best, K. 2001. Economic profitability of four muskmelon varieties grown under field conditions. J. Agric. Sci. , 5: 21-25.

De Melo, M.L.S.; N. Narain and P.S. Bora. 2000. Characterization of some nutritional constituents of melon (*Cucumis melo* hybrid AF-522) seeds. Food Chem., 68:411-414

FAOSTAT.2009. Web page of the food and agriculture organization of the United Nations. Statistic Database. Production Statistics.

Gomez, K.A. and A.A. Gomez.1984. Statistical procedures for Agricultural Research. 2nd Edn. John Willey and Sons, New York. 207-208.

Gusmimi, G and T.C. Whener. 2005. Foundation of yield improvement in watermelon. 45: 141-146.

Hosoki, T.; A. Ishibashi; H. Kitamura; N. Kai; M. Hamada and T.Chota,1990. Classification of oriental melons based on morphological, ecological and physiological differences. J. Jap. Soc. Hort. Sci., 58: 959-970.

Izge, A.U. ; A.M. Kadams and A.A. Sajo, 2007. Agronomic performance of selected cultivars of pearl millet (*Pennisetum glaucum* L.R. Br.) and their hybrids in North-Eastern Nigeria. J. Agron., 6: 344-349.

Long, R.L. 2005. Improving fruit soluble solid contents in melon (*Cucumis melo* L.) (Reticulates group) in Australian production system. Ph.D. Thesis, Central Queensland University.

Maynard, D.N.; A.M. Dunlap and B.J. Sidori. 2001. Cantaloupe variety evaluation. Scient. Horticult., 8: 16-20.

Norman, J.C. 1992. Tropical Vegetable Crops. Stockwell Ltd. New York, ISBN-13: 978-0722325957, Page:252.

Peterson, L. 2002. Analytical Methods Soil, Water, Plant Material, Fertilizer. Soil Resource Development Institute. Dhaka. 45-48.

Saftner, R.A. and G.E. Lester. 2009. Sensory and analytical characteristics of a novel hybrid muskmelon fruit intended for the fresh-cut industry. Postharvest Biol. Technol., 51: 327-333.

Sana, M.; A. Ali; M.A. Malik; M.F. Saleem and M.Rafiq. 2003. Comparative yield potential and oil contents of different canola cultivars (Brassica napus L.). J.Agron., 2: 1-7.

Seko, T. 2004. Characteristics and quality of melon plant. Vegetable Hort. Melon, 2: 129-145.

Tsegaye, E; D. Nigussie and E.V. Devakara Sastry. 2007. Genetic variability for yield and other agronomic trats in sweet potato. J.Agron., 6: 94-99.

Section 7

Outscaling

Targeting improved cropping systems in the coastal zone of Bangladesh: A decision tree approach for mapping recommendation domains

P.K. Chandna[1], A. Nelson[1], M.Z.H. Khan[2], M.M. Hossain[3], M.S. Rana[4], M. Mondal[1], S. Mohanty[1], L. Humphrey[1], F. Rashid[5] and T.P. Tuong[1]

[1]International Rice Research Institute, Bangladesh and Philippines p.k.chandna@irri.org, a.nelson@irri.org, m.mondal@irri.org, s.mohanty@irri.org, e.humphreys@irri.org, t.tuong@irri.org
[2]Institute of Water Modeling, Bangladesh zhk@iwmbd.org
[3]Soil Research Development Institute, Bangladesh moqbul_h@yahoo.com
[4]Local Government Engineering Department, Bangladesh sohel_lged76@yahoo.com
[5]Bangladesh Water Development Board, Bangladesh fazlur64@gmail.com

Abstract

Satisfying the food demands of a rising population, conserving natural resources and improving livelihoods are major challenges in the food-insecure coastal zone of Bangladesh. A large area remains either uncultivated or underused following the harvest of the *aman* crop due to excess or scarce water, salinity, inequitable water management and insufficient water infrastructure. Increasing cropping intensity on these lands could substantially improve the food supply and enhance livelihoods in the region. This paper describes a decision tree-based mapping methodology that identifies the recommendation domains of four existing and seven improved cropping systems for targeting improved agronomic and water management practices in underutilized lands of Barisal Division. Firstly, an extensive literature review and expert group discussions, taking into account new findings from the CGIAR Challenge Program on Water and Food's Ganges Basin Development Challenge, were conducted to identify land use requirements, their quantitative threshold values, and their logical integration into the decision tree. Spatial datasets representing each requirement were developed and combined following the decision tree logic into cropping system suitability maps. The suitability maps were assessed through focus group discussions in four polders across the zone to determine the validity of the recommendations. The analysis identified about 0.5 million ha areas in six districts of Barisal Division where cropping intensity could be increased from 100% to up to as much as 300% using locally tested, improved cropping systems. The methodologies and technologies used in the study are applicable to most of the salinity-prone coastal zones of South and South East Asia.

Keywords: water and soil salinity, spatial analysis, decision trees, cropping systems

1. Introduction

Increased food security and improved livelihoods in poor rural areas are major development goals for South Asian countries including Bangladesh, India, Nepal and Pakistan. Low cropping intensity is one factor that limits the achievement of both. In South Asia approximately 14 million ha (mha) of potentially productive land remains fallow during the winter (*rabi*) season after the monsoon (*aman*) rice crop (Subbarao et al. 2001; Padmanabhan 2008). This is due to four major causal factors: (1) lack of irrigation water creating in-season drought; (2) flash and stagnant floods causing waterlogging in low land areas (Chandna et al. 2010); (3) higher level of salinity in soil or water; and (4) late harvest of *aman* crop or excessively moist soils leading to late planting and lower productivity of *rabi* crops or the decision to leave land fallow (Choudhary et al. 2008; Pandey et al. 2010; Chandna et al. 2012).

In Bangladesh more than 2.65 mha are affected by flash and stagnant flooding, of which about 1.6 m ha are inundated almost every year (Mackill et al. 2006; Bailey-Serres et al. 2010; Mirza 2011; Mackill et al. 2012; Ismail et al. 2013). Around 1.1 m ha are affected by coastal salinity, which is exacerbated by sea level rise and cyclones (SRDI 2010). In addition, about 2.3 and 1.2 m ha of *aman* and *rabi* crops, respectively, are exposed to drought every year (IOP, 2009; Dey et al. 2011). In short, there is a prevailing multi-stress environment for agriculture in Bangladesh, and more particularly in the coastal polder zone (CPZ), where soil and water salinity has increased the impact of the detrimental effects of floods and droughts.

The CPZ of Bangladesh, a fertile deltaic plain, is one of the most densely populated agricultural regions in the country. Rice (*Oryza sativa)* is a major staple food crop and supports about 8 million people in the CPZ, of which 80% live below the country's poverty line (US$1.25/day/person) (Chandna et al. 2014). The main source of food security in the CPZ is a single, low yielding crop of rice grown during the rainy (*aman* rice) season. Resembling the other multi-stress prone areas of South Asia, a large area (Table 1) of potentially productive land in Barisal Division remains uncultivated in the *rabi* and *aus* (pre-monsoon) seasons following the harvest of the *aman* rice crop, mainly due to the four major causal factors mentioned above.

Another major causal factor in the CPZ is deferred maintenance of water infrastructure (sluice gates, drainage canals, etc.) leading to drainage congestion and waterlogging. Stagnant flooding (0.3-0.5 m for more than two weeks) in low lying areas during the rainy season is another major causal factor (Ismail et al. 2013; Islam et al. 2014). It not only restricts the adoption of high yielding varieties (HYV) in the *aman* season, but also affects the planting of subsequent *rabi* crops, particularly where drainage is poor (Chandna et al. 2012). Furthermore, high levels of salinity (> 4 ds/m) decrease the terminative energy and germination rate of plants and reduce productivity (Rashid et al. 2004). For example, Ali (2005) showed that a decline of rice productivity of about 69% in a village of Satkhira District between 1985 and 2003 was associated with salinity.

In spite of its increased vulnerability to various agricultural stresses and natural disasters (Milimen et al. 1989; World Bank 2009; Brammer 2010; Islam et al. 2012; Mirza 2013; UNDP 2013) the CPZ is also known as a "region of opportunities and high potential" due to:

- its fertile alluvial soil; availability of freshwater – as yet largely untapped –in the Padma, Brahmaputra and Megna River systems for most part of the year;
- a dense irrigation canal network (khals);
- the availability of short duration improved cultivars; and
- improved knowledge of agronomy and water management aspects.

In addition to these factors, semi-diurnal tidal movement (low and high tide, twice a day) in the CPZ provides an opportunity for low-cost gravity drainage and irrigation. At low tide the river level is generally lower than the land level within the polders, creating opportunities for gravity drainage of excess water (as a result of heavy rainfall) to a level that would allow for good growth and yield of HYV *aman* rice. Drainage of the earlier maturing HYV shortly prior to harvest would allow the soil to dry sufficiently for timely establishment of *rabi* crops.

Achieving good water management within a polder requires an integrated approach of improved agronomy and water and infrastructure management (Golder et al. 2013). Recent studies by the CGIAR Challenge Program on Water and Food (Mondal et al. these proceedings) have shown that it is possible to have three crops per year (triple rice or double rice plus one upland crop) in "low salinity" zones (e.g. Barisal Division); and two crops per year (double rice or one rice plus upland crop) in "moderate salinity" zones (e.g. Khulna Division). Even in the "high salinity" zones (e.g. Satkhira Division), farmers can practice shrimp-rice systems by cultivating shrimp in the dry season followed by rice in the wet season (Nuruzzamam et al. 2007; Quader et al. 2010). These innovative cropping systems can substantially increase agricultural productivity and improve farmers' livelihoods.

However, any single improved practice may not be suitable for all situations, suggesting that technologies should be targeted to their most appropriate niche (Graaff et al. 2008; Chandna et al. 2012). Assessing target zones for promising technologies facilitates out-scaling in a fast and cost-effective manner (Chandna et al. 2011; Erenstein et al. 2010).

Previous studies have utilized crop-based characterization and targeting methods. In such methods, the land use requirements of individual crops are assessed (eg. targeting of high yielding varieties) for a particular time of the year, mainly based on soil and climatic parameters (Hodson and White 2007; Behzad et al. 2009; Mamun et al. 2011; Halder 2013; Samanta et al. 2013; ESA 2014). This method may not be adequate for assessing cropping system suitability in multi-stress, lowland, coastal environments where resource profiles (e.g. salinity, submergence, inundation depth and water availability) vary both temporally and spatially.

We have observed that most of the critical biological parameters (eg. water salinity, gravity drainage) and seasonal aspects (time, season and intensity) of CPZ environments have not been fully accounted for in many past studies on crop-based characterization (Hossain et al. 2007; Jafari et al. 2010; Mamun et al. 2011; Halder 2013;). Therefore, we need to consider a method to generate 'recommendation domains' for CPZ cropping system suitability (Getnet and MacAlister 2012; Bussel et al. 2013) that accounts for the spatial and temporal complexity of cropping system parameters for coastal saline zones.

Recommendation domain analysis (RDA) is a methodology for identifying geographical areas that are suitable for the adoption of improved cropping system practices on the basis of well-defined criteria that account for each crop *as part* of the cropping system. In other words the criteria for a triple cropping system is not simply the suitable area for crop A overlaid on the suitable area for crop B and then crop C, but rather the criteria for realistically adopting the full cropping system accounting for critical timing of planting and harvesting, or residual soil moisture, for example, such that a second or third crop can be realistically and sustainably included in the system.

This paper presents RDA, as applied to the Coastal Zone of Bangladesh, for developing cropping system suitability maps for current and improved cropping systems in low, medium and high salinity zones in the Barisal region. It describes the characteristics of the region, the cropping systems under consideration, the parameters required for those cropping systems and the decision trees for suitability mapping. The resulting maps are presented and discussed alongside the outcomes of focus group discussions in the CPZ on the feasibility of the cropping systems assessed.

2. Material and Methods

2.1 Study Area

The study area, Barisal Division, is situated in the southern part of Bangladesh, between 21°49'41" to 23°05'36" N and 89°53'18" to 91°01' E (Figure 1). It occupies an area of 13,297km^2 with a population of over 8 million. The total number of farm holdings in Barisal Division is about 0.5 million, out of which 85% belong to small farmers (BBS 2011). The dominant soils are loamy, sandy loam, clay loam, and clay (SRDI 2010). Mean annual rainfall in the study area is 1955 mm and maximum and minimum annual average temperature is 12.1°C and 35.1°C, respectively.

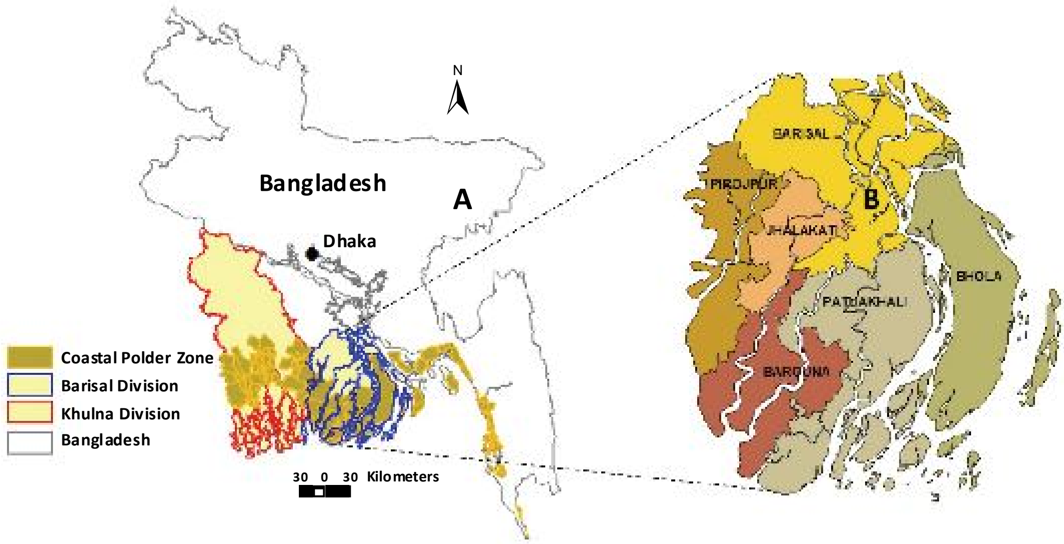


Fig. 1. Map A (left) depicts the location of the Coastal Polder Zone and Barisal Division within Bangladesh. Map B (right) shows the districts within Barisal Division.

The monsoon or rainy season (June to October) is characterized by high rainfall, high humidity, and high cloud cover. Sediment load and water levels of the area also increase during this period. The salinity in soil and water is moderately high along the coast and gradually reduces northward due to upstream freshwater flow. Occasional thunderstorms, cyclones and storm surges occur during the monsoon season. The winter season (November to February), with a northeast monsoon wind, is characterized by dry, cool, and sunny weather with occasional rain. The lowest temperatures occur in December and January and the highest during the months of May and June. Sunshine hours are lowest during the rainy and winter seasons and highest in the summer season.

The hydrology of coastal Bangladesh is different to many coastal delta regions of South and South East Asia because of its 'polders' that control saline water intrusion. A polder is a low-lying tract area, enclosed by embankments (levees) that forms an artificial, separate hydrological entity. A polder has no open connection with sea or upstream river water, except that water is allowed to enter or drain through manually operated sluice gates built at riverbanks or irrigation canals (*khals*). These sluice gates help maintain the flow of fresh or saline water through gravity irrigation or drainage during low and high tides.

Salinity concentration (in both soil and water) decreases in the inland direction and increases in the seaward direction of the CPZ. During the wet season, direct rainfall and an increased upstream flow have a dilution effect on salinity concentration. In Barisal, surface water in upstream rivers remains fresh for most of the year (Zahir et al. these proceedings), leading to an opportunity to increase cropping intensity in single cropped areas (Table 1).

The most dominant cropping systems in the Barisal Region are *aman*-fallow-fallow, T. *Aman*-T. *Aus*, T. *Aman*-*rabi* and T. *Aman*-T. *boro*. The *aman* crop covers over 0.90 m ha, or 65% of the net cultivated area (NCA), whereas T. *Boro* and T. *Aus* season crops are cultivated on 0.23 and 0.37 m ha (27% of the NCA), respectively (BBS 2011). Pulses and oilseeds (which are grown during the winter season) are the dominant *rabi* crops, extending over 0.3 m ha (22% of the NCA). Other *rabi* crops (potato, sugarcane, jute, wheat and maize) account for 0.05 m ha (4% of the NCA).

More than 50% of the area in Barisal Region remains fallow after a low yielding *aman* crop. The opportunity to increase productivity through increased cropping intensity is much higher in central and southern parts of Barisal Region (Table 1).

Table 1. An overview of land use in Barisal Division and Bangladesh - 2010

Region	**Cropped Area (000 ha)**		
	Single	Double	Triple
Bangladesh (All districts)	2577 (33)*	3934 (50)	1282 (16)
Barisal (Northern district of Barisal Division)	202 (44)	194 (42)	67 (14)
Patuakhali (Southern district of Barisal Division)	184 (61)	88 (29)	28 (9)

Note: Figures in parentheses indicate the percentage of total cropped area

Source: BBS, 2011, Yearbook of Agricultural Statistics of Bangladesh

2.2 Methodology

We first identified the existing and improved cropping systems to be mapped as well as their requirements through literature reviews and roundtable discussions with experts on agronomy, fisheries, soil and water. These requirements were quantified and related to the best available spatial data such that there was one spatial data layer for every unique requirement. A decision tree approach was chosen to combine these spatial data layers into suitability maps that delineated the recommendation domains of the cropping systems. These maps were assessed through expert opinion and through focus group discussions in the CPZ.

2.2.1 Current and Improved cropping systems in the CPZ

The description, environment and other details of these cropping systems are given in Tables 2 and 3. These descriptions or 'narratives' are the basis for the development of spatial databases of thematic layers to characterize the requirements of each cropping system, and for the decision trees that relate the combination of requirements in a given location to a specific suitability score.

Table 2. Description and environment of existing cropping systems

Extensive year round brackish water polyculture Shrimp post larvae (PL) are stocked in February, when brackish water has adequate salinity and suitable temperature; brackish water fish/shrimp are stocked few weeks later. Water is replenished as needed. Harvest starts after two months until the end of November.
Brackish water shrimp – Aman Rice (traditional) Shrimp PL are stocked in February when brackish water has adequate salinity and suitable temperature. Phased stocking and harvests are carried out throughout the dry season, until the end of July. Soil salinity is flushed/leached out of the ghers by rainfall and intensive drainage at low tide. Traditional, photoperiod sensitive rice is seeded in July, transplanted at the end of August and harvested in December and January.
T. Aus high yielding varieties (HYV) - T. Aman (traditional) Aus HYV is seeded in late April and harvested by the end of August. T. *Aman* rice is transplanted by the first week of September to be harvested by the end of December. *Aus* crop seedbeds and land preparation are irrigated with river water when it is fresh, or with groundwater or pond water. (Farmers make use of rainfall to reduce pumping costs, but T. *Aus* can be practiced only when there is a good source of irrigation water.) *Aman* rice is completely rain-fed, and local varieties that can withstand flood depths of up to 0.8 m are used.
T. Aman (Traditional) - Rabi Traditional, photoperiod sensitive Aman rice is seeded in June, transplanted in August to be harvested by end of first week of January. Rabi upland crop (e.g. sesame, and mungbean) is seeded in Feb-March, to be harvested in May-June. Aman rice is completely rainfed, local varieties that can withstand flood depth up to 0.8 m. Rabi crop is grown with residual soil moisture and supplemented with irrigation when groundwater or (stored) canal/pond water is available. Rainfall at the end of the Rabi season (April - May) negatively affects the Rabi crop, good surface drainage is important

A total of 11 cropping systems were selected for developing recommendation domains in Barisal. Four of the cropping systems (Table 2) belong to existing practices and seven cropping systems (Table 3) are 'improved packages' (Mondal et al. these proceedings) with improved cultivars, and agronomic and water management practices that have been successfully tested on farmer participatory sites at polders 3, 30 and 43/2F (which represent high, medium and low salinity zones, respectively).

Table 3. Description and environment of improved cropping systems

T.Aman HYV – T.Boro HYV Short duration, non-photoperiod sensitive *Aman* HYV rice is transplanted in July to August, to be harvested by the end of November (moderate salinity zone) or December (low salinty zone). *Boro* rice is seeded around 15 November to 15 December. *Aman* rice is rainfed. Its performance depends greatly on maximum inundation depth/land topography. When inundation depth >0.4 m drainage capacity must be considered. This in turn depends on the difference between land elevation and the water levels at low tides and on the distance from canals/rivers. *Boro* rice is irrigated with groundwater (GW) or river water (when fresh) or with water stored in canal networks. When river water is fresh, the ability to irrigate by gravity is considered. Storage capacity is considered when stored water is used. Distance from water source is considered in both cases.
T. Aus HYV - T. Aman HYV *Aus* HYV is seeded in late April, to be harvested by the end of August. HYV *Aman* rice is transplanted by the first week of September and harvested by December. *Aman* rice can be photoperiod sensitive, and can be of medium duration. *Aus* seedbeds and land preparation are irrigated with GW or from stored canal water when there is good source of irrigation water. In this case, capacity of gravity irrigation is considered. *Aman* HYV rice is mainly rainfed but may need some irrigation in December. Its performance depends greatly on maximum inundation depth/land topography. When inundation depth >0.4 m drainage capacity must be considered. This in turn depends on the difference between land elevation and the water levels at low tides and distance from canals/rivers.
T. Aus HYV - T. Aman HYV - T. Boro HYV A short duration *Aus* HYV is seeded in early April, transplanted in late April and harvested by the end of July. Short duration, non-photoperiod sensitive HYV *Aman* rice is transplanted by the first week of August and harvested by the end of November. *Boro* rice is transplanted before mid-December and harvested by mid-April. *Aus* seedbeds and land preparation are irrigated with GW or from canal water when there is a good source of irrigation water. In this case, capacity of gravity irrigation is considered. *Aman* HYV rice is completely rainfed. Its performance depends greatly on maximum inundation depth/land topography. When inundation depth >0.4 m drainage capacity must be considered. This in turn depends on the difference between land elevation and the water levels at low tides and distance from canals/rivers. *Boro* rice is irrigated with GW or river water (when fresh) or with water stored in canal networks. When river water is fresh, the ability to irrigate by gravity is considered. Storage capacity is considered when stored water is used. Distance from water source is considered in both cases.
T. Aman HYV - Rabi (winter crop) HYV *Aman* rice is transplanted by the first week of August and harvested by the end of November to early December. *Rabi* upland crop is seeded during December and harvest in early April. *Aman* rice can be photoperiod sensitive and can be of medium duration. *Aman* HYV rice is completely rainfed. Its performance depends greatly on maximum inundation depth/land topography. When inundation depth >0.4 m drainage capacity must be considered. This in turn depends on the difference between land elevation and the water levels at low tide and distance from canals/rivers. For timely establishment of *rabi* crop, land must be drained free of standing water by early December. Since we may not have adequate data on land evaluation the "proxies" for drainability will be the maximum inundation depth and proximity to canals/rivers. *Rabi* crop is irrigated with GW or river water (when fresh) or with water stored in canal networks. When river water is fresh the ability to irrigate by gravity is considered. Storage capacity is considered when stored water is used. Distance from water source is considered in both cases.

T Aus HYV - T. Aman HYV- Rabi
A short duration *Aus* HYV is seeded in early April, transplanted in late April and harvested by the end of July. Short duration, non-photoperiod sensitive HYV *Aman* rice is transplanted by the first week of August and harvested by the end of November. *Rabi* upland crop is seeded in early December and harvested in early April. *Aus* seedbeds and land preparation are irrigated with GW or from canal water when there is a good source of irrigation water. In this case, capacity of gravity irrigation is considered. *Aman* HYV rice is completely rainfed. Its performance depends greatly on maximum inundation depth/land topography. When inundation depth >0.4 m drainage capacity must be considered. This in turn depends on the difference between land elevation and the water levels at low tides and distance from canals/rivers. For timely establishment of *rabi* crop land must be drained free of standing water by early December. Since we may not have adequate data on land evaluation, the "proxies" for drainability will be the maximum inundation depth and proximity to canals/rivers. *Rabi* crop is irrigated with GW or river water (when fresh) or with water stored in canal networks. When river water is fresh the ability to irrigate by gravity is considered. Storage capacity is considered when stored water is used. Distance from water source is considered in both cases.

Brackish water shrimp - HYV Aman Rice
Shrimp PL is stocked in February when brackish water has adequate salinity and suitable temperature. Water is replenished as needed. Phased stocking and harvests are carried out throughout the dry season, until the end of July. Soil salinity is leached/flushed out of the ghers by rainfall and intensive drainage at low tide. HYV rice is seeded in August, transplanted at the end of August or beginning of September and harvested in December. When inundation depth >0.4 m, drainage capacity must be considered. This in turn depends on the difference between land elevation and the water levels at low tides and distance from canals/rivers.

2.2.2 Parameters that define the cropping system requirements

The requirements of each crop and cropping system are defined by one or more parameters. The 29 parameters are listed below (Table 4), grouped into seven factor groups.

Some parameters are estimated on weekly or monthly time steps (i.e. latest month when river water conductivity (EC) <3 dS/m, minimum salinity at PL stocking, weekly air minimum temperature at stocking). Thus the number of data layers required to assess the suitability across all systems is much larger than 29. Some examples of the spatial data sets are shown in Figure 2.

Table 4. Parameters in the spatial database used for cropping system suitability analysis

Factor (f)	Parameter
Irrigation with GW	**1** Fresh (EC < 4dS/m) groundwater availability
	2 Ground water pumping depth
Irrigation with surface water (SW)	**3** Latest month when river water EC <3 dS/m
	4 Maximum river water EC/salinity in April/May
	5 Maximum river water EC/salinity in August
	6 Difference in high water level in April and land surface for gravity irrigation
	7 Difference in high water level in March and land surface for gravity irrigation
	8 Storage capacity
	9 Proximity to river, canal, ponds for irrigation
Drainability	**10** Proximity to river, canal for drainage
	11 Maximum inundation depth/land type
	12 Maximum inundation depth for > three consecutive days in May
	13 Maximum inundation depth in September/October
	14 Maximum inundation depth for > one week in September/October
	15 Maximum inundation depth for > two consecutive weeks in September/October
	16 Difference in land surface and low water level in May for drainage
	17 Difference in land surface and low water level in September/October for drainage
Soil	**18** Soil texture
	19 Soil pH
	20 Soil salinity
Field or gher water	**21** Minimum salinity/EC at PL stocking
	22 Maximum salinity/EC
	23 Inundation depth/land type
Climate	**24** Weekly air minimum temperature at stocking
	25 Weekly mean minimum air temperature in January
	26 Two-week mean air temperature in December and January
	27 Cumulative rainfall in July and August
Social and economic	**28** Livelihood/asset index
	29 Technology adoption index

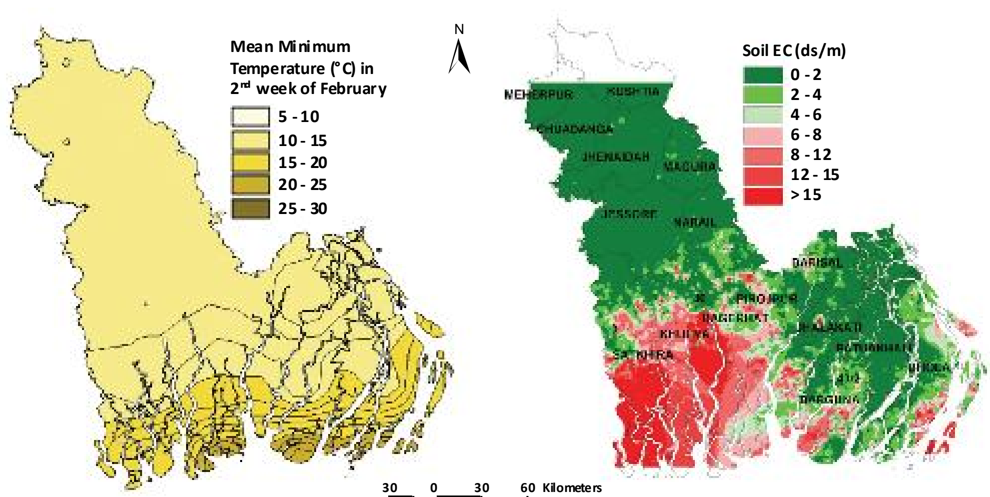


Fig. 2. Example layers; minimum temperature in February (left) and soil EC values (right).

2.2.3 Decision trees, weighting and spatial analysis of suitability classes

Using a decision tree approach (Park and Lee, 2014) in ArcGIS 10.1 software, we developed a logical model for determining suitability classes based on 'IF', 'IF NOT' and 'AND' statements. Separate decision rules were prepared for each cropping system as per their land use requirement. The method and process followed to integrate the land use parameters with decision rules for preparation of recommendation maps is given below.

1. Each cropping system is composed of a sequence of crops, where this is one crop per cropping season and one or more cropping seasons per year.

2. The suitability of any given location to cultivate a crop is assessed by a number (n) of factors (f, where f=1 to n) that are determined by expert opinion and literature.

3. Each factor may be quantified by one parameter (e.g. if soil salinity is a factor, it depends solely on a measurement of soil salinity) or by more than one parameter (e.g. if "drainability" is a factor, it depends on (i) topography, (ii) the difference between land surface and water level at low tides, and (iii) proximity to canals/rivers). These quantifiable parameters and their values are determined by expert opinion.

4. Since each factor is quantifiable, we relied on expert opinion and literature to classify each factor into ranges and assign each range a suitability score(s). To reduce complexity we limited the suitability score to four values: most suitable, s=3; suitable, s=2; marginally suitable, s=1; and not suitable (SN), s=0 (Figure 3). For example, if soil pH is factor 1 (s1) for a T. *Aus* HYV crop then expert opinion may group soil pH into four classes: most suitable (score s1=3 if 5.5 < pH < 8.5), suitable (score s1=2 if pH is in between 5.0 and 5.4 or between 8.6 and 9.0), marginally suitable (score s1 = 1 if pH in between 4.0 and 4.9 or between 9.1 and 10.0) and not suitable (score s1 = 0 if pH > 10.0 or pH < 4.0). An example of the scoring per layer is shown in Figure 3.

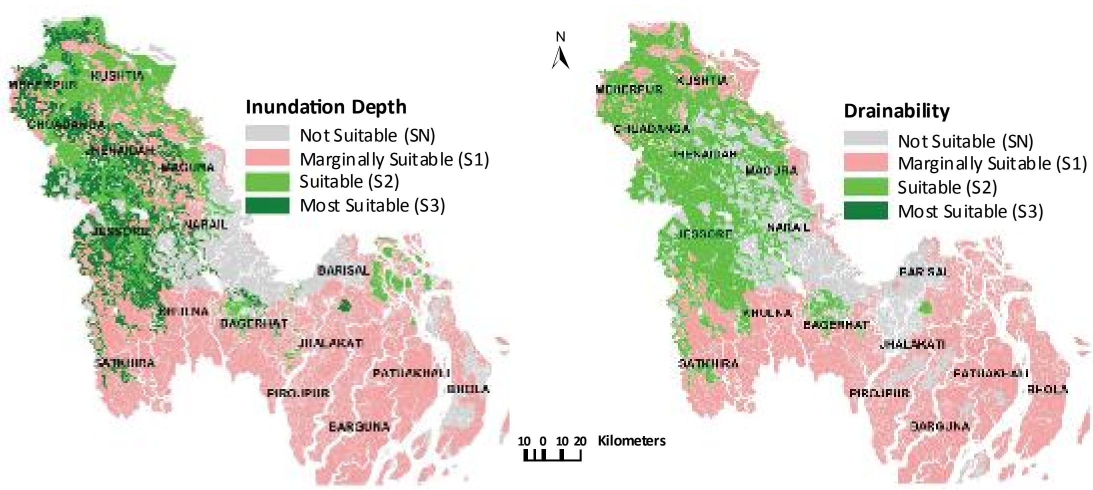


Fig. 3. Illustrating the examples of inundation depth (left) and soil drainability (right) after quantitative ranges are assigned with a suitability score for each individual layer.

5. Factors are not necessarily of equal importance in determining the suitability of the crop. Expert opinion was used to further refine the importance of each suitability score by multiplying it by a weight (0 ≤ w ≤ 1), resulting in a weighted suitability score for each factor (w1.s1 ,w2.s2 ,... wn.sn). Since the maximum weight is 1 and the maximum suitability score is 3, then the maximum weighted suitability score for a factor is 1 x 3 = 3. Conversely the lowest weighted suitability score for a factor is 0 for any factor with a suitability score of 0 regardless of its assigned weight.

6. The suitability class for the crop (Sc) is defined as follows: S1= marginally suitable, S2=suitable, S3= most suitable and SN=not suitable. This Sc class is derived by first assigning a suitability score (Ss) to the crop as the sum of the weighted suitability scores of all factors divided by the sum of the weights of all factors:

$$S_s = \frac{\sum_{f=1}^{f=n} w_f s_f}{\sum_{f=1}^{f=n} w_f}$$

and then assigning a suitability class to the suitability score as follows:

Sc = S1 (marginally suitable) if 0 < Ss < 1.5

Sc = S2 (suitable) if 1.5 ≤ Ss < 2.5

Sc = S3 (most suitable) if Ss ≥ 2.5

Sc = SN (not suitable) if any one weighted score (wfsf) is 0

7. The suitability class for the cropping system (Scs) is derived by computing the average of the suitability scores (Ss) from the component crops in that cropping system and then applying the same S1, S2, S3 and SN classification. For example, at a given location individual crops of the triple rice system *Aus* HYV - *Aman* HYV - *Boro* HYV may have suitability scores Ss of 3.0, 2.4 and 2.0. The average of these is 2.47 so the cropping system suitability score Scs is S2. The result is a map for each crop system with suitability classes S1, S2, S3 or SN.

An example decision tree for the water requirements of a *boro* (dry) season rice crop are shown in Figure 4 where the tree first considers the availability and depth of fresh groundwater. If no groundwater is available the lower part of the tree considers the duration of fresh surface water during the season and the availability and access to stored fresh surface water.

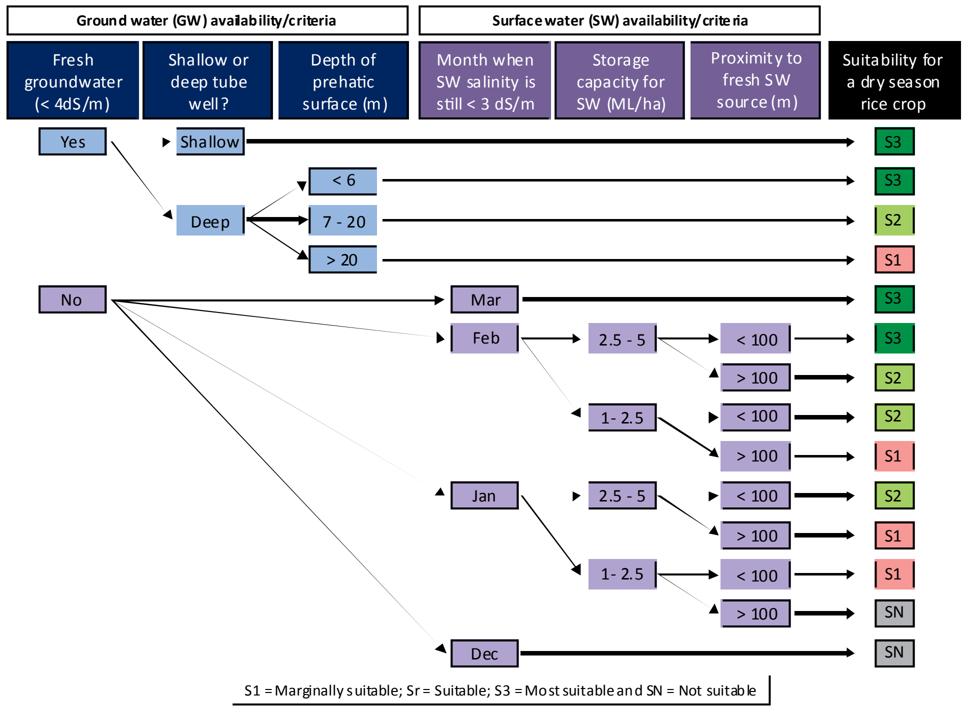


Fig. 4. Decision tree for water availability parameters for *boro* rice.

2.2.4 Focus Group Discussions

An independent evaluator conducted focus group discussions (FGD) between September and November 2014 in four polders P-39/2, P-43/2F, P-44, and P-55/1 in order to evaluate and validate the innovative cropping systems maps for the CPZ. FGDs were conducted at randomly selected locations within each of the selected polders. The independent evaluator initially made a reconnaissance visit to familiarize himself with the present situation of the polders including water management infrastructure, cropping systems and agricultural practices. A simple three-page survey was prepared in order to conduct a FGD in one location in each polder. About 20 polder-level maps (about four to six maps of different cropping systems for each selected polder) of different improved cropping systems were provided to the evaluator to elicit comments from the group. The FGDs included more than 60 farmers (including 14 females) in four polders where the domain map method was explained and the resulting maps were presented as a means to elicit responses and opinions on the feasibility of each improved cropping system domain as shown in the maps. The discussion first captured the current cropping patterns and current limitations and challenges faced by the farmers. Then, using the printed maps to focus the discussion, the feasibility/acceptance of the improved systems was assessed and the farmers discussed how current limitations would also limit the feasibility of the improved systems and what needed to be done in the polder to improve current and future cropping system productivity.

3. Results and discussion

3.1 Recommendation domains for existing systems

The suitable areas for existing cropping system are shown in Table 5. The maps of the suitability classes for existing cropping systems are shown in Figure 5. The results for each system are discussed in turn below.

Table 5. District wise area (1000 ha) of the recommendation domains for existing cropping systems in Barisal Division

Cropping system	S_c	Barguna	Barisal	Bhola	Jhalokhati	Patuakhali	Pirojpur	Total
Transplanted Aus-Aman	S1	73	93	76	45	97	40	424
	S2	34	45	1	15	67	11	174
Transplanted Aman-Rabi	S1	108	135	77	57	165	49	591
	S2	*	3	*	2	*	2	8
Brakish Water Shrimp - T Aman	S1	5	1	66	*	15	*	88
	S2	47	3	5	*	37	10	102
Year Round Aquaculture	S1	*	*	47	*	6	*	54
	S2	46	4	32	*	55	8	144

Note: * = No suitable area; S_c = 'Suitability Class', where S1 represent marginal suitable; S2 – Suitable and S3 represent most suitable area; Areas less than 1000 ha are not shown in the table

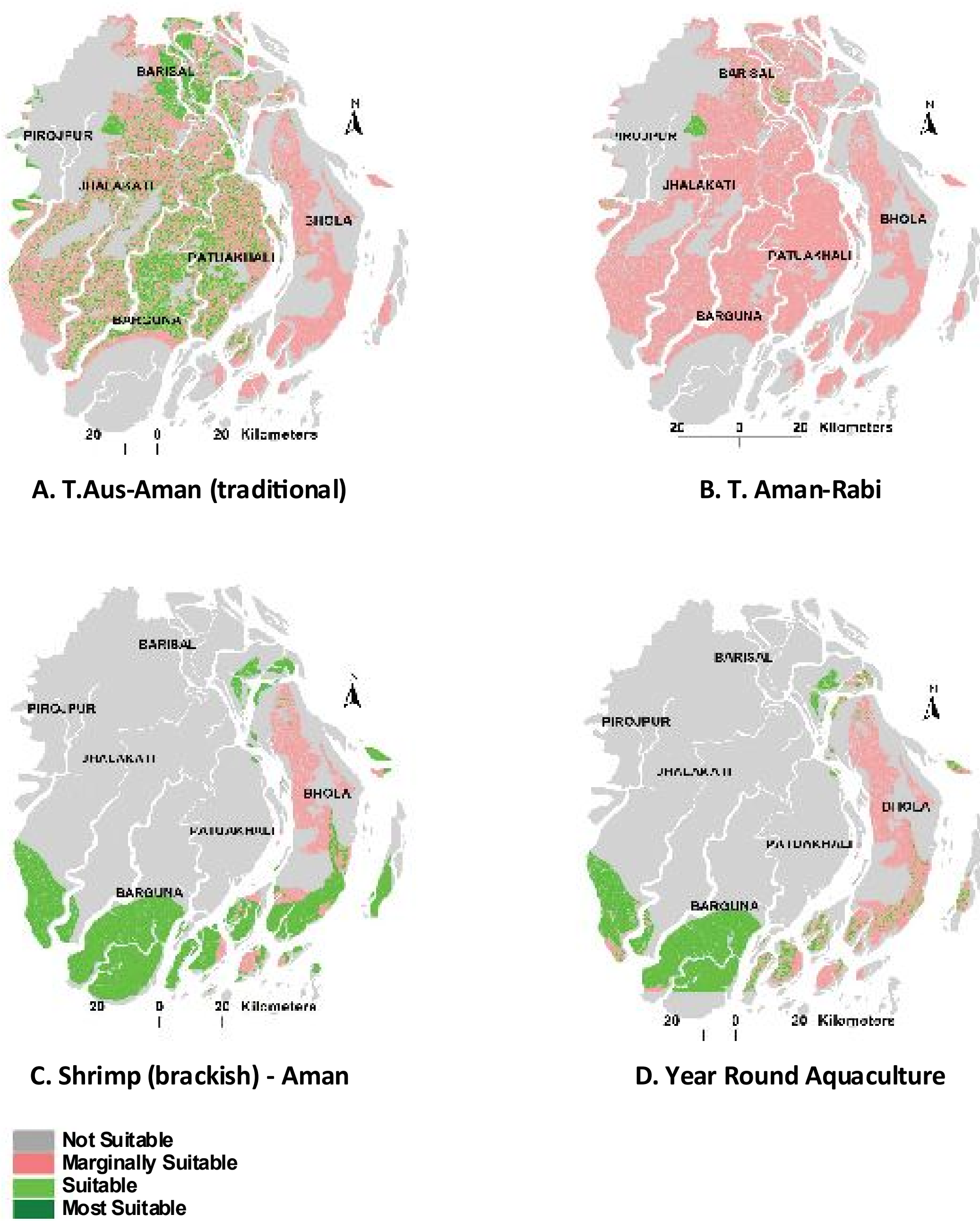


Fig. 5. Recommendation domain maps for the four current cropping systems in Barisal.

3.1.1 T.Aus (HYV) – T.Aman (traditional) system

The results of the RDA revealed that about 0.60 m ha (44%) of the NCA is suitable for T.*Aus-Aman* system cultivation (Figure 5A), of which 31% and 13% of the area was found under moderately suitable (S1) and suitable (S2) categories, respectively. Barisal, Patuakhali and Berguna districts were primarily found suitable for a T.*Aus-Aman* system.

In terms of individual crop suitability, about 0.7 m ha (51% of the NCA) was found suitable for a traditional *aman* crop under the marginally suitable category. It is estimated that farmers are growing traditional *aman* on about 0.89 m ha—about 20% more than our suitable area figure. In the recommendation domain analysis, we excluded areas where the inundation depth is higher than 0.8 m, whereas in reality farmers grow traditional *aman* crop varieties in fields where flood depth is as high as 1.0 m or more. This is one major reason (along with drainage congestion) why a large area of traditional *aman* crop is damaged by stagnant floods almost every year during the rainy season. RDA analysis also revealed that about 0.54 m ha (39% of the NCA) is individually suitable for T.*Aus*, of which about 30% and 9% were found under the S1 and S2 categories, respectively.

3.1.2 Traditional Transplanted Aman - Rabi (T.Aman-Rabi)

About 0.60 m ha (44% of the NCA) is suitable for a T. *Aman* - *Rabi* crop system, of which 43% and 1% were found under S1 and S2 categories, respectively, mainly in Patukhali, Barisal, Barguna and Bhola districts (Figure 5B). This suitable area is almost double the area (around 0.35 m ha) presently under T. *Aman* – *Rabi* cropping systems.

3.1.3 Extensive year-round brackish water polyculture system

In the southern part of Barisal Division, water becomes saline during the dry season between February and June. Saline water (particularly with EC > 6 ds/m) plays a pivotal role in brackish water shrimp aquaculture and makes it highly favorable for bagda shrimp farming. About 0.20 m ha (14%) of the net cultivable area (1.38 m ha) is suitable for year round brackish water aquaculture, of which 4% and 10% of the area was found under marginally suitable (S1) and suitable (S2) categories, respectively, in the southern districts of Barisal Division.

Barisal, Pirojpur and Jhalokati districts are mostly unsuitable for extensive year-round brackish water polyculture systems due to low water salinity in adjacent river systems, as brackish water is a major prerequisite for brackish water shrimp (Fig. 5C).

3.1.4 Brackish water shrimp - Traditional Aman Rice

The results for extensive a year-round brackish water polyculture system and brackish water shrimp - Traditional *Aman* rice system are the same due to their analogous land use requirements. About 0.20 mha (14%) of the NCA is suitable for a brackish water shrimp - Traditional *Aman* rice system, of which 4% and 10% of the area was under marginally suitable (S1) and suitable (S2) categories, respectively, in the southern districts of Barisal Division. About 90% of the total suitable area for Brackish water shrimp - Traditional *Aman* rice is confined to the southern parts of Bhola, Berguna and Patuakhali districts due to the favorable environment for both shrimp culture and traditional *aman* rice crop (Figure 5D).

3.2 Recommendation domains - improved cropping systems

The suitable areas for improved cropping systems are shown in Table 6. The maps of the suitable areas for improved cropping systems are shown in Figure 6. The results for each system are discussed in turn below.

Table 6. District wise area (1000 ha) under recommendation domain for improved cropping systems in Barisal division

Cropping system	S_c	Barguna	Barisal	Bhola	Jhalokhati	Patuakhali	Pirojpur	Total
Shrimp - T.Aman (HYV)	S1	5	1	66	*	10	*	82
	S2	43	3	5	*	32	8	92
T.Aman (HYV) - T.Boro (HYV)	S1	80	108	70	44	132	36	468
T.Aus (HYV) - T.Aman (HYV)	S1	79	112	68	43	128	37	467
T.Aman (HYV) – Rabi (Long)	S1	80	108	70	44	132	36	468
T.Aus (HYV) - T.Aman (HYV) - T.Boro (HYV)	S1	79	106	71	43	130	36	465
T.Aus (HYV) - T.Aman (HYV) - Rabi	S1	79	106	71	43	130	36	465
Year Round Aquaculture	S1	*	*	47	*	6	*	54
	S2	46	4	32	*	55	8	144

Note: * = No suitable area; S_c = 'Suitability Class', where S1 represent marginal suitable; S2 – Suitable and S3 represent most suitable area. Areas less than 1000 ha are not shown in the table.

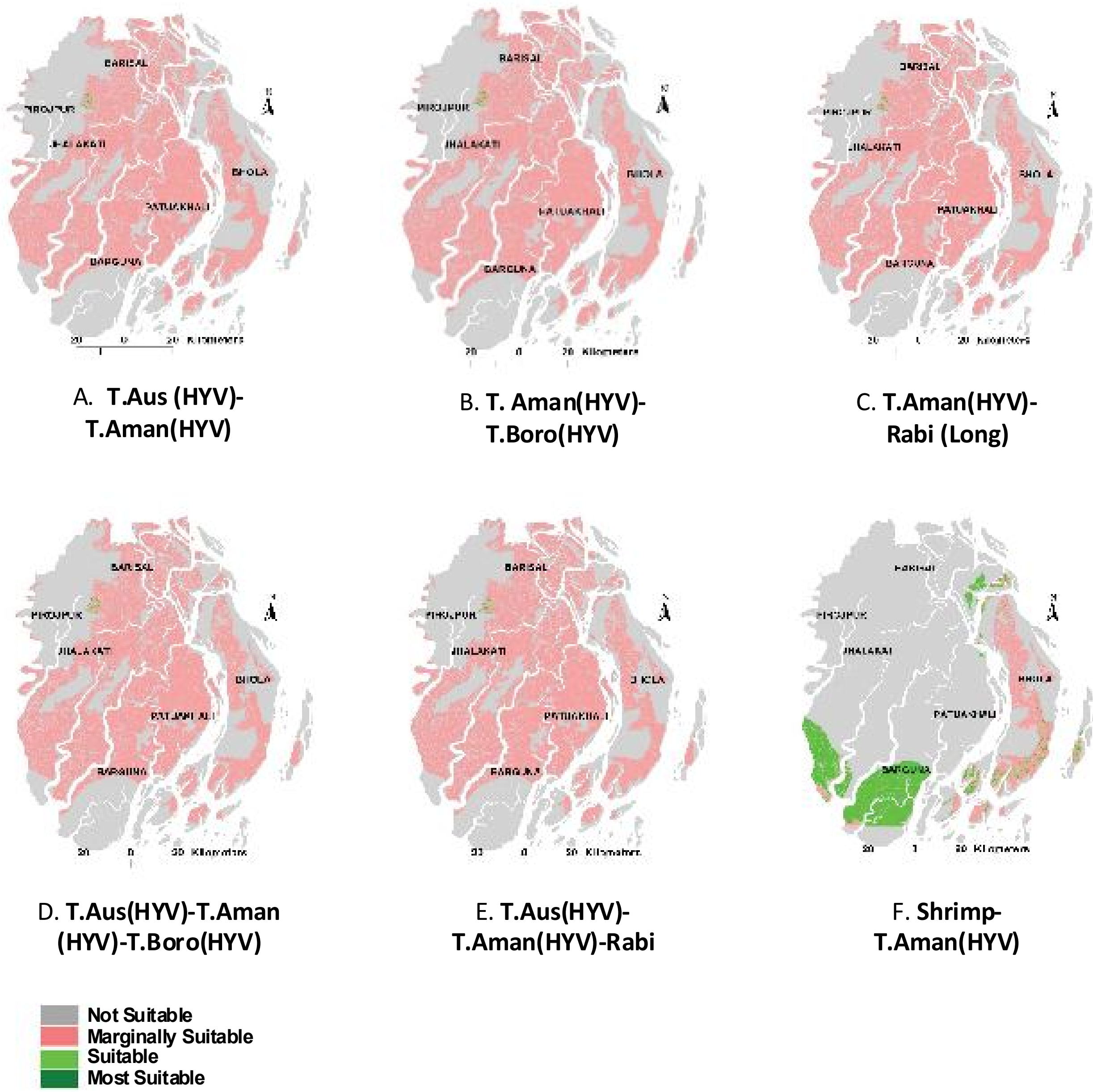


Fig. 6. Recommendation domain maps for improved cropping systems in Barisal.

3.2.1 T.Aus (HYV) – T.Aman (HYV)

Although the T.*Aus* -T.*Aman* system is the third major cropping system of Barisal Division after *Aman*-Fallow-Fallow and T.*Aman*-T.*Boro*, nearly 83% and 92% land area is under traditional low yielding *aus* and *aman* crops, respectively, in comparison to the national averages of 48% and 59% (BBS, 2011), respectively. Nearly 0.54 m ha (under S1 category) were found suitable for cultivation of *Aus* (HYV) - *Aman* (HYV) in Barisal Division (Table 6, Figure 6A). This indicates that there is great potential for converting a large area under traditional low yielding T.*Aus* – T.*Aman* to HYV.

3.2.2 T.Aman HYV - T.Boro (HYV)

T.*Aman* (HYV) - T.*Boro* (HYV) is the most popular cropping system in Barisal region. The yield of T.*Aman* (HYV) - T.*Boro* (HYV) is generally 30-40% higher than T.*Aus* (HYV)-T. *Aman* (HYV) systems. A total of 0.90 and 0.23 m ha area were under *aman* and *boro* rice (;ocal and HYVs together) in Barisal division. Out of this total, only 7% and 74% of the area was recorded under HYVs in *aman* and *boro* seasons, respectively. Barisal and Bhola Districts contributed about 80% of the total area under *boro* rice (BBS 2011).

Nearly 0.47 m ha area (34% of the NCA) is suitable for cultivation of T.*Aman* (HYV) - T.*Boro* (HYV), categorized under the marginally suitable class (Figure 6B). T.*Boro* (HYV) has huge potential in Patuakhali, Barisal, Bhola, and Berguna Districts as an individual crop as well as at cropping system level. Currently, very little area is under *boro* rice in Patuakhali and Berguna Districts, while the RDA revealed that 0.22 m ha of single crop area in these two districts can be converted into double crop through introduction of improved crop and water management practices in the *boro* rice season.

3.2.3 Aus (HYV) - T.Aman (HYV) – T.Boro (HYV)

Nearly 0.47 m ha (34% of the NCA) is under the marginally suitable (S1) category for cultivation of T.*Aman* (HYV)- T.*Boro* (HYV). About two-thirds of the total suitable area is found in Patuakhali, Barisal and Berguna Districts (Figure 6D).

3.2.4 Aus (HYV) - T.Aman (HYV) - Rabi

The map of recommendation domains for T.*Aus* (HYV) - T.*Aman* (HYV) - *rabi* (Figure 6E) is the same as T.*Aus* (HYV) - T.*Aman* (HYV) - T. *Boro* (HYV) (Figure 6D) because of similar land use requirements. Weekly mean minimum temperature during the early stages (December and January) of *boro* rice is the only additional criteria for a T. *Boro* (HYV) crop in comparison to *rabi* (long). Insignificant spatial variation in temperature (< 1.5˚C) within the Barisal region during these months did not reveal any major difference between these two systems in terms of our RDA. The same applies to T. *Aman* (HYV) – *Boro* (HYV) and T.*Aman* (HYV)– *rabi* (Long) systems (Figures 6B and 6C, respectively).

3.2.5 Shrimp -T.Aman(HYV)

Nearly 0.17 m ha (7% of the NCA) is suitable for the cultivation of shrimp-T.*Aman* (HYV) in Barisal Division (Figure 6F). About 0.08 and 0.09 m ha were estimated to be under the marginally suitable (S1) and suitable (S2) categories, respectively. About 90% of the total suitable area for a shrimp-*aman* (HYV) system is confined to the southern parts of Bhola and some parts of Berguna and Patuakhali Districts due to favorable environments for shrimp in the dry season (saline water) and traditional *aman* rice (freshwater) in the wet season.

3.2.6 Improved yea- round brackish water polyculture system

About 0.20 m ha (14% of the NCA) is suitable for imrpvoed yearround brackish water aquaculture, of which 4% and 10% of the area was found under marginally suitable (S1) and suitable (S2) categories, respectively, in the southern districts of Barisal Division. Areas of Barisal, Pirojpur and Jhalokati Districts are mostly unsuitable for improved year-round brackish water polyculture systems due to lower levels of water salinity in adjacent river systems (same as Figure 5C).

3.3 Farmer group discussions and validation of recommendation maps

The results of the FGD in four polders in Barisal division are shown in Table 7. The FGDs revealed that most of the improved cropping systems are acceptable to farmers in low saline zone polders, except the shrimp-*aman* (HYV) system. In well managed polders (eg. P-43/2F), IS5 to IS9 are mostly acceptable. IS5, IS7 and IS9 are more acceptable in P-44 and P-55/1 and IS5, IS6 & IS8 in polder 39/2D. In general, IS7 and IS9 are relatively less acceptable due to issues related to water availability. Note that FDG results in medium and high salinity polders are not shown in this short conference paper.

Some general observations were also drawn from the FGDS. Firstly, that all improved cropping systems will be acceptable to the farmers in the low salinity zones, except IS11. Secondly, the recent trend of producing cost effective *rabi* crops need to be taken into consideration. Thirdly, the adoption of improved systems in many areas requires:

- regular maintenance of water management infrastructure;
- upgrading of drainage and flushing capacity by adding draining/flushing infrastructure (sluice/inlet/canals); and
- ensuring availability of good quality agricultural inputs and modern equipment.

Finally, demonstrations of the systems at polder or sub-polder level will expedite acceptance and adoption.

Table 7. FGD polder characteristics and summarized responses on area deemed suitable per improved cropping system per polder

Polder name	People		Polder characteristics			Suitable area (%) per improved cropping system (targeted salinity zone in brackets)						
	M	F	Salinity	Area (000) ha	Cultiva table (%)	IS-6 (L)*	IS-7 (L)	IS-8 (L)	IS-5 (L/M)	IS-9 (M)	IS-10 (H)	IS-11 (H)
39/2D	9	5	Low (L)	10	75	15		64	64		9	
43/2F	7	3	Low (L)	4	79	59	39	59	59	16	8	
44	18	3	Low (L)	18	71		43	28	53	18	7	
55/1	13	3	Low (L)	10	70		35	18	35	53	7	

Note: M and F in the table represents number of male and female participants in the FGD, respectively. * IS-5. Aman HYV - Boro HYV; IS-6. Aus HYV – Aman HYV; IS-7. T.Aus HYV – Aman HYV – Boro HYV; IS-8. T.Aus HYV – Aman HYV – Rabi; IS-9. Aman HYV – Rabi (long); IS-10. Improved year-round aquaculture; IS-11. Shrimp – HYV Aman

4. Conclusions and recommendations

The recommendation domain analysis approach resulted in detailed, cost-effective delineation and mapping of cropping system suitability maps for the Barisal region of Bangladesh. Approximately 0.5 m ha of land was identified on which double or triple crop system could be adopted. A further 0.20, 0.60 and 0.59 m ha were found suitable for year-round brackish water aquaculture (and brackish water shrimp), T.*Aus*-T.*Aman* (traditional) and T.*Aman* (traditional)-*rabi* crop systems, respectively. Approximately 4.7 m ha were found suitable for improved cropping systems including T.*Aus* (HYV) - T.*Aman* (HYV), T.*Aman* (HYV) - T.*Boro* (HYV), T.*Aman* (HYV)-*rabi* (long) and T.*Aus* (HYV) - T.*Aman* (HYV) - T.*Boro* (HYV) systems under various suitability classes.

T.*Boro* (HYV) or T.*Aus* (HYV) or rabi crops/systems have enormous potential in Patuakhali and Berguna Districts. Approximate 60% of the cropped area remains fallow after a single traditional *aman* crop in Patuakhali and Berguna Districts. The RDA revealed that 0.22 m ha of single crop area in these two districts can be converted into double or triple crop systems through the introduction of improved crop and water management practices.

Specific improved and productivity-enhancing cropping systems have been described that can improve productivity in low salinity zones of Barisal Division. Given that proven technologies exist to ameliorate many of the problems encountered in these stress prone areas, the work undertaken in this study has the potential to increase the efficiency of technology transfer and targeting with limited resources.

Further benefits of RDA include the identification of areas for targeting next generation stress tolerant cultivars (salt, submergence and drought tolerant) or new cropping systems in coastal and inland zones of South and South East Asia.

4.1 Limitations of the study

Several limiting factors including technical and biophysical factors must be taken into account because they may impede the smooth and successful transfer of technologies.

- Though the study was conducted using the best available datasets and techniques, not all layers were of the same quality or detail and a few low resolution, old or proxy layers were used to complete the datasets.
- The study has used the following breakpoints between classes (< 1.5 = marginal suitable (S1); 1-5-2.5 = suitable (S2), and; > 2.5 is most suitable (S3)), however this choice could be revised based on a sensitivity analysis using different breakpoints.
- Gravity Irrigation (an input parameter for RDA) is unlikely to play a bigger role in the future considering the increasing number of investments from donor funded projects, banks and service providers to buy small sized pumping sets in Barisal region.
- Given the limited time, the FGDs were conducted at one place in each of the selected polders, which may not be enough to pick up representative opinions of farmers, particularly for very large polders.
- As mentioned in section 3.3, results for medium and high salinity zones were not presented in this paper. We also omitted the socio-economic indices (potential technology adoption index and livelihood index) that also play a role in the full RDA methodology. These other areas and factors will be described in future papers.

Acknowledgements

We acknowledge the funding support provided by the CGIAR Challenge Program for Water and Food under the Ganges Basin Development Challenge program for conducting this research project. We also acknowledge BBS, BMD and BWDB (National Institutes of Govt. of Bangladesh) for sharing research and census data for conducting this study. We also thank Mr. AHM Kausher (an independent evaluator and consultant for the FGD part of this study) for his dedicated efforts in conducting FGDs in selected polders of CPZ.

References

Ali, A. M. S. 2006. Rice to shrimp: Land use/land cover changes and soil degradation in southwestern Bangladesh. Land use Policy 23(4): 421–35.

Bailey-Serres, J., Fukao, T., Ronald, P.C., Ismail, A.M., Heuer, S., Mackill, D., 2010. Submergence tolerant rice: SUB1's journey from landrace to modern cultivar. Rice 3: 138–147.

BBS. 2011. Yearbook of Agricultural Statistics of Bangladesh. Bangladesh Bureau of Statistics (BBS), Statistic Division, Ministry of Planning, Government of People Republic of Bangladesh, Dhaka.

Behzad, M., Albaji, A., Papan, P., Nasab, S.B., Naseri, A.A. and Bavi, A., 2009. Qualitative Evaluation of Land Suitability for Prinicpal Crops in the Gargar Region, Khuzestan Province, Southwest Iran. Asian Journal of Plant Sciences 8: 28-34.

Brammer, H., 2010. After the Bangladesh Flood Action Plan: looking to the future. Environ. Hazards 9 (1): 118–130.

Bussel, L.G.J. van; Wart, J. van; Wolf, J.; Grassini, P.; Boogaard, H.L.; Groot, H.L.E. de; Claessens, L.; Yang, H.; Ittersum, M.K. van; Cassman, K.G 2013. *Climate Zonations As Extrapolation Domains for Yield Gap Assessments*. In: Proceedings of ASA, CSSA and SSSA International Annual Meetings on Water, Food, Energy & Innovation for a Sustainable World, Tampa, Florida, USA, 3-6 November 2013.

Chandna, P., Ladha, J. K., Singh, U. P., Punia, M., Erenstein, O., Pathak, H., et al. 2009. Technology targeting in underused lands in the Gangetic Plains of South Asia. pp. 335e354. In J. K. Ladha, Y. Singh, O. Erenstein, & HardyB.. (Eds.), Integrated crop and resource management in the rice-wheat system of South Asia (pp. 395). Los Banos (Philippines): International Rice Research Institute.

Chandna, P., Singh, S. S., Erenstein, O., Khan, A. R., Ladha, J. K., Gupta, R. K., et al.2010. Geo-spatial techniques for assessing natutal resource and targeting resource conserving technologies. In Khan., et al. (Eds.), Resource conservation technologies for food security and rural livelihood. Rice wheat consortium for the Indo- Gangetic plains, P 527

Chandna, P., Khurana, M. L., Ladha, J. K., Punia, M., Mehla, R. S., & Gupta, R. 2011. Spatial and seasonal distribution of nitrate-N in groundwater beneath the rice wheat cropping system of India: a geospatial analysis. Environmental Monitoring and Assessment Vol- 178: 545-562.

Chandna, P., Ladha, J. K., Singh, U. P., Punia, M., Gupta, R., Sidhu B. S. 2012. Using remote sensing technologies to enhance resource conservation and agricultural productivity in underutilized lands of South Asia. Applied Geography Vol-32: 757-765.

Chandna, p., Nelson A., Toung P., Khan Z., Hossain M., Rana S., and Rashid F. 2014. Extrapolation domains for efficient technology targeting in coastal zones of Bangladesh. Rice Today. Vol.13-2: 20-21.

Chowdary, P. K., Chandran, R. V., Neeti, N., Bothale, R. V., Srivastava, Y. K., Lingle, P., et al. 2008. Assessment surface and subsurface waterlogged area in irrigation command area of Bihar state using remote sensing and GIS. Agricultural Water Management Vol-95: 754-766.

Dey, N. C., M. S. Alam, A. K. Sajjan, M A. Bhuiyan, L. Ghose, Y. Ibaraki and F. Karim. 2011. Assessing Environmental and Health Impact of Drought in the Northwest Bangladesh. J. Environ. Sci. & Natural Resources Vol- 4(2): 89-97.

Erenstein O., Hellin J., Chandna P., 2010. Poverty mapping based on livelihood assets: A meso-level application in the Indo-Gangetic Plains, India. Applied Geography Vol-30: 112–125 Esa, E., 2014. Land Suitability Assessment for Sorghum and Maize Crops Using a SLA and GIS Approach in Dera Wereda, ANRS, Ethiopia. ERJSSH 1, 119-139.

Forkuo, E.K., Nketia, A.K., 2011. Digital Soil Mapping in GIS Environment for Crop-Land Suitability Analysis. International Journal of Geomatics and Geosciences 2: 133-146.

Golder, P.C., Sastry, R.K., Srinivas, K., 2013. Research Priorities in Bangladesh: Analysis of Crop Production Trends. SAARC J. Agri. 11: 53-70.

Getnet K., MacAlister C., 2012. Integrated innovations and recommendation domains: Paradigm for developing, scaling-out, and targeting rainwater management innovations, Ecological Economics, Vol -76: 34–41.

Graaff, J., Amsalu, A., Bodnár, F., Kessler, A., Posthumus, H., & Tenge, A. 2008. Factors influencing adoption and continued use of long-term soil and water conservation measures in five developing countries. Applied Geography Vol-28: 271-280.

Hodson. D., White. J., 2007. Use of spatial analyses for global characterization of wheat-based production systems. Journal of Agricultural Science Cambridge Journal of Agricultural Science 145 (1):115-125.

Halder, J.C., 2013. Land Suitability Assessment for Crop Cultivation by Using Remote Sensing and GIS. Journal of Geography and Geology Vol. 5-3:65-74.

IOP, 2009. Adaptive measures for coping with increased floods and droughts in Bangladesh, IOP Conf. Series: Earth and Environmental Science 6: 292001.

Islam, K.M.N., Islam, M.N., 2014. Spatial assessment of Livelihood, Poverty and Water Vulnerability. Bangladesh Integrated Water Resources Assessment Project Report: 1-28.

Islam, M.S., Rahman, M.A., Sultana, N., Nath, B., Paul., A., 2012. Using Geospatial Techniques to assess the Salinity Impact on Agricultural Landuse: a study on Shyamnagar Upazila, Satkhira. Journal of Agriculture and Environment for International Development – 106: 157-169.

Ismail A.M., Singh U.S., Singh S., Dar M., Mackill D., 2013. The contribution of submergence-tolerant (Sub1) rice varieties to food security in flood-prone rainfed lowland areas in Asia. Field Crop Research Vol. 152: 83-93.

Jafari, S., Zaredar, N., 2010. Land Suitability Analysis using Multi Attribute Decision Making Approach. International Journal of Environmental Science and Development 1, 441-445.

Mackill, D.J., Coffman, W.R., Garrity, D.P., 1996. Rainfed Lowland Rice Improvement. International Rice Research Institute, Los Ba˜nos, Philippines, 242 pp.

Mackill, D.J., Ismail, A.M., Singh, U.S., Labios, R.V., Paris, T.R., 2012. Development and rapid adoption of submergence-tolerant (Sub1) rice varieties. Adv. Agron. 115: 303–356.

*M*amun S.A., Rahman F., Yeasmin F., Islam M.A. 2011, Suitability of the Physical Properties of Soil for Crop Production: A Study in Tangail Sadar. *J. Environ. Sci. & Natural Resources,* 4(2): 121-125.

Milliman, J.D., Broadus, J.M. and Frank G. (1989). Environmental and Economic Impact of Rising Sea Level and Subsiding Deltas: The Nile and Bengal Examples. In Bangladesh Quest. Vol-1:11-12.

Mirza, M.M.Q., 2011. Climate Change, Flooding in South Asia and Implications. Regional Environmental Change Vol 11- 1: 95- 107.

Mondal, M.K., Paul, P.L.C., Humphreys, E., Tuong, T.P., Ritu, S.P. and Rashid, M.A. 2015. Opportunities for cropping system intensification in the coastal zone of Bangladesh. These proceedings.

Nuruzzamam, Md., 2006. Dynamics and Diversity of Shrimp Farming in Bangladesh: Technical Aspects. Bangladesh Centre for Advanced Studies (BCAS) and University Press Ltd. 431-460.

Padmanabhan, G. (2008). UN situation report no. 8. on Bihar, Uttar Pradesh and Orissa. At. www.un.org.in/UNDMT/sitrep/260908_SIT_REP.pdf Accessed 17.01.14

Pandey, A. C., Singh, S. K., & Nathawat, M. S. (2010). Waterlogging and flood hazards vulnerability and risk assessment in Indo Gangetic plain. Natural Hazards. 55-2: 273-289.

Park I., Lee S., 2014. Spatial prediction of landslide susceptibility using a decision tree approach: a case study of the Pyeongchang area, Korea. International Journal of Remote Sensing Vol 35 -16: 6089-6112

Quader, O., Islam, Z., Rahman, H., Rahman, M., Sarkar, M.H., Khan, A.S., 2010. Suitable Site Selection of Shrimp Farming in the Coastal Areas of Bangladesh using Remote Sensing Techniques (4 S Model). Proc. of International Conference on Environmental Aspects of Bangladesh.

Rahman, Md. R., Ando, K., Takeda, S., 2013. Effect of Shrimp-Based Cropping Systems on Salinity and Soil Fertility in a Coastal Area of Bangladesh: A Village-Level Study. Journal of Agricultural Science 5: 1-10.

Rashid, M.M., A.K.F. Hoque and M.S. Iftekhar, 2004. Salt tolerances of some multipurpose tree species as determined by seed germination. J. Biological Sci. 4: 288-292.

Salam, M.A., Islam, S.M.M., Gan, J., Ross, L.G., 2012. Crab culture potential in southwestern Bangladesh: alternative to shrimp culture for climate change adaption. IRJALS 1: 15-31.

Samanta, S., Pal, B., Pal, D.K., 2011. Land suitability analysis for rice cultivation based on multi-criteria decision approach through GIS, International Journal of Science & Emerging Technologies. International Journal of Science Vol 2-1: 12-20.

SRDI, 2010. Coastal saline soils of Bangladesh. Soil Report published by Soil Resources Development Institute. Ministry of Agriculture, Dhaka, Bangladesh. pp.96.

Subbarao, G. V., Kumar, Rao, J. V. D. K., Kumar, J., Johansen, C., Deb, U. K., Ahmed, I., et al. 2001. Spatial distribution and quantification of rice-fallows in South Asia: Potential for legumes. International crops research institute for semi arid tropics, national remote sensing agency and DFID plant sciences research programme. Patancheru, Andhra Pradesh, India: ICRISAT

UNDP, 2013. Policy Study on The Probable Impacts of Climate Change on Poverty and Economic Growth and the Options of Coping with Adverse Effect of Climate Change in Bangladesh. Support To Monitoring PRS And MDGs in Bangladesh, General Economics Division, Planning Commission, Government of the People's Republic & UNDP Bangladesh. (http://fpd-bd.com/wp-content/uploads/2013/04/ The-probable-impacts-of-climate-change-on-poverty-and-economic-growth-andthe-options-of-coping-w.pdf).

The World Bank, 2009, South Asia: Shared Views on Development and Climate Change, Chapter 8: Natural Disasters, 2009, p. 117

Decentralized surface water irrigation as a pathway for sustainable intensification in southern Bangladesh: On how much land can the drop be brought to the crop?

U. Schulthess, T.J. Krupnik, Z.U. Ahmed, and A.J. McDonald

International Maize and Wheat Improvement Center, Mexico, Bangladesh and Nepal, u.schulthess@cgiar.org, t.krupnik@cgiar.org, z.ahmed@cgiar.org, a.mcdonald@cgiar.org

Abstract

Bangladesh faces threats to the sustained intensification of crop production, but opportunities also exist. Declining groundwater tables and escalating irrigation prices in northern *boro* rice-producing districts have focused attention on the south where surface water is perceived as abundant and the opportunity for crop intensification is considered to be great. The Government of Bangladesh recently requested more than $7 billion of donor funds to develop surface water irrigation (SWI) to boost dry season (*rabi*) intensification in the south. This region is agro-ecologically complex due to temporal water and soil salinity dynamics, and there is poor information on current land-use intensity. We describe the opportunities and constraints encountered in developing a procedure to estimate the land area for which SWI could be successfully deployed to intensify fallow land in 3.375 Mha and bring it into double (*aman-rabi*) cropping, as well as to boost yields and/or enable the use of alternative crops on land currently under low-yielding, rainfed, and non-intensive *rabi* cropping patterns. Using Landsat 5 and 7 scenes for a segment-based classification with the random forest algorithm, we isolated current cropland and waterways in the area south of Bangladesh's major rivers, excluding Sunderbans. Based on Landsat 7 and 8 scenes we extracted maximum *rabi* season enhanced vegetation index values, which we classified into fallow, low-, and high-intensity use of cropland for the last three years. A 385 m buffer was applied to waterways carrying water in late March to estimate the command area serviceable by decentralized irrigation water sellers using independent pump sets. We investigated the potential for SWI on fallow and low-intensity land by applying a cropping risk matrix to address the twin threats of soil and water salinity. Our analysis indicates that there are at least 20,000 ha of fallow land under the low-risk category, while more than 100,000 ha of low-intensity cropland could potentially be be brought into intensified production using SWI. Focusing on Bangladesh's south-central hydrological zone, in which considerable volumes of surface water are available, our results indicate about 15,000 and 63,000 ha of fallow and low-intensity crop land could be irrigated with SWI with little risk to soil or water quality. This information can aid in technology targeting for the efficient deployment of SWI as a tool for intensification.

Key message: We identified about 120,000 ha of cropland suitable for moving from dry season fallows to surface water irrigated cropland. Detailed maps are available and will facilitate technology targeting.

Keywords: remote sensing, technology targeting, geo-spatial analysis, crop intensification, surface water irrigation

1. Introduction

Population growth projections and increases in per capita income indicate that global food requirements will continue to expand for at least four more decades before they plateau, with estimates indicating that a doubling of current staple crop production is required by 2050 (Godfray et al. 2010; Tilman et al. 2011).

Cereals production could be boosted by expanding the land area devoted to cropping, rather than by raising yield potential alone, though this will entail negative environmental externalities (*e.g.* reduced biodiversity) that should be avoided (Tilman et al. 2011). Sustainable agricultural intensification, defined as use of sound agronomy and purposeful manipulation of ecological processes to achieve increased productivity while minimizing land expansion and environmental degradation, has been proposed as a potential solution to these issues (Garnett et al. 2013; Godfray et al. 2010). A key strategy for sustainable intensification is multiple cropping, whereby at least two crops are grown per year on the same piece of land. Currently, 59, 39, 47 and 93% of the arable land in the Indo-Gangetic Plains of Bangladesh, India, the Nepali Terai, and Pakistan, respectively, are irrigated (AQUASTAT 2013). Combined with the predominance of flooded rice as the stable crop, these figures have led to the perception that most potentially irrigable land in South Asia has already been brought into intensified production (see for example de Fraiture and Wichelns 2010; Godfray et al. 2010).

This situation raises the question: What agricultural environments of South Asia offer the greatest opportunities for sustainable intensification? Rather than focusing on already irrigated environments, the answer may lie in more "game-changing" strategies to transform agricultural productivity in the remaining rainfed or partially irrigated environments where water resources are available yet land-use intensity is currently low, and where low-cost investments in surface water irrigation (SWI) could enable the move from single to double cropping. In these marginal environments, many of which lie in the under-developed eastern Indo-Gangetic plain states of coastal Bangladesh and West Bengal in India, water resources development is low, and farmers typically grow only one rainfed monsoon season rice crop per year. Access to shallow groundwater is limited because upper aquifers are saline and may be restricted due to silty-clay in upper soil strata (MOA and FAO 2012). Moreover, increases in salinity of existing aquifers can be expected as sea levels will rise in the future due to climate change. This will further threaten food security. Deep tube well expansion is similarly problematic because of the potential for salinization resulting from the draw-down of upper water layers by industrial and domestic users (Brammer 2010) in addition to concerns arising from the natural contamination of groundwater with ground rock derived arsenic (Hossain 2006). SWI could help to ameliorate these problems.

New low-lift SWI pumps that increase the efficiency of water delivery per unit of fuel have recently become available, which could help to lower costs and potentially encourage intensification (Santos Valle et al. 2014). However, where SWI is unplanned and poorly targeted, less than optimal performance may also be expected and social and environmental problems may arise from over-extraction and water competition. It is therefore important to approach decentralized SWI development intelligently, by identifying and targeting appropriate blocks of low-intensity cropping and fallow land for irrigation that can benefit from irrigation, and by insuring that sufficient water supply is available to sustain adequate crop growth without undesirable levels of surface water depletion. What is lacking, however, is up-to-date and precise information on how and where to target SWI efforts while making the best use of available freshwater resources without exhausting supply or degrading water quality.

Southwestern Bangladesh hosts two of the country's three administrative divisions with the most people living below the poverty line (World Bank 2010). Only 50% of the region's 3.4 million farming households grow more than one *aman* rice crop per year (MOA and FAO 2012). These farmers typically fallow their land during the dry season, while those that do manage a second crop usually cultivate low-input and -output legumes such as grasspea *(Lathyrus sativus*), lentil (*Lens culinaris*) and mungbean (*Vigna radiata*) using residual soil moisture. Only 15% of the region's farmers have access to groundwater to grow dry season *boro* rice (MOA and FAO 2012).

Using the southwest of Bangladesh (Fig. 1) as a case study this paper shows how remote sensing and GIS technologies can be used to assess land suitability for intensification through decentralized SWI in deltaic environments. Because of the regional specificity of the agronomic constraints that farmers face in southwestern Bangladesh, additional information on soil and water salinity, and dry season planting dates were also employed. The basic analytical steps described in this paper can be modified and adapted to assess similar questions pertaining to fallow or low-productivity land intensification and SWI in similar deltaic environments, thereby providing a tool for more effective technology targeting to mobilize sustainable intensification and SWI development interventions.

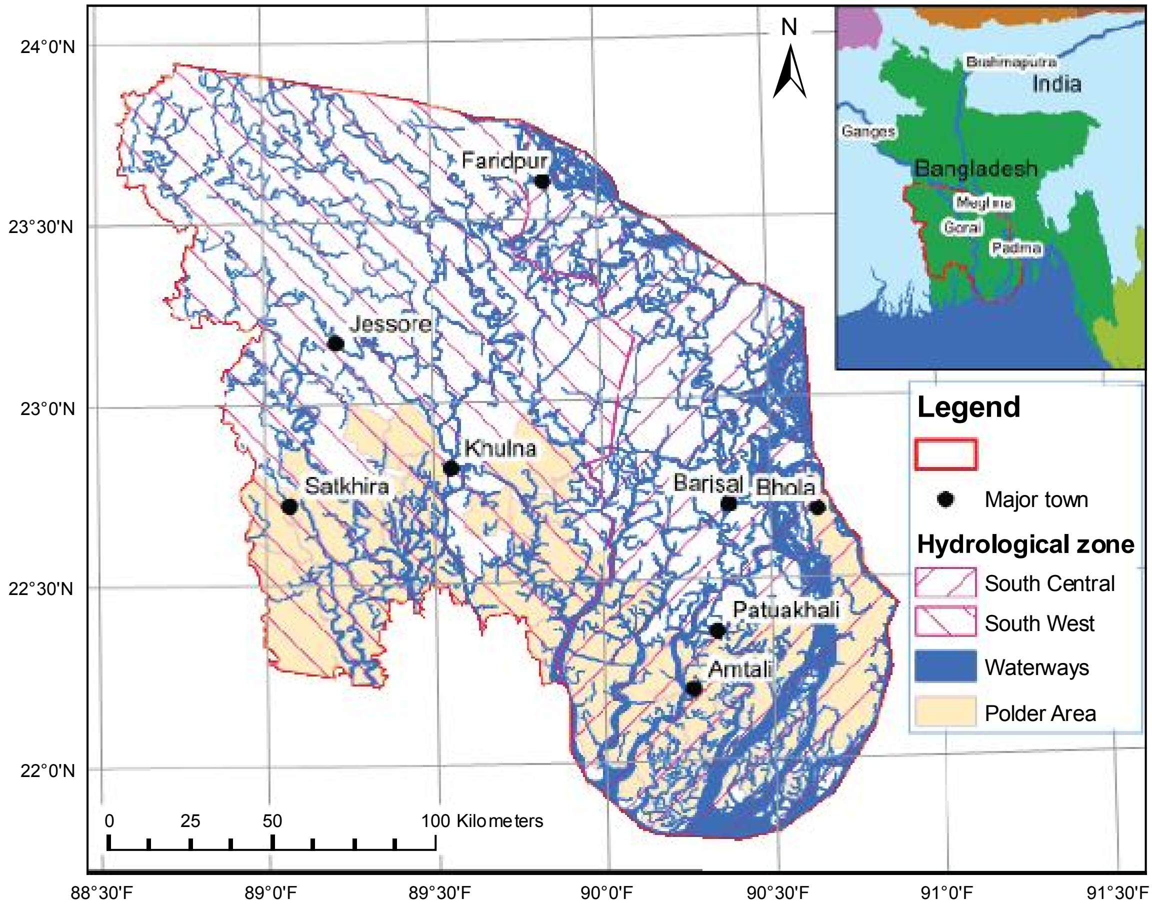


Fig. 1. Overview of study area, located in the southwest of Bangladesh. It contains two hydrological zones: south-central and southwest. Most of the land near the coast is enclosed by polders.

2. Material and methods

2.1 Data sources

This analysis is based on Landsat 5, 7 and 8 satellite imagery (Level 1T), available for free from http://earthexplorer.usgs.gov. We used the blue, green, red, near infrared (NIR) and both short wave infrared (SWIR) bands, all of which have a resolution of 30 m. The western side of the study area is covered by Landsat path 138, row 44 and the eastern side is covered by path 137, rows 44 and 45.

Data on surface water salinity covering the period from 2002 to 2012 had been obtained from the Bangladesh Water Development Board. Shape files of the most recent and reliable land elevation and soil salinity classes were collected from the Bangladesh Country Almanac (BCA 2006) and Soil Resource Development Institute (SRDI 2000), respectively. The BCA landtype shape file contains inundation classes including Highland, Medium-Highland 1, Medium-Highland 2, Medium-Lowland, Lowland, and Very Lowland, corresponding to the depths at which floodwater is encountered during the monsoon season, as a marker for elevation class, i.e., no consistent floodwater, <90 cm, 90–180 cm, 180 -275 cm, and more.

2.2 Cropland identification

Cropland was identified using a set of Landsat 5 scenes acquired on either 21 or 31 January 2010. In late January cropland could be easily separated from forest since vegetation cover on cropland is generally low at that time. The images were classified into two categories: cropland and “other” which included water, forest, urban areas and land used for aquaculture. In order to avoid potential misclassification due to calibration errors, raw images from the 2 Landsat paths were classified separately. We first created segments with eCognition 9 (Trimble Navigation Ltd., Westminster, CO). Segments are image regions that are more homogeneous within themselves than with nearby regions and represent discrete objects or areas in the image. Each image region then becomes a unit analysis for which a number of attributes, on top of spectral attributes, can be measured and used during the classification (Carleer et al. 2005).

The entire study area measured more than 3 million ha and systematic sampling of ground truth data for the cropland identification would have been a big endeavor. We therefore relied on high resolution background satellite imagery available in ArcGIS 10.1 (ESRI, Redlands, CA) and visually classified more than 250 segments for each of the two classes to create a training data set. High resolution satellite imagery contains much more detailed information than 30 m Landsat images or segments. Therefore, we chose those segments for training for which the corresponding pixels in the high resolution images showed uniformity. This was made simpler by the fact that we had to identify just two classes, cropland and non-cropland.

For each segment the following attributes were used for classification: mean of the digital numbers of bands 1–5 as well as texture (all directions) (Haralick 1973) and the normalized difference vegetation index (NDVI). Additionally, we calculated the ratio of the NIR band to the visible ones (Equation 1) as follows:

$$Ratio_{NIR\_visible} = \rho_{\text{band4}} / (\rho_{\text{band1}} + \rho_{\text{band2}} + \rho_{\text{band3}}) \qquad (1)$$

Subsequently, the Random Forest Classifier algorithm in WEKA (see Hall et al. 2009) was used to generate the classification rules. Machine learning algorithms do not depend on normal data distribution assumptions and allow for lumping together distinct classes such as forest, water, urban, etc. This reduces the effort needed to create distinct training classes. It also automatically chooses the relevant variables and discards the other ones. Once the classifier was trained it was used to classify the remaining segments. Subsequently, a visual quality control of the automatically classified segments was conducted, again using high resolution background imagery as a reference. Wrongly classified segments were manually assigned to the other class.

2.3 Identification of waterways and surface water duration

We used Landsat 5 images acquired on 26 October 2009 and 8 November 2011, coinciding roughly with the end of the monsoon when waterways are at their maximum extent, to identify them. The same methodological approach used for the classification of cropland was employed. Some waterways in the study area are ephemeral. We therefore checked for the presence of water in rivers, canals and creeks using the Automated Water Extraction Index (AWEI; Feyisa et al. 2014) with atmospherically corrected Landsat 8 images from 21 and 30 March 21 2014. $AWEI_{sh}$ was chosen because of its effectiveness in improving water extraction accuracy despite the presence of shadows resulting from trees lining rivers, canals and water bodies, following Equation 2:

$$AWEI_{sh} = \rho_{\text{band2}} + 2.5 * \rho_{\text{band3}} - 1.5 * (\rho_{\text{band5}} + \rho_{\text{band6}}) - 0.25 * \rho_{\text{band7}} \qquad (2)$$

where ρ is the value for reflectance of the respective Landsat 8 imagery bands. Using the same threshold as described in the Feyisa et al. (2014) paper, $AWEI_{sh}$ values above 0 were assumed to be water pixels and values below 0, nonwater pixels.

2.4 Assessment of land-use intensity

Land-use intensity was determined on the basis of a total of 44 Landsat 7 and 8 images acquired between 31 December and 10 April of 2011-12, 2012-13, and 2013-14. The Landsat 7 scenes had already been calibrated to surface reflectance by the United States Geological Survey (USGS). The Landsat 8 images were first calibrated to reflectance using the TOA-DOS approach (Chavez 1996). Since the NIR band of Landsat 8 has different spectral properties than Landsat 7, the Landsat 8 data were cross-calibrated using Landsat 7 imagery acquired within eight days before and after the respective scene analyzed.

The enhanced vegetation index (EVI), as described by Huete et al. (2002), is a direct measure of the quantity of light intercepted for photosynthesis (Equation 3):

$$\mathrm{EVI} = G \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{(\rho_{\mathrm{NIR}} + C_1 \times \rho_{\mathrm{red}} - C_2 \times \rho_{\mathrm{blue}} + L)} \quad (3)$$

where ρ is the reflectance surface after atmospheric correction, C_1 and C_2 are coefficients of the aerosol resistance term using the blue band to correct for aerosol caused errors in the red band, and L is the canopy background adjustment to rectify differential, nonlinear radiant red and NIR transfer through the crop canopy. When tracked during the course of a cropping season and used to determine maximum light interception, which typically corresponds to the peak of a crop's leaf area index (LAI; Huete et al. 2002), EVI can be a good indicator of the productivity of a crop community (Schulthess et al. 2012). We therefore measured the intensity of crop productivity by quantifying the maximum EVI reached by the most widely grown field crops in the study area including lathyrus, fallow, wheat, mustard, mung bean, *boro* rice and maize. We extracted EVI trends from 10 or more known fields for each of the above crops in each of the three years. The use of repetitive and sequential observation is critical to capture maximum EVI because of the heterogeneous nature of agriculture in the study region, resulting in divergent crop phenology both within and across crop species.

Following extraction, EVI values for each of the main crop types were plotted (Fig. 2) as a function of the number of days before or after 1 January until the 100th day of the year upon which the observation in question was made, corresponding roughly to the first two-thirds of the *rabi* dry season. We grouped each of the cropland types into three intensity classes: (1) fallow land; (2) low-intensity cropland, comprised of lathyrus, lentil and mungbean, neither of which are typically fertilized, weeded or irrigated, and which are broadcasted resulting in sub-optimal crop stands and poor yields (Dalgliesh and Poulton 2011), and; (3) high-intensity cropland, including wheat, *boro* rice, maize and mustard, all of which are more intensively grown with higher levels of fertilizer application, weeding, pest management and irrigation than in the case of the first three.

After checking for normality and homoscedasticity following Sokal and Rohlf (1995), we subjected data from the date upon which the maximum EVI value (corresponding to maximum LAI as a measure of peak productivity) was observed in each class to a one-way ANOVA using JMP 8.0.2 (SAS Institute Inc., Cary, NC) for the 2011-12, 2012-13 and 2013-14 dry seasons. The F-test indicated significance (P<0.001) between classes in each of the three seasons analyzed. Separation of means with the Tukey-Kramer's range test at $\alpha = 0.05$ showed that the fallow, low-intensity and high-intensity classes were consistently different and independent in each season.

Because of the significant differences between cropland use intensity classes we then set thresholds to separate classes to be used for all subsequent EVI analyses. Thresholds were set as the mid-distance point between the lower boundary for the standard deviation of the lowest maximum EVI observation for the high-intensity cropland types, and the uppermost boundary of the standard error for the highest EVI observation for the low-intensity crop types. For example, in the 2012-13 season maize exhibited the lowest maximum EVI within the high-intensity crop use class at 83 days after January 1, while the EVI of lathyrus peaked as the highest observation within the low-intensity class at 27 days. The threshold between high- and low-intensity crop was therefore set as the mid-distance between the lower and upper boundaries for the standard deviations of these observations, respectively. This conservative process was used to distinguish the low-intensity and fallow crop classes for each season studied. The last step in this analysis consisted of the extraction of the maximum EVI value for each pixel of the calibrated Landsat scenes for the entire study area in order to broadly map the three land-use intensity classes for cropland (Fig. 3).

2.5 Creation of a buffer area around rivers, canals and creeks

Since the efficiency of axial flow pumps decreases with lift height and because they can only push water horizontally without gravity feed within a limited distance (Santos Valle et al. 2014), we created a 400 m buffer around those waterways in which water was present in late March. The 400 m width of the buffer was chosen as an empirical value, assumed reachable under most circumstances given feedback from irrigation service providers using the pumps in tandem with flexible hose piping. Intensive agricultural practices can result in sedimentation and nutrient loading of watercourses. Riparian buffers planted with species capable of ameliorating these problems could aid in mitigating the negative effects of crop intensification. We consequently reduced the 400 m buffer further, excluding a 15 m strip adjacent to rivers and canals from cropping. This resulted in a 385 m wide buffer, which we deemed potentially suitable for SWI.

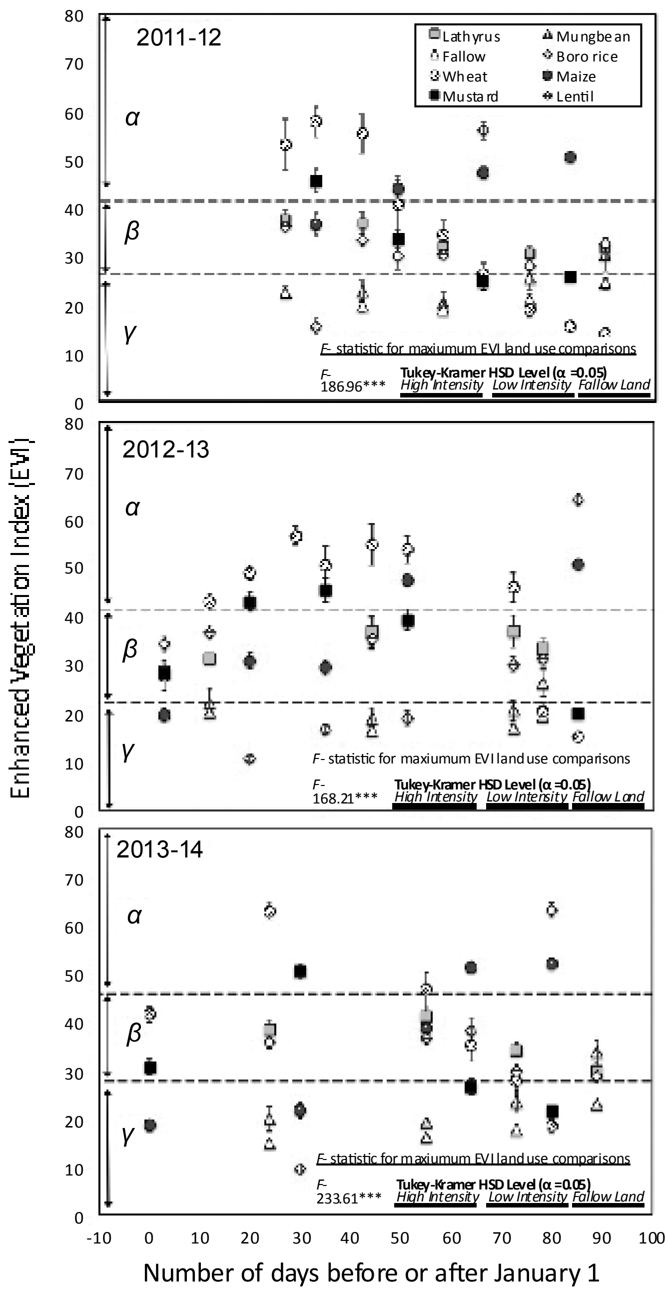


Fig. 2. Dynamices of the Enhanced Vegetation Index (EVI) derived from Landsat 7 and 8 images collected over three winter seasons in southern Bangladesh for fallow land (α), low- (lathyrus, lentil, and mungbean, indicated by β) and high-intensity (wheat, maize, mustard, and Boro rice, indicated by γ) crops.

2.6 Interpolation and temporal evaluation of surface water salinity dynamics

Salinity concentrations in the Bangladesh tidal estuary vary in time, with salinity typically increasing as the dry season progresses. This results from the gradual reduction of southward river, canal and creek water flow following the monsoon season (Brammer 2013), with important ramifications for irrigation water quality. To account for temporal changes in water salinity we created four datasets based on the median of the observed data from the second halves of the months January to April over the 11-year period (2002–2012). Each dataset was interpolated using Indicator Kriging to create a surface map of salinity. Salinity of river water is measured at stations on the main rivers only. No data exist for the other water bodies. Hence, kriging was deemed to give a good approximation of the salinity levels of smaller rivers, canals and creeks. Those maps were then classified into three water salinity classes: 0–2 dS m^{-1} (high–quality), 2–4 dS m^{-1} (medium–quality) and >4 dS m^{-1} (low–quality). Water salinity tolerance varies greatly among crops. While maize is rather sensitive, wheat is much more tolerant. In Australia a 10% yield reduction for maize at 1.7 dS m^{-1} was reported, while for wheat that threshold was 4.7 dS m^{-1} (Evans 2006).

2.7 Reclassification and application of soil salinity and inundation land types shape files

The publically available soil salinity map provided by SRDI (2000) comes with various classes, some of them being "mixed", i.e., a polygon may belong predominantly to one class, but may also contain data from another class. To simplify the analysis we reclassified all data into three classes, <2, 2–4, and >4 dS m^{-1}, by assigning the highest reported value in each class as the identifier for the new class.

2.8 Matrix of land suitability based on soil and surface water salinity

Since either high soil and/or surface water salinity are severe constraints for crop production we created a matrix as shown in Table 1 as a heuristic tool to simplify the analysis. These thresholds take into account crops that are rather salt intolerant, such as maize. Crop species and even cultivars within a crop species can vary greatly in their ability to withstand soil salinity (Ayers and Westcot 1989).

2.9 Intersection of the layers and suitability analysis

Cropland, EVI, surface water salinity, soil salinity, hydrozone and landtype layers were intersected to assess the suitability of cropland for sustainable intensification. Lastly, a subset of the land within the 385 m buffer was created. This resulted in a geospatial database that can be queried for extraction of descriptive statistics.

Table 1. Salinity thresholds of soil and surface water used to determine the suitability classes for agricultural intensification and surface water irrigation.

		Water Salinity (dS m^{-1})		
		0 -2	2 - 4	> 4
Soil Salinity [dS m^{-1}]	0 -2	Highly suitability	Medium suitability	Non suitable
	2 - 4	Medium suitability	Low suitability	Non suitable
	> 4	Non suitable	Non suitable	Non suitable

3. Results and discussion

The study area covered 3.375 million ha of which 57% or 1.926 million ha were identified as cropland. Cropland coverage was rather evenly distributed, except for the southwest where large tracks of land with high surface water and soil salinity levels are being used for aquaculture. The network of waterways is much denser in the south-central hydrozone than in the south-west hydrozone. Most waterways in the latter hydrozone carry no or relatively small amounts of water in the dry season. Water recharge in that part of

Bangladesh has been drastically reduced since the 1976 completion of the Faraka Dam in West Bengal and the plume of saline water in the Khulna-Sathkira region grows steadily in the winter months. Intermediate soil salinity is an issue in the coastal zones of the south where salinity can range from 2-4 dS m^{-1} and sometimes can be even higher. Unfortunately, there are no regularly reported surface water salinity data available for the stretch of land south of Amtali to the coastline. Hence, actual water salinity levels for that area are not known and the interpolated data may not be entirely representative for this region.

Land-use intensity levels for all cropland in the study area are summarized in Table 2. Our analysis revealed that in the three years analyzed fallow land area ranged between 219,000 and 271,000 ha or between 11 and 14% of the total cropland area. The Ministry of Agriculture and FAO (2012) placed the number for fallow land at 136,000 ha, while the Bangladesh Bureau of Statistics estimated 240,000 ha (2011). Hence our numbers are largely in agreement with the Bangladesh Bureau of Statistics but are about double as high as those of the Ministry of Agriculture and FAO. Different definitions of what constitutes fallow land and slight differences in the land area assessed may contribute to this discrepancy.

Table 2. Land-use intensity levels of cropland during the *rabi* season in the south of Bangladesh in ha. Data were derived based on an analysis of Landsat 7 and 8 images and ground truth data collected by agronomists.

Land-use intensity	2012	2013	2014
Fallow land	271,078	218,806	230,824
Low-intensity	779,095	915,548	906,382
High-intensity	876,338	790,732	789,735
Total	1,926,511	1,925,086	1,926,941

Other estimates of fallow land and land that is suitable for intensification are higher. Using both remotely sensed and administrative data, Rawson et al. (2011) estimated that 800,000 ha of *rabi* season fallow or underutilized land suitable for cropping was available in southwestern and southeastern Bangladesh. The Bangladesh Agricultural Development Corporation estimated that 634,000 hectares are regularly fallowed or under low levels of productivity in Khulna and Barisal Divisions during the *rabi* season (2010), exclusively in the southwest. Taking the average of 2012 to 2014, we estimate that about 867,000 ha are under low-intensity cropping. Our results are slightly higher than those other estimates.

Noticeable are the intensive production levels of crops grown in the northern half of the study area (Fig. 3). Presumably, most of these fields are planted with *boro* rice, wheat or maize, and irrigated with groundwater. In the south-central hydrozone, a clear gradient of declining production intensity from the north to the south can be noticed. Groundwater in that region has high salinity levels, hence irrigation in the winter months is not commonly practiced. The large tracks of land being cropped at the intermediate and low intensity levels indicate that there is substantial potential to increase food production in the southern part of the south-central hydrozone. Most of that land is actually enclosed by polders. Hence, with appropriate management of the sluice gates it might be possible to “harvest” water with low salinity levels for irrigation.

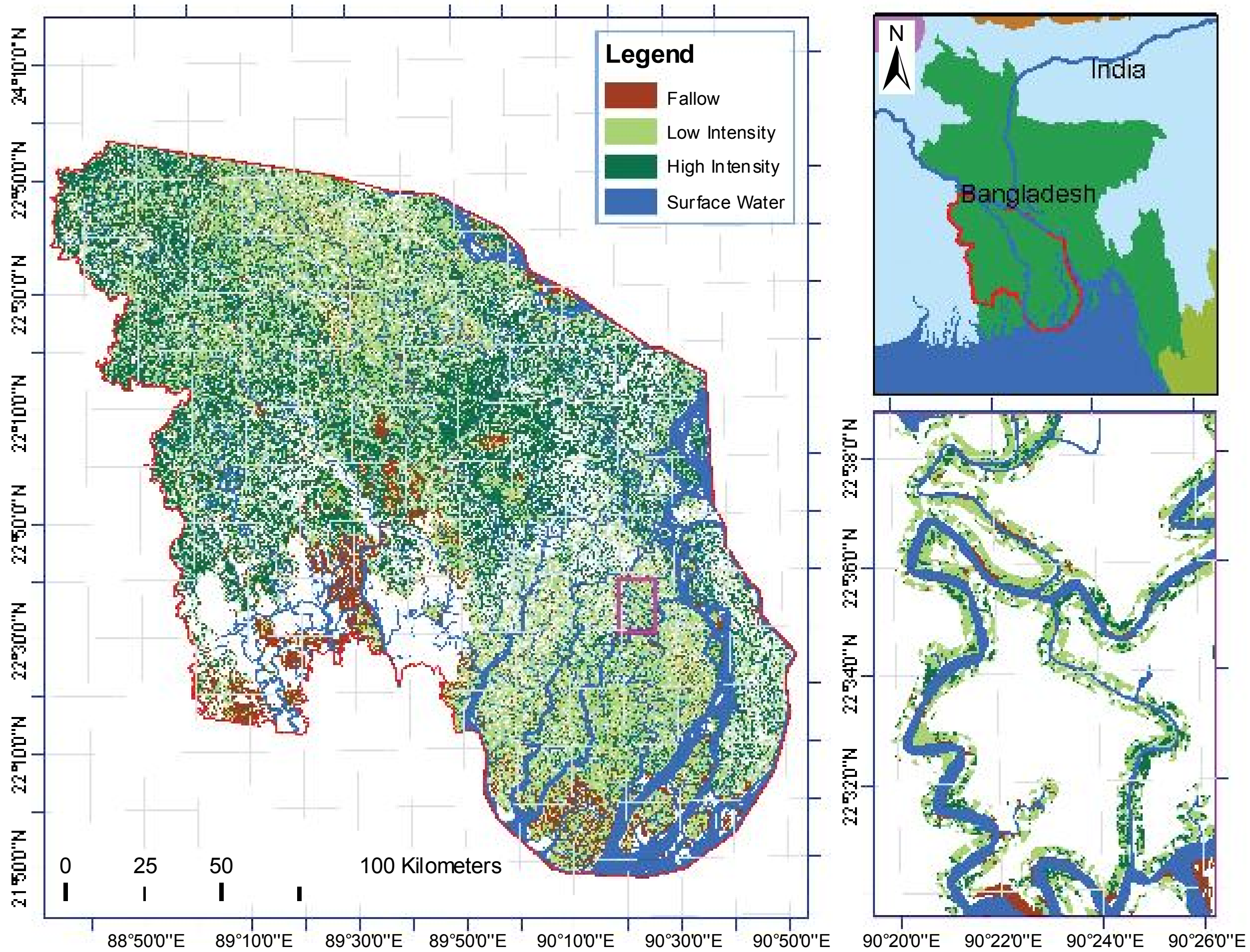


Fig. 3. Land use intensity of cropland during the 2014 *rabi* season in southern Bangladesh. The analysis was based on a series of Landsat 8 images acquired between 31 December 2013 and late March 2014. At the lower right, a detailed view of the cropping intensity levels within a 385 m buffer is given.

Since our main objective was to identify areas suitable for technology targeting with axial flow and similar low-lift, surface water pumps, we created a 385 m wide buffer within a 15 m distance adjacent to the waterbodies for which water could be detected with Landsat images. They have a resolution of 30 m and therefore a large portion of waterways went undetected. But we might also have included false positives, i.e., land that is adjacent to surface water bodies that are shallow or have a low flow rate and therefore are not a reliable source for irrigation water; we could only detect whether surface water is present or not. When comparing surface water maps for the months of January to April we noticed a remarkable reduction in the southwest hydrological zone. Hence, due to limited availability of water it may not be possible to address large tracks of land with SWI in that hydrological zone (see Fig. 1). The data reported in Table 3 are preliminary indications only of the area of land that might be addressed. A more detailed study especially for the south-central hydrological zone, which contains most of the fallow and low-intensity land, is needed to accurately determine the potential for SWI. High surface water salinity may pose a severe limitation to intensification in the south only. Almost 80% of the land within the 385 m buffer zone next to waterways carrying water in March is in areas where soil and water salinity are below 2 dS/m, whereas only 13% is in areas that are not suitable. In addition to salinity levels, land elevation is another constraint limiting usability of land. However, we determined that when analyzing the land types of the buffer land, a total of only 3% of the land is in areas that are either Lowland or Very Lowland. Hence, land elevation is not a major constraint. Based on these constraints, our initial data in this hydrological zone point to approximately 15,300 and 62,600 hectares of fallow and low-intensity land, respectively, in the south-central zone that is not too saline for cropping and that could receive quality surface water irrigation.

Table 3. Current land-use intensity of cropland and its suitability for surface water irrigation in the delta region of Bangladesh. Suitability classes are the result of an intersection of soil and water salinity levels as defined in Table 1. Numbers indicate the area in ha of land that are within a 385 m buffer adjacent to water bodies on which water was detectable in late March of 2014. Land in the Lowland and Very Lowland classes was excluded from these statistics. Values in parentheses indicate land area specific to the south-central hydrological zone, for fallow and low-intensity land, respectively.

Land-use intensity	Highly suitable	Medium suitability	Low suitability	Non suitable
Fallow land	14,403 (8,711)	6,866 (6,361)	2,144 (2,144)	23,653 (6,730)
Low-intensity	86,159 (47,939)	17,262 (14,688)	6,640 (6,640)	22,049 (11,206)
High-intensity	66,562	6,524	999	7,382
Total	**167,124**	**30,652**	**9,783**	**53,084**

4. Conclusions and recommendations

In order to assess the potential of using surface water irrigation in the delta area of Bangladesh, we used a series of Landsat images to analyze current cropping intensities and assess the potential for sustainable intensification through surface water irrigation, considering various constraints such as surface water availability, land elevation and salinity. In the western hydrological zone, there is only very limited potential for intensification due to a lack of good quality surface water. However, in the southern part of the south-central hydrological zone there is a lot of land that is currently cropped at low-intensity levels or left fallow. The detailed maps derived in this study will allow for a targeted introduction of axial flow pumps into the delta area of Bangladesh. Field trials will be required to determine optimal irrigation schedules for various crops that can be grown in these areas.

Acknowledgements

This research was conducted under the Cereal Systems Initiative for South Asia - Mechanization and Irrigation (CSISA-MI) project funded by the USAID Mission in Bangladesh. The contents and opinions expressed herein are those of the authors and do not necessarily reflect the views of USAID or the United States Government and shall not be used for advertising or product endorsement purposes. We thank the Soil Resources Development Institute and Bangladesh Water Development Board for access to soil and water quality information.

References

AQUASTAT. 2013. AQUASTAT main country database. Food and Agriculture Organization of the United Nations.

Ayers, R.S. and D.W. Westcot. 1989. Salinity problems. In: FAO, editor Water quality for agriculture. FAO, Rome, Italy. p. 1-32.

BADC. 2010. Minor irrigation survey report. 2009-2010. BADC Bangladesh Agricultural Development Corporation (BADC), Dhaka.

BBS. 2011. Yearbook of Agricultural Statistics of Bangladesh 2011. Bangladesh Bureau of Statistics (BBS), Dhaka. p. P. 305.

Brammer, H. 2010. After the Bangladesh Flood Action Plan: Looking to the future. Environmental Hazards 9: 118-130.

Brammer, H. 2013. The Physical Geography of Bangladesh University Press Limited, Dhaka.

Dalgliesh, N.P. and P.L. Poulton. 2011. Potential for mungbean in sequence with Rabi-season wheat in southern Bangladesh. In: H. M. Raws, editor Sustainable intensification of Rabi cropping in southern

Bangladesh using wheat and mungbean. Australian Centre for International Agricultural Research, Canberra. p. 256.

de Fraiture, C. and D. Wichelns. 2010. Satisfying future water demands for agriculture. Agric. Water Manage. 97: 502-511.

Evans, L. 2006. Salinity tolerance in irrigated crops. NSW Department of Primary Industries, available online at http://www. dpi. nsw. gov. au/agriculture/resources/soils/salinity/crops/tolerance-irrigated.

Feyisa, G.L., H. Meilby, R. Fensholt, R. Simon and S.R. Proud. 2014. Automated Water Extraction Index: A new technique for surface water mapping using Landsat imagery. Remote Sensing of Environment 140: 23-35.

Garnett, T., M.C. Appleby, A. Balmford, I.J. Bateman, T.G. Benton, P. Bloomer, et al. 2013. Sustainable intensification in agriculture - premises and policies. Science 341: 33-34.

Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, et al. 2010. Food security: the challenge of feeding 9 billion people. Science 327: 812-818.

Godfray, H.C.J., I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, N. Nisbett, et al. 2010. The future of the global food system. Philosophical transactions of the Royal Society of London. Series B, Biological sciences 365: 2769-2777.

Hall, M., E. Frank, G. Holmes, B. Pfahringer, P. Reutemann and I.H. Witten. 2009. The WEKA data mining software: An Update. . SIGKDD Explorations 11: 1.

Haralick, R.M., K. Shanmugam and I. Dinstein. 1973. Textural features for image classification. IEE Transactions on Systems, Man, and Cybernetics SMC-3: 610–621.

Hossain, M.F. 2006. Arsenic contamination in Bangladesh—An overview. Agr. Ecosyst. Environ. 113: 1-16.

Huete, A., K. Didan, T. Miura, E.P. Rodriguez, X. Gao and L.G. Ferreira. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment 83: 195–213.

MOA and FAO. 2012. Master Plan for Agricultural Development in the Southern Region of Bangladesh. Ministry of Agriculture (MoA, Government of Bangladesh) and United Nations Food and Agriculture Organization, Dhaka, Bangladesh. p. 122.

Rawson, H.M.E. 2011. Sustainable intensification of Rabi cropping in southern Bangladesh using wheat and mungbean. In: R. H.M., editor ACIAR Technical Reports No. 78. Australian Centre for International Agricultural Research:. Canberra. p. 256 pp.

Santos Valle, S., Qureshi, A.S., Islam, M.S., Hossain, M.A., Gathala, M.K., Krupnik, T.J., 2014. Axial flow pumps can reduce energy use and costs for low-lift surface water irrigation in Bangladesh. , Cereal Systems Initiative for South Asia Mechanization and Irrigation (CSISA-MI) Project, Research Report No. 1. CIMMYT, Dhaka, Bangladesh.

Schulthess, U., J. Timsina, J.M. Herrera and A. McDonald. 2012. Mapping field-scale yield gaps for maize: An example from Bangladesh. Field Crop. Res. 143: 151-156.

Sokal, R.R. and F.J. Rohlf. 1995. Biometry. W.H. Freeman and Company, New York.

SRDI. 2000. Soil Salinity Bangladesh. Soil Resources Development Institute., Dhaka, Bangladesh.

Tilman, D., C. Balzer, J. Hill and B.L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America 108: 20260-20264.

World Bank. 2010. Updating Poverty Maps of Bangladesh. The World Bank, Bangladesh Bureau of Statistics, World Food Program, Dhaka. p. 17.

Potential for expansion of surface water irrigation through axial flow pumps to increase cropping intensification in southern Bangladesh

A.S. Qureshi[1,2], S. Yasmin[1], N.C. Howlader[1], K. Hossain[1] and T.J. Krupnik[1]

[1]International Maize and Wheat Improvement Center, Bangladesh,
a.qureshi@biosaline.org.ae, s.yasmin@cgiar.org, t.krupnik@cgiar.org, n.howlader@cgiar.org
[2]Current address: International Center for Biosaline Agriculture, UAE

Abstract

In southern Bangladesh, the lack of irrigation and drainage facilities has resulted in poor land use, low crop productivity, and increasing poverty. Minor irrigation is dependent on poor quality groundwater extraction, whereas surface water irrigation is deficient due to lack of irrigation infrastructure. Limited availability of suitable water lifting devices is one of the major bottlenecks. As a result, an estimated 17,000 ha of land are left fallow in the dry season, whereas another 95,000 ha have lost their production potential. To unlock the production potential of this region, improvements in surface water irrigation services are required. Through the Cereal Systems Initiative for South-Asia – Mechanization and Irrigation project (CSISA-MI), the International Maize and Wheat Improvement Center (CIMMYT) is approaching these issues from a value chain and targeted technology transfer perspective to move towards the sustainable intensification of agriculture in this area.

The centrifugal pumps widely used to lift water from irrigation canals are technically less efficient and have high operational costs. As an alternative, CSISA-MI introduced imported axial flow pumps (AFPs) to farmers on a trial basis. During this study, AFPs have produced higher water discharge than centrifugal pumps while also reducing fuel use, and thus operational costs. Due to reduced time required to irrigate *boro* rice, an AFP would save about USD70 per season at 1-m head to USD38 at 3-m head, relative to centrifugal pumps. CSISA-MI is now working with domestic manufacturers to modify pump design and material to make AFPs more suitable for local conditions and to reduce costs. During the next three years, the project's target is to make AFPs economically affordable to the maximum number of irrigation service providers who can supply water to smallholder farmers in south-central Bangladesh. Among other on-going initiatives (canal rehabilitation, drainage improvements, introduction of new crop varieties and agricultural machinery), increased access to surface water irrigation is a step towards increasing agricultural productivity in this region.

Key message: Hydro-economic superiority of axial flow pumps over centrifugal pumps makes them a potential technology for the expansion of irrigated dry season and double cropping in southern Bangladesh.

Keywords: low lift pump, value chain, irrigation infrastructure, *rabi* crops

1. Introduction

Agriculture is the major user of water in Bangladesh. Rice (*Oryza sativa*) is the main staple food and is grown on 75% of the total cultivated land, constituting 90% of total grain production in the country (BADC 2013). Due to its comparatively high yield (national average 3.4 tons ha^{-1}) compared to early summer *aus* (1.6 tons ha^{-1}) and monsoon *aman* (2.0 tons ha^{-1}), dry season winter *boro* rice production has expanded in the last two decades (Talukder et al. 2008). *Boro* is currently cultivated on an area of 4.8 Mha and contributes about 55% of the overall rice production in Bangladesh. The unprecedented increase in *boro* production has helped Bangladesh to increase its total rice production from 18.3 million tons in 1991 to 33.8 million tons in 2013, achieving near rice self-sufficiency (BBS 2013). Most areas of *boro* are in the northern parts of the country. The expansion of *boro* in the southern parts of the country has been slow.

Currently, about 80% of Bangladesh's groundwater is used for irrigation, of which 73% is estimated to be used exclusively for *boro* cultivation (Rehman and Ahmed 2008). However, groundwater development problems (i.e. declining water tables, deteriorating water quality, and increasing energy costs and carbon emissions) threaten the sustainability of irrigated agriculture in Bangladesh. Increasing uncertainties regarding rainfall patterns due to climate change (which may impact groundwater recharge) also suggest that dependence on groundwater use for irrigation should be reduced and surface water resources must be developed to meet future crop water requirements. The extension of irrigation services in the areas where surface and groundwater resources are relatively less developed (such as southern Bangladesh) could help considerably in reducing the pressure on areas where land and water resources are already stressed. Realizing this, the Government of Bangladesh (GoB) has developed the "Master Plan for the Southern Region", to attract foreign investments of over USD7 billion with a large focus on the expansion of existing surface water infrastructure to increase cropping intensity and productivity of poorly productive land (FAO and MoA 2012).

Historically, agricultural development in southern Bangladesh, which accounts for 27% of the country's area and 21% of its population, has been largely ignored. This region now lags behind the north, with about 15% of the total cultivable land either fallow and/or not being used for cultivation due to soil and water salinity, waterlogging, and lack of access to surface water for irrigation (Bala and Hossain 2010). Surface water is perceived as abundant in parts of the South where river and canal networks have perennial flow, and where salinity levels do not cross crop-damaging thresholds. Conversely, saline shallow aquifers are common and prohibit the use of shallow groundwater for irrigation. One of the major bottlenecks in expanding irrigation facilities, despite abundant surface water availability, is the lack of surface water irrigation infrastructure and the limited availability of appropriate water lifting devices. For this reason, an estimated 50% of southern Bangladesh's farmers currently grow only one rain-fed rice crop per year (FAO and MoA 2012).

Currently, centrifugal pumps (also known as low lift pumps, LLPs) are occasionally used for lifting water from canals for irrigating crops in the southern region. Centrifugal pumps usually require "priming" before operation by manually adding water through the outlet until the entire tube and interior pump system is completely filled to avoid efficiency losses resulting from air pockets in the suction system. At least partly due to these technical difficulties and higher operational and maintenance costs, wide scale adoption of centrifugal pumps by farmers remains limited for dry season irrigation in southern Bangladesh.

Through the Cereal Systems Initiative for South-Asia – Mechanization and Irrigation (CSISA-MI) project, the International Maize and Wheat Improvement Center (CIMMYT) is working on a strategy to develop public-private partnerships for the deployment of axial flow pumps (AFPs) imported from Thailand, with the longer-term aim of developing domestic production capacity at scale. AFPs are widely used in Thailand and Vietnam where irrigation lift requirements are low and where large volumes of water need to be lifted at low pressure (Biggs 2011). This situation is similar to that found in the southern delta of Bangladesh. The AFP is not a new technology. Use of the AFP in Thailand enabled many farmers to move from single to double rice cropping (Chinsuwan and Cochran 1986) and there exists a relatively mature AFP manufacturing industry in Thailand and Vietnam. However, AFPs remain relatively unknown in Bangladesh despite the country's similar deltaic geo-morphology and potential for surface water irrigation (SWI). Based on their research in the 1980s, the International Rice Research Institute (IRRI) also found AFPs well suited to low-lying, deltaic environments such as those found in the southwest and south-central zones of Bangladesh. However, before CSISA-MI's work, they had not yet been introduced on a large scale within Bangladesh.

The private sector has shown considerable interest in AFP technologies and is driving this initiative in collaboration with CSISA-MI. This paper discusses this unique public-private approach for motivating irrigation service providers and farmers to adopt AFPs to increase agricultural productivity through improved surface water irrigation. The paper also highlights other interventions that are necessary for boosting agricultural production in this region of Bangladesh.

2. Methodology and approach

We tested the technical efficiency and social acceptability of axial flow pumps before introducing them to farming communities. For this purpose, a two-tier approach was used. The first approach was related to the testing of technical aspects of axial flow and centrifugal pumps, whereas the second was associated with the field scale performance assessment of both pumps. The methodology used for both performance assessments is discussed below.

2.1 Hydro-economic performance assessment of axial and centrifugal flow pumps

Since no information on the characterization and performance of axial flow and centrifugal pump under different conditions was available, it was necessary to collect this data through tests before developing recommendations for farmers about the use of these pumps. Such data could provide sound basis for extension officers and institutions to educate farmers about the efficient use of these pumps under different field conditions.

The hydraulic and economic efficiency performance tests of axial flow and centrifugal pumps were conducted from April through May of 2013 at the Bangladesh Agricultural Research Institute (BARI) located in Gazipur, Bangladesh (for details of these experiments and results, please refer to the report by Santos-Valee et al. (2014)). Four locally made prototype AFPs (AFP1-4) based on Thai designs were compared with two commonly used centrifugal pumps. The pumps used for on-farm demonstration were similar to AFP1-4, but were of different sizes and manufacturers (Table 1). This paper reports the averages of for each kind of pump, which were compared using ANOVA and *post hoc* LS means planned contrast tests.

The economic performance of the pumps was compared through *ex-ante* analyses (see Santos-Valee et al. 2014 for details). Parameters recorded during the tests included engine fuel consumption (l/h), and pump discharge (l/s). Hydraulic performance was assessed using the standard head verses discharge (H/Q) relationship for each pump, employing calculations of pump discharge efficiency and determination of the theoretical and actual pump discharges. Economic analysis included both fixed and variable costs. The former primarily comprised key capital outlays (e.g., costs of full pump set, engine, V-belts, etc.), with costs collected from local markets. The fixed cost per year was calculated from the sum of depreciation and interest on investment.

Table 1. Specification of pumps demonstrated and tested during the *rabi* season of 2013-14

Pump ID	Thai manufacturer	Diameter (cm)	Length (m)	Impeller (cm)
AFP1	Pattanakarnkol	12.7	4.3	20.3
AFP2	Pattanakarnkol	15.24	4.3	20.3
AFP3	Pattanakarnkol	12.7	6.1	20.3
AFP4	Pattanakarnkol	15.24	6.1	20.3
AFP5	Somphonlohamachine	12.7	4.3	25.4
AFP6	Somphonlohamachine	15.24	4.3	25.4
AFP7	Somphonlohamachine	12.7	6.1	25.4
AFP8	Somphonlohamachine	15.24	6.1	25.4
AFP9	Ruapatanakarn Chang	12.7	4.3	20.3
AFP10	Ruapatanakarn Chang	15.24	4.3	20.3
AFP11	Ruapatanakarn Chang	12.7	6.1	20.3
AFP12	Ruapatanakarn Chang	15.24	6.1	20.3
AFP13	Vichakarnkon	12.7	4.3	25.4
AFP14	Vichakarnkon	15.24	4.3	25.4
AFP15	Vichakarnkon	12.7	6.1	25.4
AFP16	Vichakarnkon	15.24	6.1	25.4
AFP17	SuthamKarn Chang	12.7	4.3	--
AFP18	SuthamKarn Chang	15.24	4.3	--
AFP19	SuthamKarn Chang	12.7	6.1	--
AFP20	SuthamKarn Chang	15.24	6.1	--
CEN1	Centrifugal pump (4m head)	10	N/A	--
CEN2	Centrifugal pump (4m head)	12.7	N/A	--

2.2 Field-scale performance assessment of axial and centrifugal flow pumps

The CSISA-MI project is being implemented in partnership with International Development Enterprises (iDE), which, through CSISA-MI, works closely with Rangpur Foundry Limited (RFL), a large scale manufacturer in Bangladesh and sales agent of imported AFPs. In 2013-14, field demonstrations of AFPs were therefore conducted in collaboration with iDE and RFL. During the demonstrations, CIMMYT and iDE led in explaining technical aspects of the pumps, whereas RFL looked after the marketing and accessibility and operational issues such as pricing, after sale services and spare parts. Field-testing of axial flow pumps was carried out at 90 locations in Barisal Region, where quality surface water is relatively plentiful. These short demonstrations were arranged with the collaboration of RFL, and were used to encourage purchase of imported Thai pumps. The locations for pump demonstrations were determined after discussions with RFL dealers, water user associations and several farmer groups in different *Upazillas* (sub-districts).

These brief demonstrations were followed by several focus group discussions to select interested local service providers (LSPs) and potential farmers for: (1) season-long demonstrations including the use of normally fallow lands for *rabi* crops, and; (2) short roaming promotional demonstrations where LSPs installed AFPs for at least three weeks to deliver water to farmers. In total, 70 LSPs were selected and each LSP was tasked to bring 5 ha of fallow land under cultivation during the dry season by providing surface water irrigation. Seventy-eight percent of the LSPs irrigated *boro* rice crops, 15% irrigated maize, 4% irrigated mixed maize and wheat parcels, and 4.5% irrigated wheat parcels. To identify potential LSPs for the demonstration of AFPs, the following criteria were used:

- Irrigation service provider/Block Manager
- Power tiller engine owner
- Existing centrifugal pump owner
- Identified irrigation LSP according to the Department of Extension's (DAE) records
- Has current service provider business and business tendency
- Literate with at least a Secondary School certificate
- Recognized as a social leader by farmers
- Technically proficient
- Willing to provide services, and willing to experiment with new technologies.

Based on the above, 70 pumps were distributed to LSPs for longer-term field demonstrations. Most LSPs replaced their centrifugal pumps with the AFPs, while others opted to establish newly cropped areas (Table 2 and Figure 1).

Table 2. Distribution of AFPs for demonstration in three districts of Barisal Division

Demos managed by	Barisal	Bhola	Patuakhali
CIMMYT	13	7	7
iDE	15	14	14
Total	28	21	21

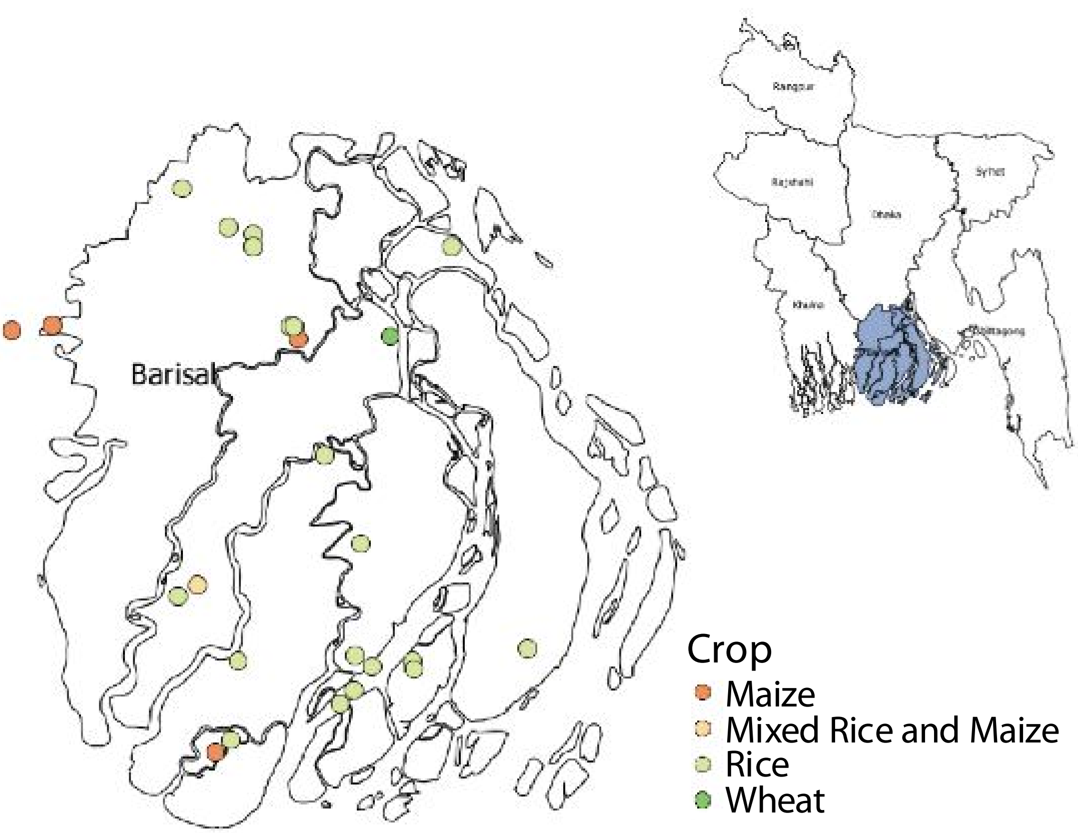


Fig. 1. Spatial distribution of AFP demonstrations in southern Bangladesh (largely in Barisal Division). In each location, more than one pump may have been demonstrated. Note that because of the proximity of locations, some dots overlap.

To assess the field performance of the AFPs, 19 LSPs and 28 irrigation service recipient farmers belonging to Barisal, Bhola, and Patuakhali Districts were interviewed. The primary data for this assessment was collected by filling out two different sets of semi-structured questionnaires with Lead Farmers/LSPs, as well as two service recipient farmers per Lead Farmer/LSP. The subjects for which recipient farmers' and LSPs' responses were recorded included:

- Demographic information (e.g. basic profile, household's involvement with non- farm activities, access to credit, assets, specification of the machinery and investment)
- Past and present agricultural volume and associated income
- Technical performance of pumps (ease of operation, discharge, fuel consumption, efficiency of the pump, etc.)
- Operational problems and level of satisfaction
- Customer satisfaction
- After sales service delivery
- Service received through AFPs (e.g. duration, cultivated land area, service charges, accessibility, timely availability, level of satisfaction regarding service)

The selected LSPs and lead farmers were trained in the use and technical aspects of axial flow pumps before they used them in the field. The training also included book keeping for recording data on the size of irrigation blocks, operating time of each pump, fuel used, operating cost, and any technical and operational problems encountered. The trainings were held in all three districts both for female and male members of the farming community (Table 3).

Table 3. Details of trainings on AFP under Barisal region

District	Intervention	Male	Female	Total
Bhola	AFP + Mechanical repair + Business skill development	100	0	100
Barisal	AFP + Mechanical repair + Business skill development	261	6	267
Patuakhali	AFP + Business skill development	42	1	43

3. Results and discussion

3.1 Hydro-economic performance assessment of axial and centrifugal flow pumps

The testing results indicate that the AFPs produced higher water discharge than centrifugal pumps at low heads (Table 4), consuming less fuel which, in turn, increases the potential for service providers to save fuel costs and boost profits (Santos-Valee et al. 2014). The hydraulic performance (discharge rate) of AFPs was higher at low lifts (i.e. 1–2 m), and dropped significantly at heads exceeding 2.8 m. On the other hand, centrifugal pumps produced low discharge but with consistent discharge rate at 1–3 m heads (Santos-Valee et al. 2014). For example, at 1-m head, average discharge of AFPs was 72% higher than of centrifugal pumps, whereas at 2 m and 3 m heads, AFP discharge was 55% and 28% higher than centrifugal pumps, respectively. Although the discharge rates obtained by AFPs at 3-m heads were significantly lower than at 1-m head, they remained higher than with centrifugal pumps (Table 4).

Water delivery per unit of fuel (m^3/l) was highest with AFPs at 1 m head, and gradually decreased as head increased. This was not the case for centrifugal pumps, where water delivery per unit of fuel used remained almost the same at all heads. The water delivery per unit of fuel for AFPs at 1-m head was 112.4 m^3/l, which declined to 91 m^3/l and 69 m^3/l at 2-m and 3-m head, respectively. Water delivery per unit of fuel for centrifugal pumps at 1-m, 2-m and 3-m heads was 75 m^3/l, 75 m^3/l and 73 m^3/l, respectively. The average water delivery per unit of fuel for AFPs was found to be 41% higher than centrifugal pumps at 1-m head, though it declined thereafter, as indicated by the LS Planned contrasts test (Table 4).

Table 4. Water discharge (m^3/h) of different pumps at different head levels (adapted from Santos Valle et al, 2014)

Water discharge (m^3/h)			
	1-m	2-m	3-m
AFP [1]	215 a	187 a	149 a
CEN [2]	125 b	121 b	116 b
F-values	1428**	1124**	1106**

[1] Indicates Axial Flow Pump.

[2] Indicates Centrifugal Pump. Values in columns for the Least Squares (LS) Planned Means Contrasts for Horsepower and Pump Type are significantly different at α=0.05 according to the Student's T Test. ANOVA results with a * indicate significance at P≤ 0.05, and ** indicates significance at P≤ 0.001.

The four prototype AFPs used proportionally less fuel per unit of water delivered up to a head of 2.8 m compared to centrifugal pumps. After 2.8 m of head, AFPs continue to deliver more water than centrifugal pumps but consumed more fuel per unit of water delivered. The higher discharge rate of the AFPs can make significant reductions in the time needed to irrigate a crop. The maximum time required to irrigate one hectare of *boro* rice by an AFP was estimated at 86 h compared to 110 h for a centrifugal pump at 3-m lift height (Santos-Valee et al. 2014). At 1-m and 2-m heads, 42 and 36 h less pumping time would be needed. When compared to centrifugal pumps, an AFP would save about USD70 per season at 1-m head and USD38 per season at 3-m head for irrigating *boro* rice.

3.2 Field-scale performance assessment of axial and centrifugal flow pumps

Local Service Providers also found the field performance of AFPs to be better than centrifugal pumps in terms of discharge, fuel consumption, and operational cost. The average operational cost of AFPs (labour, maintenance and fuel costs) was much lower than that of centrifugal pumps. The LSPs confirmed that AFPs can save up to BDT200/ha (USD 2.6/ha) per irrigation for *boro* rice, which is significant for a crop that may require 15 to 30 irrigations depending on field water depth, soil type, and proximity of the perched ground water table, indicating the potential for large aggregate savings (USD39 to 78/ha) when considered throughout the entire cropping season. Due to their higher discharge rate, AFPs required less irrigation time per hectare, which allowed irrigation service providers to provide water to more farmers than with centrifugal pumps, indicating the potential to scale up use of the AFPs to service more farmers while saving costs for irrigation water sellers. The LSPs also expressed satisfaction with the ease of operation (no priming is required with AFPs), water lifting capacity, service charge recovery, maintenance and repair. However, due to heavy weight, pump mobility and associated labor requirements were reported as primary issues. LSPs favoured AFPs due to technical backstopping by RFL and CSISA-MI, and reduced fuel costs (Figure 2).

Large tracts of agricultural land in southwest Bangladesh can easily be brought under *rabi* season cultivation by extending surface water irrigation through the adoption of AFPs. Flexible hosepipes (FHP) can also be used to transport irrigation water up to 500 m from canals to fields. With their superior hydraulic performance, AFPs can help in irrigating more area per unit of time while saving fuel. Following the field demonstrations, 173 AFPs were purchased commercially by farmers in south-central Bangladesh to replace their centrifugal pumps. The AFPs were purchased commercially through RFL, with CSISA-MI's facilitation.

Despite these benefits, large scale adoption of AFPs could be constrained by minor technical problems encountered during the field-testing, and the economic limitations of farmers to buy imported pumps. The technical problems can be partially attributed to the lack of knowledge of LSPs and farmers about the proper installation and operation of these pumps under Bangladeshi conditions. Therefore, solving technical problems and reducing costs would be the key for large-scale adoption of AFPs by farmers to intensify agriculture in this region.

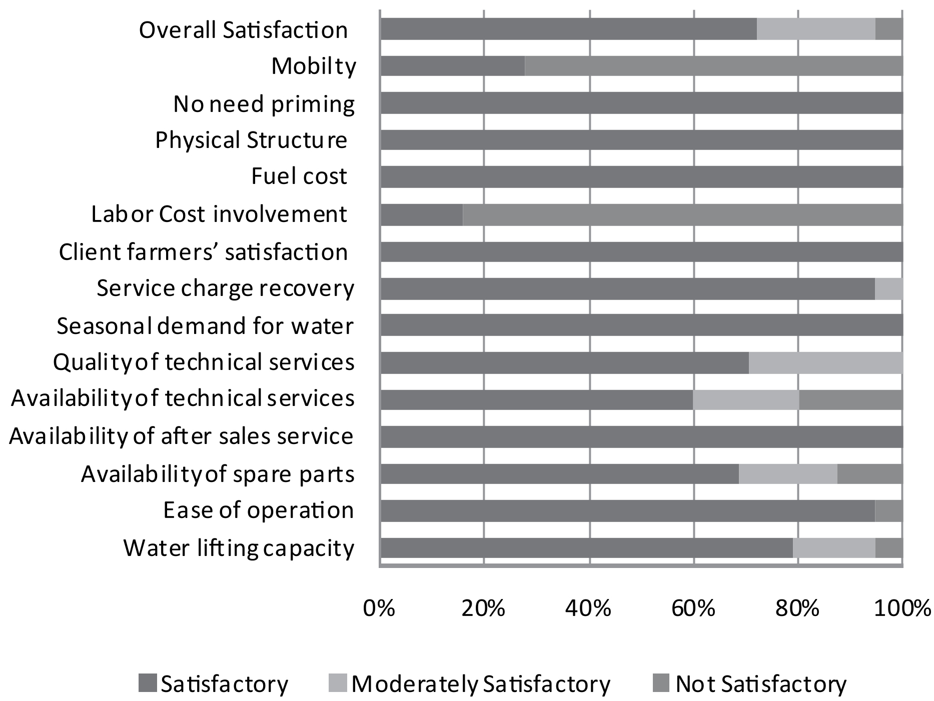


Fig. 2. Level of satisfaction of LSPs with the axial flow pumps (*n* = 19).

4. Improving crop intensification in southwestern Bangladesh

The southwest and south-central zone of Bangladesh is coastal and is prone to cyclones, storm surges, and extreme weather events including violent early monsoon season storms that can have devastating effects on crops grown in unprotected coastal areas. Since 1960, a total of 34 major cyclones have affected this region (BBS 2013). In southern Bangladesh (Khulna, Bagerhat and Satkhira Districts in particular), insufficient southward freshwater flow has resulted in seawater intrusion during the dry season, which affects the salinity of groundwater and creates waterlogged conditions (MoA 2012). Considerable efforts were made during the 1960s and 1970s to improve drainage conditions and build embankments for the early release of floodwater, and to protect agricultural land from the sea. As a result 145 polders were developed covering more than 70% of the coastal area (MoA 2012).

Due to persistent neglect and poor maintenance, at many places embankments are damaged, canals are silted, sluice gates are missing and the existing ones are not operated systematically to regulate flow of water. Infrastructure in the polders is therefore often inappropriate for effective use of water for irrigation. This is one of the major reasons why large tracts of land are left fallow during the dry winter season, which reduces the cropping intensity of cultivated lands. For this reason cropping intensity of this region is much lower than the rest of the country, particularly in Khulna, Patuakhali, and Barisal districts, the latter two of which are well-suited for the use of surface water irrigation (Figure 3).

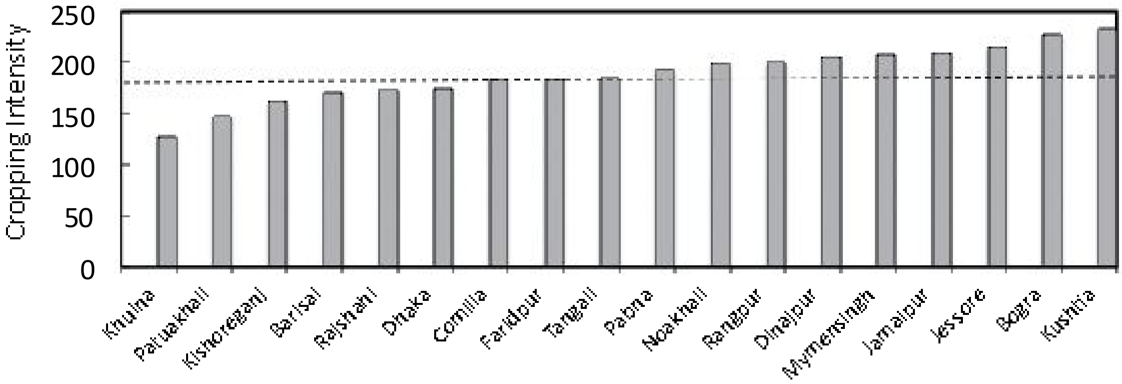


Fig. 3. Cropping intensity (2009-10) of selected districts of Bangladesh, excluding Chittagong (southeast) and Sylhet (northeast) (BBS 2013). The dotted line presents average cropping intensity.

In the areas where service providers practice surface irrigation during the dry season, low-lift water (centrifugal) pumps are usually rented from local organizations that are managing minor irrigation works in the region. However, the lack of widespread pump markets restricts the availability of pumps in the densities needed to encourage uptake of surface water irrigation practices. There are many other steps that need to be taken simultaneously into account if the potential of AFPs are to be fully realized.

4.1 Increase access to canal water

Southern Bangladesh has a network of rivers and canals. A considerable amount of fresh surface water is available in the eastern part of this zone (especially in Barisal District) throughout the year apart from the dry, winter months (*rabi).* However, water availability between April to June (pre-*Kharif*) is relatively limited (Schulthess et al. 2015). Most of the rivers in Barisal, Patuakhali and Pirojpur Districts are influenced by tidal water movement that increases water salinity, especially in the second half of the *rabi* season when it sometimes goes beyond the tolerance level of most crops. This presents a challenge to increasing dry season cropping. The geographical heterogeneity of water availability also poses a problem. This is particularly the case where canals are silted up due to restricted southward water flow (resulting in large part from trans-boundary water management and barraging in India), which raises riverbed levels (MoA 2012).

For improved agricultural production in this region, irrigation and drainage infrastructure need to be redesigned, repaired, or even newly constructed. Dredging (de-silting) of targeted canals to lower their bed level could help bring more fresh water from the rivers into the polders. These interventions should be supported by the repair and construction of water control structures and pump houses (to bring water in during low tide periods), and backed by the development of cooperative water users associations. Water structures such as rubber dams/cross dams and regulators can be of great importance for the development of minor irrigation (MoA and FAO 2012).

The water infrastructure also needs to be designed for equitable and optimal use of water by different stakeholders. This can result in significant water savings and increases in crop and aquaculture productivity in the coastal region (MoA 2012). The Government of Bangladesh is already working on a large-scale canal dredging and community polder management plan with the financial and technical assistance of the Dutch government (Blue Gold: Program Document, 2012). The “Blue Gold” project focuses on polders in three districts—Patuakhali, Khulna and Satkhira—and presents opportunities for partnerships with CSISA-MI and similar programs. This project aims to cover 160,000 ha with an estimated 150,000 households as direct beneficiaries. The scope of this work needs to be further extended for the benefit of large communities of farmers.

4.2 Increase farmer participation in water management

To ensure sustainable management of irrigation and drainage infrastructure, participation of farmers must be encouraged. This process can be best initiated by favoring community ownership of water management infrastructure, backed by educational programs to encourage cooperative and effective management. In many South Asian and Latin American countries where large-scale surface water irrigation is practiced (such as Pakistan, India, China, and Mexico) water user associations have been established to collect additional water charges beyond those given to LSPs. These fees are employed to maintain irrigation and drainage infrastructure at the tertiary level (the downstream part of the canal system from where farmers take control of water). In the Philippines, farmers are even involved in the planning, design and operation of irrigation systems (Meinzen-Dick et al. 1995). Levine et al. (1998) have shown that joint management by farmers and government agencies have been successful in implementing water allocation and cropping plans in Mexico. In Bangladesh, a mixed model approach may be most useful. The 'irrigation boom' (*sensu*, Shah et al. 2009) in Bangladesh and parts of South Asia has been built on the installation of shallow tube wells and small irrigation command areas – often less than 20 ha – in which LSPs play an active role in canal maintenance (Chowdhury 2012). Shared care of irrigation infrastructure between water users associations and LSPs may prove to be promising.

This decentralized approach has been successful in other countries and farmers have shown interest in taking over water management responsibilities if community ownership is made explicit (Latif and Pomee 2009). Plusquellec et al. (1994) noted that operation and management goals can be achieved if proper infrastructure and modernized irrigation systems based on the service concept are introduced. Hassan et al. (2004) argue that farmers are willing to pay an irrigation service fee if additional benefits are assured.

4.3 Rationalizing cropping patterns

Despite limited surface irrigation water availability and high production costs, many farmers – including those surveyed in this study – are growing a water intensive *boro* crop. Since surface water availability in some of the canal systems in south-central Bangladesh is limited, farmers can be encouraged to switch to less water demanding crops (such as oilseeds, wheat and maize, and even more profitable horticultural operations). In Bangladesh, *boro* crops are still continuously flooded for most of the season. This practice wastes scarce water resources and increases irrigation costs (Alam et al. 2009). BRRI (2000) has estimated that, on average, ~4.0 m^3 of water is used to produce one kg of *boro* rice in farmers' fields, compared to 2.0 m^3 used in research trials without compromising crop yields.

The seasonal irrigation water requirement of *boro* crop varied from 4,840 to 5,720 m^3 ha^{-1} in Dhaka District, and from 6,000 to 7,100 m^3 ha^{-1} in the higher elevation Barind area (Karim et al. 2009; Rashid et al. 2009). In contrast, water application for *boro* rice in Mymensingh is 12,800 m^3 ha^{-1} (Sarkar and Ali 2010), and for the north-western region it varies from 12,000 to 13,500 m^3 ha^{-1} for light and heavy soils, respectively (Dey et al. 2013). Rashid et al. (2009) showed that of the total applied irrigation water only 55% is used for ET and the remaining amount is lost as seepage and percolation. The cost of this excess pumped water is ultimately borne by farmers and ranges from USD26 to 65 ha^{-1} for electric deep tube wells, and up to USD90 ha^{-1} for diesel operated STWs (Dey et al. 2013).

Due to shallow water tables, a significant amount of crop water requirements could be met through the use of residual soil water at the end of the rainy season and capillary rise from the shallow water table in southern Bangladesh. Estimated irrigation requirements for wheat are approximately 100 mm (Poulton and Rawson 2011) in these environments. The actual irrigation requirements for Bhola and Barisal are estimated to be 29 and 65 mm, respectively (Poulton and Rawson 2011), because of contribution via capillary rise. Field studies indicate that relatively high yielding wheat (up to 4.77 t ha^{-1}) can be grown in south-western Bangladesh using only two appropriately timed irrigations, though yield will decline in environments prone to soil and water salinity (Krupnik et al. 2014).

4.4 Increase land productivity

Increased access to surface water through the rehabilitation of irrigation and drainage infrastructure, provision of axial flow pumps to lift water from canals and improved on-farm water management practices could all help to ameliorate the constraints to increased cropping intensity in southern Bangladesh. However, increases in annual land productivity will also require the availability and rational use of inputs (seed, fertilizer, weed control, etc.), appropriate agricultural technologies and agronomic practices. Considerable quantities of perishable and high value agricultural products produced in the coastal zone are wasted during storage or *en-route* to the market due to lack of proper storage facilities, processing and post-harvest operations; for fruit and vegetables losses are estimated at 20 to 45%, for cereals 15%, and 12% of fish and milk products are estimated to go to waste (MoA 2012). Therefore, there is a need to develop storage facilities at appropriate locations to avoid these losses. Increased agricultural production and diversification in cropping systems is also hypothesized to help create additional employment in the area.

4.5 Involvement of the private sector

In Bangladesh, where the reach of public projects is limited, the role of the private sector in the development of agricultural production becomes very important. While much of the farm production in the coastal zone is subsistent in nature, farmers depend on the private sector for the provision of inputs and machinery/equipment, and in particular on post-harvest LSPs for milling rice grain. In parts of south-western Bangladesh, where farmers are increasingly becoming involved in the marketing of their crops, recent increases in maize production were mainly successful due to the establishment of feed mills, which generated market demand. The provision of crop reapers, land preparation equipment, planters and threshers in Bangladesh is also driven primarily by the private sector, though often with government subsidies. CSISA-MI therefore works with the private sector to make AFPs available to LSPs and farmers at affordable rates. In the long term, private sector investment in the development of the commercial AFP market is envisioned as a key means of assuring the sustainable deployment of pumps in the southwest.

5. Conclusions

The extent of surface water irrigation is currently rather small due to limited availability of water lifting devices (such as low lift pumps), farmers' reluctance to intensify due to poor knowledge of best-bet agronomic practices, perceived risk (especially where tenure is insecure), and poorly developed input and output markets. These conditions have resulted in poor land use, low crop productivity, and increasing poverty in the area.

To promote surface water irrigation, access to water lifting devices needs to be increased. Our work showed that axial flow pumps (AFPs) are a better alternative to existing centrifugal pumps because of their hydro-economic superiority. They produce higher discharge rates, consuming less fuel at low lifts, and can irrigate more area in a given time than centrifugal pumps. Their large-scale adoption, however, will require that related technical and operational problems are resolved and that local manufacturing is facilitated to reduce costs and make the pumps affordable to service providers.

The widely used approach of local service provision, through which pump owners sell water to farmer-clients, can also be a workable solution if a stronger trust relationship is developed between LSPs and farmers. Efforts are underway to develop equitable and profitable business models that balance LSP's needs for income with farmers' needs for affordable irrigation. Work to facilitate the manufacturing and commercial availability of domestically produced pumps is also expected to lower costs. This will make AFPs more affordable to small farmers and service providers, an important component in efforts to extend surface water irrigation in southern Bangladesh. The diversification of agricultural production systems and improved water management are also prerequisites to improving food and income security in this otherwise overlooked region.

In addition to increased availability of surface water irrigation access to agricultural technologies, the rational use of inputs and best-bet agronomic practices, farmer education, and proper linkage to output markets is of paramount importance for encouraging crop intensification in this region. Farmer and LSP participation in the maintenance of irrigation and drainage infrastructure is also necessary if intensification is to be achieved.

Acknowledgements

This research was supported by the USAID Mission in Bangladesh through the Cereal Systems Initiative for South Asia – Mechanization and Irrigation (CSISA-MI) project. The contents and opinions expressed herein are those of the author(s) and can in no way be taken to reflect the views of USAID and the United States Government.

References

Alam, M.S., Islam, M.A., Islam, M.A., 2009. Economics of alternate wetting and drying method of irrigation: Evidences from farm level study. The Agriculturists 7(1&2); P: 82-89.

BADC (Bangladesh Agricultural Development Corporation), 2013. *Minor irrigation survey report 2012-2013.* Bangladesh Agricultural Development Corporation, Ministry of Agriculture, Government of Bangladesh.

Bala, B. K., Hossain, M.A., 2010. Food security and ecological foot print of the coastal zone of Bangladesh. Env. Dev. Sust. 12: 531-545.

BBS, 2013. Statistical Yearbook of Bangladesh. Bangladesh Bureau of Statistics (BBS) 2012. Dhaka, Bangladesh. P 554.

Biggs, D., 2011. Small machines in the garden: Everyday technology and revolution in the Mekong Delta. *Modern Asian Studies*. 46(1): 47–70.

BRRI (Bangladesh Rice Research Institute), 2000. *In:* BRRI Annual Research Review for 1999. XIX. Rice Farming Systems. October 9-12, 2000. Bangladesh Rice Res. Inst. Gazipur, Bangladesh.

Chowdhury, N.T., 2012. Irrigation Institutions of Bangladesh : Some Lessons, Problems, perspectives and challenges of agricultural water management. InTech, Rijeka, Croatia, pp. 113-132.

Chinsuwan, W., Cochran, B.J., 1986. The axial flow low lift pump in Thailand in small farm equipment for developing countries. *Proceedings of the International Conference on Small Farm Equipment for Developing Countries.* International Rice Research Center, Los Banos, Philippines. 2-6 September. Pp. 195- 203.

Dey, N.C., Bala, S.K., Saif-ul-Islam, A.K.M., Rashid, M,A., 2013. Sustainability of groundwater use for irrigation in northwest Bangladesh. Policy Report prepared under the National Food Policy Capacity Strengthening Programme (NFPCSP). Dhaka, Bangladesh. 89 pp.

Government of the Netherlands, 2012. Blue Gold: Program Document for Integrated sustainable Economic Development by improving the Water and Productive Sectors in selected Polders. Embassy of the Kingdom of the Netherlands, Dhaka, Bangladesh.

Hassan, M., Starkloff, R., Nizamedinkhodjayeva, N., 2004. Inadequacies in the water reforms in the Kyrgyz Republic: an institutional analysis. IWMI Research Report No. 81. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Karim, N.N., Talukder, M.S.U., Hassan, A.A., Khair, M.A., 2009. Climate change and its impacts on actual crop evapotranspiration of boro rice in north central hydrological region of Bangladesh. Journal of Agricultural Engineering, The Institution of Engineers, Bangladesh, Vol. 37/AE; P: 73-82.

Latif, M., Tariq, J.A., 2009. Performance assessment of irrigation management transfer from Government to farmer-managed irrigation system: a case study. Irrigation and Drainage 58: 275-286.

Levine, G., Cruz Galvan, A., Garcés-Restrepo, C., Johnson III, S., 1998. Performance of two transferred modules in the *Lagunera* region: water relations. IWMI Research Report No. 23. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Meinzen-Dick, R., Reidinger, R., Manzardo, A., 1995. Participation in Irrigation. Paper No. 003. Social Policy and Resettlement Division, Washington, D.C.

MoA (Ministry of Agriculture), 2012. Master Plan for the Agricultural Development of Southern Bangladesh. 6th Five Year Plan, Dhaka, Bangladesh.

MOA and FAO, 2012. Master Plan for Agricultural Development in the Southern Region of Bangladesh. Ministry of Agriculture (MoA, Government of Bangladesh) and United Nations Food and Agriculture Organization, Dhaka, Bangladesh, P. 122.

Plusquellec, H., Burt, C.M., Wolter, H.W., 1994. Modern water control in irrigation: concepts, issues and application. World Bank Technical Paper No. 246.

Rawson, H.M., (ed) 2011. Sustainable intensification of Rabi cropping in Southern Bangladesh using wheat and mungbean. ACIAR Technical Reports No. 78. Australian Centre for International Agricultural Research: Canberra. 256 pp.

Kabir, M.A. Khan, W., Saleh, L.R., Khair, M.A., 2009. Estimation of water Loss from irrigated rice fields. SAARC Agri., 7(1), P: 29-42.

Krupnik, T.J., Ahmed, Z.U., Timsina, J., Shahjahan, M., Kurishi, A.S. M.A., Miah, A.A., Rahman, B.M.S., Gathala, M.K., McDonald, A.J., 2014. Forgoing the Fallow in Bangladesh's Stress-Prone Coastal Deltaic Environments: Effect of Sowing Date, Nitrogen, and Genotype on Wheat Yield in Farmers' Fields. Field Crop. Res. 170, 7–20.

Schulthess, U., Krupnik, T.J., Ahmed, Z.U. and McDonald, A.J. 2015. Decentralized surface water irrigation as a pathway for sustainable intensification in southern Bangladesh: On how much land can the drop be brought to the crop? These proceedings.

Shah, T., 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. Environmental Research Letters 4, 035005.

Santos Valle, S., Qureshi, A.S., Islam, M.S., Hossain M.A., Gathala, M.K., Krupnik, T.J., 2014. Axial flow pumps can reduce energy use and costs for low-lift surface water irrigation in Bangladesh. Research Report No. 1. International Maize and Wheat Improvement Center, Dhaka, Bangladesh. 36 pp.

Sarkar, A.A., Ali, M.H., 2010. Irrigation Management for Optimizing Rice Yield and Nitrate leaching. Proceedings, paper Meet-2010. Agricultural Engineering Division, Institution of Engineers, Bangladesh. pp:17-28.

Talukder, R.K., 2008. "Food security in Bangladesh: National and global perspectives," In Proceedings BKAS 13th National Conference and Seminar on Climate Changes: Food Security in Bangladesh, Vol. 13, Dhaka, Bangladesh.

Increasing agricultural and aquacultural productivity in the coastal zone of Bangladesh

M. Sirajul Islam, S.K. Biswas, D. Gain, M.A. Kabir and T.A. Quarashi

BRAC, Bangladesh sirajul.i@brac.net, shankar.biswas@brac.net, dhiman.gain@brac.net, abid.km@brac.net, tausif.qurashi@brac.net

Abstract

The coastal zone of the Ganges delta is very susceptible to salinity intrusion and seasonal cyclonic storms. The poverty of farming families in the polders of the coastal zone is extreme. Physical and social factors have prevented many farmers from taking advantage of the technological improvements in rice farming and aquaculture that could increase profitability, productivity and resilience in the polder areas. Coastal zone farmers usually grow a single rice crop using low yielding traditional varieties. Furthermore, cropping intensity is low with the result that productivity of this region is also low. There are great opportunities to increase productivity in the coastal zone through crop intensification and diversification. In light of this, BRAC is scaling out suitable technologies and varieties across a wide range of people throughout the coastal zone. The program described here focused on increasing farming system productivity and profitability to improve livelihoods. A participatory approach was applied to facilitate the scaling out process from varietal selection to technology adoption. Hybrid variety trials and cropping system trials demonstrated better production in the polders than was previously possible. Several promising short duration rice varieties as well as salt-tolerant non-rice (*rabi*) varieties were introduced and were widely accepted by the farmers and are becoming very popular. All the single crop land in the demonstration blocks is now being converted to double or triple crop land. Rice-fish integrated culture with horticulture on dykes is now well established among the participating farmers. Additionally, we piloted community-based brackish water aquaculture to improve productivity. Results of validation activities found double the production both in agriculture and aquaculture, enabling farmers to obtain more profit than in the previous year. The results of the study will be useful for further scaling out of endeavors in another regions. This type of participatory validation work will have a great future impact on agricultural extension work as well as research work in Bangladesh.

Keywords: rice varieties, aquaculture, improved technology, scaling out

1. Introduction

Bangladesh is a small country with an area of about 147,570 km^2 and a large population of about 160 million. The coastal zone covers about 20% of the country and over 30% of the net cultivable area. As an agrarian country, agriculture is the key economic driver in Bangladesh. More than 50% of the people are directly involved and 30% indirectly involved in this sector. It has been estimated that the population of Bangladesh will be 194 million by 2050, when the total rice demand will be 49 million tons per year. As a result it is essential to ensure increasing crop production at a rate that will guarantee food security in the near future.

The coastal zone of Bangladesh largely missed the benefits of the green revolution. Many polders were created in the coastal zone during the early 1960s. The primary functions of the polders were the protection of the land from tidal flooding and salinity intrusion. This enabled the cultivation of traditional *aman* rice crop varieties, which were long duration and low yielding. After harvesting of rice the majority of lands within the polders were left fallow, or sown with a low input, low yielding legume crop in some locations. Production of high yielding or high value *rabi* crops was not possible because of the late harvesting of *aman* rice. Most of the lands in the polders are not suitable for growing the improved high-yielding varieties of rice because the water is too deep for their shorter stature. Shrimp and fish are being farmed in many coastal polders but yields are low and well below potential.

Keeping these challenges in view, BRAC, the largest non-governmental organization of the world, has worked to validate and scale out climate smart agricultural and aquacultural technologies to farmers in the coastal zone of Bangladesh since 2012 with the following objectives:

- To enhance system productivity by increasing aqua-cultural and agricultural cropping intensity
- To ensure food security and to improve the livelihood status of the coastal communities through disseminating aquacultural and agricultural technologies
- To develop farmer's capacity in increasing climate change adaptation and resilience.

In this paper we present the activities and findings of the 2013-14 program.

2. Methodology

BRAC Agriculture and Food Security Program (AFSP) disseminates agricultural technologies through farmers' participatory large scale block demonstrations. It is considered that large scale demonstration of improved technologies in crop fields and *ghers* inspires the neighboring non-participant farmers to adopt the improved and modern technologies in their fields.

The technology dissemination strategy is to convert single crop areas to double or triple cropped areas. This is done by introducing stress tolerant agricultural rice and fish varieties to the cropping systems, and by incorporating high value *rabi* crops in the rice-based cropping systems through the use of shorter maturing rice varieties to enable 'early' (timely) *rabi* crop establishment.

BRAC AFSP organizes groups of 40 to 50 marginal farmers farming in a contiguous area (demonstration block) and provides them with partial support to cultivate modern varieties of crops, using improved production technologies and practices. The farmers are provided with training and the latest information for increasing production from their field. It has been estimated that the farmers provide about 55% of the rice production cost, mainly in terms of labor, fertilizer and irrigation, and the program provides about 45% of the production cost in the form of cash to purchase inputs. At present, AFSP is operating its extension activities in 50 sub-districts of 12 districts of Bangladesh. Most of the operational sites are disaster and stress prone areas of the coastal area where the target is to cover around 60,000 direct participants with improved technologies by 2015. The target group is mainly poor and marginal farmers in coastal communities.

Results from the 2013-14 seasons are reported in this paper. Yield data were taken from an area of 20 m^2 in five randomly selected farmers' fields in each demonstration block. Grain moisture content was determined using a grain moisture meter and yield is presented at 14% moisture content for cereal crops and at 10% for oil seed crops.

3. Activities and results of the 2013-14 program

3.1 Extending improved rice varieties

High yielding rice varieties, both hybrid and inbred, were demonstrated during the *aus*, *aman* and *boro* cropping seasons. Hybrid rice as well as salt tolerant *boro* inbred rice were demonstrated in the *aus* and *boro* seasons, while high yielding varieties of inbred rice were demonstrated during the *aman* season.

3.1.1 Aus

Hands-on training for rice cultivation was given to the participants in the 2013 *aus* season and they were advised to cultivate hybrid rice. The farmers cultivated hybrid rice (Alloran, Shakti-2 and Sathi) from April to August 2013 in Barisal and Khulna regions. They applied irrigation at the beginning of the cropping season, usually up to May. Later on the fields were inundated with tidal water that came naturally, and which was sufficient to meet crop water requirements in most cases.

Eighty-eight farmers cultivated hybrid dhan Shakti-2, 80 cultivated hybrid dhan Sathi and 179 cultivated hybrid dhan Alloran. With identical growth duration, all varieties had similar average yield (7.1-7.6t/ha). The average hybrid *Aus* production was 7.32 t/ha (Table 1). Average net return was 63,000 to 90,000Tk/ha (Fig. 1).

Table 1. Block number, farmer number, seedling age, growth duration, yield and yield components of hybrid rice in *aus* season 2013

Variety	No. of blocks	No. of farmers	Seedling age (d)	Growth duration (d)	Effective tillers/ hill	1000 grain weight (g)	% filled grains	Yield at 14% (t/ha)
Hybrid Shakti-2	20	88	20	119	9	25	86	7.29
Hybrid Sathi	16	80	23	118	11	26	93	7.58
Hybrid Alloran	37	179	22	120	10	28	87	7.08

Average yield: 7.32 t/ha

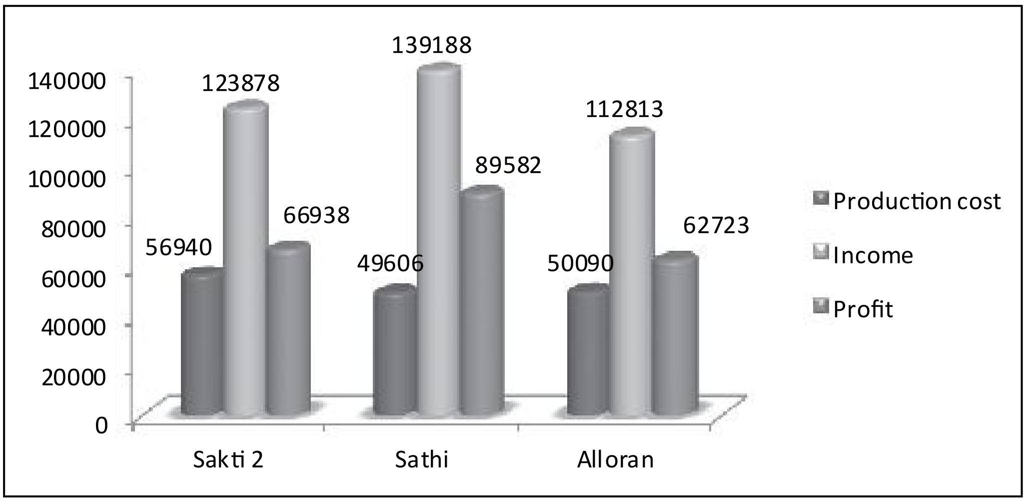


Fig. 1. Average production cost, income and profit of three hybrids during *aus* season 2013 (Tk/ha).

3.1.2 Aman

Nine *aman* varieties were cultivated in 430 blocks of 12 districts by over 2,000 participants. Five crop cuts (1 m^2) were taken in four locations in five fields in each block for yield determination. Average variety yields in the main block ranged from 5.2 t/ha (BRRI dhan39) to 7.1 t/ha (BRRI dhan54) (Table 2). The national average *aman* yield for 2011-2012 has been estimated at 2.29 t/ha, less than half the average production in the demonstration blocks (5.84 t/ha). Average cost of production was 43,000 Tk/ha, which brought an average net profit of 66,000 Tk/ha (Table 3).

In main blocks farmers followed the improved cultivation technology where the yield of the *aman* varieties was 0.5 to 1.6 t/ha higher than yield of the same varieties grown by farmers outside the demonstration blocks ("non-block farmers"), who usually follow traditional cultural practices. Yield of BRRI dhan54 in the non-blocks (6.2 t/ha) was much higher than yield of all the other improved varieties (4.2-5.0 t/ha) and of the local varieties (2.1-5.4 t/ha).

Table 2. Number of demonstration blocks and farmers, seedling age at time of transplanting, growth duration, yield and yield components of HYV *aman* rice in 2013 in demonstration blocks ("Main Block") and fields outside the blocks ("Non-block")

Variety	No. of blocks	No. of farmers	Seedling age (d)	Growth duration (d)	Yield and yield components			
					Effective tillers/ hill	% filled grains	1000 grain weight (g)	Yield at 14% (t/ha)
1.0 Main Block								
BINA dhan7	86	430	21	115	12	90	24	6.06
BRRI dhan33	61	302	22	117	11	88	24	5.47
BRRI dhan39	6	30	24	119	9	83	22	5.15
BRRI dhan41	10	50	25	145	10	92	22	5.44
BRRI dhan49	107	532	23	134	12	89	23	5.84
BRRI dhan51	22	110	23	147	10	90	23	5.40
BRRI dhan54	2	10	24	171	16	95	26	7.08
BR22	21	105	23	144	9	82	23	5.81
BR11	115	570	23	139	12	88	25	6.27
Total/mean	430	2139						5.84
2.0 Non-block								
BINA dhan7	-	88	32	127	11	86	23	4.93
BRRI dhan33	-	36	32	125	10	82	24	4.72
BRRI dhan39	-	4	30	122	10	80	23	4.65
BRRI dhan41	-	10	32	145	10	83	23	4.43
BRRI dhan49	-	102	32	140	12	86	24	4.96
BRRI dhan51	-	12	37	152	9	81	24	4.25
BRRI dhan54	-	4	38	173	12	87	25	6.15
BR23	-	50	38	156	8	76	24	4.14
BR22	-	4	35	140	9	74	22	4.22
BR11	-	165	36	147	11	84	24	4.63
Jamaibabu (local)	-	23	35	122	10	78	22	5.40
Duthkalam (local)	-	51	36	116	8	82	25	2.67
Sadamota (local)	-	13	44	154	9	78	25	2.10
Sworna (local)	-	30	47	165	9	85	24	4.59

Table 3. Total production cost, gross income, profit and BCR of HYV rice in *aman* season 2013

Variety	Total production cost (Tk./ha x 1000)	Gross income (Tk/ha x 1000)	Profit (Tk/ha x 1000)	BCR
BINA dhan7	45.6	118	73.2	2.70
BRRI dhan33	43.2	106	62.9	2.49
BRRI dhan39	44.2	103	59.3	2.41
BRRI dhan41	42.3	106	63.5	2.55
BRRI dhan49	43.4	111	67.7	2.60
BRRI dhan51	42.3	106	63.9	2.52
BRRI dhan54	42.8	111	68.4	2.62
BR22	44.8	113	67.7	2.51
BR11	42.3	113	70.4	2.66
Average	**43.3**	**110**	**66.3**	**2.56**

3.1.3 Boro

In the 2013-2014 *boro* season around 1200 farmers cultivated a range of hybrids and inbreds in 262 blocks. The highest average yield of ~9.5 t/ha was observed with the hybrids Sakti-2 and Sathi. Average non-block yields of respective hybrids were 1.2 to 1.9 t/ha lower than yields in the demonstration blocks. In non-block fields, the average yield of hybrid Shakti-2 was about 3 t/ha higher yield than yield of the local variety Vojon (Table 4).

Table 4. Number of demonstration blocks and farmers, yield and yield components of rice in the 2013-14 *boro* season.

Variety	No. of blocks	No. of farmers	Yield and yield components			
			Effective tillers/ hill	% filled grains	1000 grain weight (g)	Yield at 14% (t/ha)
1.0 Main Block						
Hybrid Shakti-2	42	210	13	83	27	9.45
Hybrid Alloran	27	135	10	92	28	7.71
Hybrid Sathi	93	430	13	93	30	9.54
BRRI dhan28	100	420	12	85	24	6.70
Total	**262**	**1195**				
2.0 Non-block						
Hybrid Shakti-2		34	13	87	27	7.93
Hybrid Alloran		10	6	88	25	5.78
Hybrid Sathi		54	11	87	28	8.32
BRRI dhan28		332	10	82	24	5.51
ACI		10	11	86	27	8.60
HERA		34	14	66	27	7.30
Vojon (local)		24	9	85	26	4.83

3.2 Extension of non-rice crops

3.2.1 Maize

During the 2013-14 *rabi* season, more than ten thousand (10,147) farmers cultivated maize hybrids (Pacific 984, and Pacific 999 super) on 2,572 ha. Yield and yield component data were taken from 742 farmers across 188 main and satellite blocks (areas where a technology is only demonstrated for one season). Crop cuts were taken from the fields of five participants per main block and from two farmers' fields per satellite block. Average yield of maize was 8.5t/ha and varied from 6.3 t/ha in Jhalokathi District to 11.2 t/ha in Bogra District (Table 5). Average yields in excess of 10 t/ha were also achieved in Rangpur, Lalmanirhat and Kurigram Districts. Yield in the medium salinity coastal districts (Khulna, Bagerhat and Sathkhira) were lower at 8 to 9 t/ha.

Table 5. Yield and yield components of maize in different locations including the coastal region of Bangladesh during *rabi* season 2013-14

District	Plants per m^2	Yield and plant characters			
		Grains per cob	% of filled grains	1000 grain weight (gm)	Yield at 10% (t/ha)a
1. Main Block					
Barguna	4.69	463	98	307	8.25
Jhalokathi	5.26	508	96	288	6.26
Pirojpur	4.82	665	99	312	8.21
Bagerhat	4.81	561	99	346	8.11
Khulna	5.75	352	97	320	8.33
Satkhira	5.70	640	99	369	9.09
Bogra	7.02	129	99	351	11.23
Rangpur	6.76	119	99	344	10.79
Lalmonirhat	6.94	125	99	363	10.75
Kurigram	7.45	107	99	451	10.67
Average	5.92	367	98	345	9.17
2. Satellite Block					
Barguna	4.73	663	90	300	7.73
Patuakhali	4.76	546	95	325	8.04
Jhalokathi	5.03	575	93	310	6.92
Pirojpur	4.66	642	98	309	7.55
Bagerhat	4.76	521	98	329	7.25
Khulna	5.36	531	98	343	8.28
Satkhira	5.98	573	97	351	6.55
Rangpur	6.04	105	97	322	8.34
Lalmonirhat	7.24	122	99	320	9.03
Average	5.39	475	96	323	7.74
Overall average	5.66	421	97	334	8.46

Fig. 2 Maize cultivation in the 2013-14 *rabi* season in Pirojpur district.

3.2.2 Sunflower

In the 2013-14 *rabi* season, critical inputs were provided to 11,299 farmers for hybrid sunflower (Hi-sun33) cultivation on 2,844 ha in both coastal and northern regions of Bangladesh. Yield and yield component data were collected from 961 farmers' fields across 260 blocks (both main and satellite). Five crop cuts were taken from each main block and two from each satellite block. Average yield of sunflower was 2.79 t/ha and average district yield varied from 2.01 to 3.26 t/ha. Highest grain yield (3.26 t/ha) of sunflower was observed in Barguna District (Table 6).

Fig. 3. Sunflower in the 2013-14 *Rabi* season in Bagerhat

Table 6. Yield and plant characters of sunflower in *rabi* season 2013-14 (average of five crop cuts per main block and two per satellite block)

District	Yield and plant characters					
	Population (plants/m^2)	Flower diameter (cm)	Seed per flower	% of filled seeds	1000 seed weight (g)	Yield a 10% (t/ha)
1. Main Block						
Barguna	2.80	68	708	93	76	3.26
Patuakhali	2.78	75	1,220	87	86	3.15
Jhalokathi	2.99	15	635	85	94	2.78
Pirojpur	2.98	21	581	96	108	2.84
Bagerhat	2.94	18	985	88	99	2.85
Khulna	2.87	21	1,341	86	92	3.04
Satkhira	3.60	19	1,152	92	76	2.88
Bogra	2.41	20	179	84	53	1.88
Rangpur	3.05	26	249	80	71	2.18
Lalmanirhat	3.09	21	235	86	67	2.23
Kurigram	2.825	23	243	72	79	2.01
Average	2.94	30	685	86	82	2.64
2. Satellite Block						
Barguna	2.81	23	781	93	75	3.14
Patuakhali	2.82	22	945	90	82	2.98
Jhalokathi	3.09	20	569	79	107	2.72
Pirojpur	2.60	23	636	89	213	2.89
Bagerhat	2.89	18	1,191	89	94	2.70
Khulna	2.75	14	1,082	87	91	3.03
Satkhira	3.60	19	1,152	92	76	2.88
Gopalgonj	2.75	10	1,544	92	75	3.17
Average	2.91	19	987	89	102	2.94
Overall average	2.93	24	836	88	92	2.79

3.3 Aquaculture in ghers

Gher aquaculture is a year-round activity and profitable business for the farmers of southern Bangladesh. The participants were given experience in a range of improved management practices including feed formulation and fish-rice-vegetable integration. Fish production data were collected from 266 farmers who were engaged in fish cultivation in a total of 37 ha of *ghers* across 15 *upazilas*. Production cost was highest in Tala sub-district of Sathkhira (319 thousand Tk/ha) compared with the average cost of 244 thousand Tk/ha (Table 7). Morrelgonj sub-district of Bagerhat District showed very good performance in both total income (over 1 million Tk/ha) and net profit (almost 800 thousand Tk/ha). Average total income and net profit were 417 and 173 thousand Tk/ha, respectively. Average fish production of the 15 *upazilas* was 1,325 kg/ha, while the highest production of 3,873 kg/ha was obtained at Morrelgonj. Production was lower in areas affected by salinity.

Table 7. Productivity and profitability of fish in *ghers* during 2013

Sl. no	Name of upazila/ sub-district	No. of farmers	Total water body (bigha)[1]	Production cost (tk/ha x 1000)	Fish production (kg/ha)	Income (tk/ha x 1000)	Net profit (tk/ha x 1000)	BCR
1	Morrelgonj	25	26	288	3,873	1,087	799	3.78
2	Fakirhat	12	11	316	1,318	786	470	2.49
3	Mollahat	14	38	291	3,207	975	684	3.35
4	Mongla	26	17	191	372	279	88	1.46
5	Rampal	14	13	261	2,620	713	452	2.74
6	Satkhira Sadar	17	17	209	788	240	31	1.15
7	Tala	25	23	319	707	214	(105)	0.67
8	Kaligonj	14	12	226	908	264	38	1.17
9	Assasuni	12	12	196	1,072	356	160	1.82
10	Shyamnagar	12	11	209	2,090	803	594	3.84
11	Kalaroa	19	18	216	2,271	294	78	1.36
12	Debhata	14	13	287	230	24	(263)	0.08
13	Dacope	27	32	208	143	48	(160)	0.23
14	Koyra	16	14	249	280	170	(79)	0.68
15	Paikgacha	19	15	200	-	-	(200)	-
Total		266	273					
Average				244	1,325	417	173	1.71

[1] 1 ha = 7.47 bigha

a

b

Fig. 4. Successful *gher* activity in (a) Bagerhat and (b) Satkhira Districts during 2013.

4. Conclusions

Increasing production, productivity and income from farm holdings is possible through increased cropping intensity, shifting from local crop varieties to improved varieties and diversification. By scaling out the results obtained from validation activities, production of both agriculture and aquaculture can be doubled. The results of the study will be useful for further research and extension work. An integrated approach focusing on training, block level demonstrations, farm level advisory support, financial support and field days ensured successful demonstration and promotion of new knowledge among farmers.

Acknowledgements

BRAC acknowledges the support of the CGIAR Challenge Program on Water and Food's Ganges Basin Development Challenge.

Agricultural machinery ownership and intensification in South Asia: What can we learn from Bangladesh?

K.A. Mottaleb and T.J. Krupnik

International Maize and Wheat Improvement Center, Bangladesh k.mottaleb@cgiar.org, t.krupnik@cgiar.org

Abstract

Use of scale-appropriate farm machinery is an important component of sustainable intensification efforts to boost farm productivity and conserve natural resources. Where appropriate machinery is employed, farmers can benefit through increased returns to labor and sometimes to land. Investment in machinery, however, can entail substantial costs. Consequently, relatively few households can invest in farm machinery in developing countries. But in South Asia farmers from a range of economic groups are able to purchase or 'rent' services from machinery owners under a widely established system of service provision. This model has driven agricultural mechanization in Bangladesh in particular. But in order to expand the use of scale-appropriate machinery in areas that are currently underserved it is important to understand what socioeconomic characteristics distinguish machinery owners and service providers from the general farming populace. Isolation of these characteristics and the over-arching conditions that favor the spread of appropriate planting, crop management, and harvesting equipment has important policy and activity targeting relevance for development programs aimed at expanding farmers' access to productivity enhancing technologies. Using census data from 814,058 farm households we applied a multinomial probit model estimation approach to characterize households that invest in irrigation pumps, post-harvest threshers, and two-wheeled tractor driven power tillers. Econometric results indicate that households endowed with more physical assets (e.g., land, livestock and ponds) are more likely to invest in agricultural machinery (all $P < 0.001$). Basic civil infrastructure, for example the availability of electricity, particularly for irrigation pumps, the provision of paved and gravel road, and access to loan facilities also significantly and positively affect machinery ownership. Our results indicate that policy planners and development projects aimed at increasing farmers' access to agricultural machinery should consider these prerequisite issues, which may underpin the agricultural service provision economy in Bangladesh. Where prerequisite conditions are met, policy planners and development projects are most likely to be successful; where they are not, such as in coastal regions – broader preliminary interventions to assure access to credit and civil infrastructure may be needed to boost agricultural mechanization.

Keywords: scale-appropriate machinery, irrigation pump, thresher, two-wheeled tractor driven power tiller, ownership, infrastructure, sustainable intensification

1. Introduction

By 2050 the world's population will reach 9.1 billion, 34% higher than in 2009 (FAO, 2009). The largest proportion of this population increase will take place in South Asia and Sub-Saharan Africa. This growth is expected to increase the consumption of staple cereals along with other agricultural products, specifically meat and fish – which rely largely on cereal- and silage-based feeds (Cassman et al. 2003; Godfray et al. 2010; Tilman et al. 2011; Mueller et al. 2012).) To ensure only cereal food security in 2050, growth requirement estimates indicate the need for an additional three billion tonnes from 2.1 billion tonnes– a 43% increase over 2009 levels (FAO 2009). However, boosting aggregate production by expanding land area is not a sustainable option (Miah and Sarma 2000; Pimental and Wilson 2004). This is particularly the case in densely populated South Asia, where farm size is already small and per capita arable land has been declining steadily (World Bank 2014). In Bangladesh and in India, for example, per capita arable land was 0.16 and 0.34 hectares, respectively, in 1961, though in 2009 these figures fell to 0.05 and 0.14 hectares respectively (World Bank 2014).

An important avenue to lower production costs and potentially enhance yields is to produce more food with increasing efficiency, thereby raising returns to labor and ideally land (e.g. Sison et al. 1985). The use of scale-appropriate farm machinery has an important role to play in this process. Here we distinguish scale-appropriate machinery from farm machinery generally, as large-scale machinery commonplace in developed countries may not always be appropriate for the small field sizes and farming enterprises encountered in South Asia (Krupnik et al. 2013). After replenishing capital investments, use of scale-appropriate machinery can help to further reduce farmers' production costs by replacing arduous manual labor and traditional tools with increasingly efficient equipment designed for optimal performance (World Bank 2007; Kienzle et al. 2013). In Bangladesh, machinery appropriate for precise direct seeding, fuel-efficient irrigation, and bed planting is becoming more readily available (Krupnik et al. 2013). The question arises, however, as to how to facilitate farmers' access to scale-appropriate machinery in Bangladesh's and South Asia's underserved regions.

A clear understanding of the characteristics of farm households that invest in farm machinery and provide services to other smallholders is a prerequisite for development programs and farm policies seeking to boost the use of scale-appropriate machinery. Studies of this kind can bring insight into the factors that facilitate or limit investments in machinery by farm households, thereby helping development planners and policy makers to target investments appropriately. Crucially, there are a wide-range of socioeconomic factors that may limit uptake of farm machinery. Where these factors present formidable barriers, investments and policies that focus on overcoming these barriers may be necessary before initiating programs promoting the commercialization and adoption of farm machinery.

To our knowledge research on this area is scant. In response, this research identifies the factors that facilitate or limit the adoption of the most common agricultural machinery used in Bangladesh. This includes irrigation pumps, threshers and two-wheeled tractor driven power tillers, of which at least 420,000 and potentially 700,000 are operating in Bangladesh, depending on the source cited (iDE 2013; Justice and Biggs 2013; Ahmmed 2014). As a case study, Bangladesh is noteworthy because of the rapid pace at which mechanized irrigation, land preparation, and post-harvest activities have taken place in the last 25 years compared to the rest of South Asia, although development has been geographically heterogeneous (Quayum and Ali 2012; Justice and Biggs 2013). Thus, analysis of the conditions that foster the ownership of machinery and supply of machinery services can provide important lessons for development projects and policy makers – both within Bangladesh but also across South Asia – to help target activities and investments aimed at sustainable intensification.

Using the BBS (Bangladesh Bureau of Statistics) Agricultural Census from 2008, we applied an econometric estimation approach to determine if farmers endowed with more physical assets (e.g., land, livestock, ponds) are more likely to invest in irrigation pumps, rice and wheat threshers, or two-wheeled, tractor driven power tillers. We also examine if and how civil infrastructure (rural electrification and the provision of paved and gravel roads) also affects the expansion of mechanization through increased household machinery ownership. We begin by describing the growth of agricultural mechanization in Bangladesh since the 1970s, focusing mainly on government policy liberalizing the farm machinery sector and underwriting it with subsidy programs. We next describe the survey data set, after which we specify the econometric model and present major findings. We conclude with generalized policy recommendations.

2. The growth of agricultural mechanization in Bangladesh

Agricultural mechanization has been a historical priority issue for the Government of Bangladesh (GoB). Eighty-two percent of the country's 153 million people live in rural areas where agriculture is the principal livelihood source. The GoB has also given considerable subsidies to support intensification (GoB 1999). The GoB has historically pursued agricultural mechanization, specifically for irrigation pumping and land preparation by two-wheeled, tractor driven power tillers, in order to move towards rice self-sufficiency. For example, irrigation pumps were first introduced by the public sector, but later by the private sector following the GoB's voluntary liberalization of the machinery market and relaxation of machinery import tariffs from 1988-1995 (Hossain 2009). Bangladesh's green revolution started with the introduction of short-duration, irrigation- and fertiliser-responsive semi-dwarf high yielding rice varieties (HYV) in the late 1960s (Mottaleb et al. 2014). Initially the GoB actively introduced four-wheel tractors (Ahmmed 2014), which are arguably scale-inappropriate in parts of Bangladesh given the small average field size of 0.53 hectares within the country (Hossain et al. 2007). The government also introduced centralized irrigation facilities by establishing deep tube wells (DTWs) and supplied low-lift pumps (LLPs) to farmers on a rental basis from the Bangladesh Agricultural Development Corporation (BADC). The GoB also supplied fuel at a 75% subsidized rate to pump owners through BADC until the 1970s. By 1978, BADC had managed and rented out a total of 9,000 DTWs and 35,000 LLPs, respectively (iDE 2012).

The management of 44,000 irrigation pumps under nearly complete government control, however, was a large logistical and financial burden for BADC. Eight years following independence, in 1979, Bangladesh undertook liberalization policies and as a result the government gradually changed from state-led support of mechanization and started privatizing the irrigation and fertilizer markets. BADC started sales to liquidate DTWs and LLPs (both new and reconditioned), first to farmers cooperatives, and later to individual farmers, many of whom became service providers. The privatization of irrigation markets only gained momentum after the removal of a number of tariff and non-tariff barriers on the import of irrigation and diesel engines and two-wheeled, tractor driven power tillers.

Nearly a decade later, a cyclone with wind speeds of more than 150 kilometers hit Bagerhat, Barguna, Bhola, Jessore, Khulna, Patuakhali, Pirojpur, Satkhira Districts and the Sundarban areas of Bangladesh on November 29, 1988 (UNDRO 1988). The cyclone took a major toll on human lives and also drastically reduced the number of draught oxen and buffalos used for land preparation. The deficiency was estimated at approximately 5.8 million draught animals, which was equivalent to 132,000 mechanical tillers (GoB 1989). The average national draught power energy requirement was 0.373 kW per hectare, while the average available draught power was estimated at 0.271 kW per hectare. The resulting deficit was about 27% less than the total estimated requirement (GoB 1989). The GoB made a quick decision to facilitate mechanized tillage by encouraging imports to provide the draught power needed to prepare land immediately following the cyclone. By this time, Bangladesh had initiated preliminary liberalization policies, although import tariffs were still in place for some sectors. The GoB's Standardized Committee of Bangladesh was responsible for the quality of imported machinery, including agricultural equipment. The committee mainly prescribed the import of high-cost Japanese tractors, pumps, and engines, but discouraged more affordable Chinese made machinery that they deemed to be of low quality (Justice and Biggs 2013).

The urgency of the cyclone and threat of food and hence political insecurity prompted the GoB under then President Hussain Muhammad Ershad to take a number of steps. In 1988, most major import taxes on standardized diesel engine and two-wheeled, tractor driven power tillers were voluntarily eliminated. The following year, Ershad disbanded the Standards Committee, which had initially upheld tariff restrictions following the cyclone, to facilitate the rapid import of cheap diesel engines and two-wheeled, tractor driven power tillers from China that were more appropriate for the small fields encountered in Bangladesh than four-wheeled tractors, at a fraction of the cost (Justice and Biggs 2013). Six years later, the import of two-wheeled, tractor driven power tillers and two-wheeled tractors was made completely duty free (iDE 2012).

Table 1. Import of agricultural machinery to Bangladesh from 2004 to 2013

Year	Number of importers	Two-wheeled tractor driven power tillers[b]		Seeders and transplanters		Value of other parts and machinery (million USD)
		Number	Price[a] per unit (USD)	Number	Price per unit (USD)	
2004-05	109	54,675	639.77	56	578.95	0.87
2005-06	99	52,863	729.87	69	1812.13	1.13
2006-07	77	37,606	733.40	66	563.69	1.89
2007-08	106	56,460	765.55	173	586.63	4.10
2008-09	103	55,604	949.93	45	1460.98	5.16
2009-10	119	44,872	894.90	195	581.38	12.27
2010-11	113	70,843	991.85	425	667.48	7.13
2011-12	116	51,266	1105.65	662	483.31	10.39
2012-13	112	30,771	1135.64	246	419.62	2.54

[a] Price is reported as import value plus 2.01% import tax.

[b] Other parts and machinery include agricultural, horticultural, or forestry machinery for soil preparation or cultivation; lawn or sports-ground rollers, excepting two wheeled tractor driven power tillers and seeders, or transplanters.

Note: 1US$= BDT 77.2

Source: GoB (2014a).

The combined elimination of the Standards Committee and market liberalization resulted in a dramatic increase in imports of small diesel engines for irrigation pumps and two-wheeled, tractor driven power tillers. The number of shallow tube wells (STWs) increased from 93,000 in 1982 to 260,000 in 1990 (iDE 2012). Presently, more than 420,027 two-wheeled, tractor driven power tillers—the vast majority of which are made in China—are engaged in preparing 80% of Bangladesh's cropland (iDE 2012). In Bangladesh, a total of 1.63 million STWs, DTWs and LLPs are currently engaged in irrigating nearly 55% of all cropland (BBS 2011). During the 1990s use of post-harvest crop threshers and crop management equipment increased significantly. Because the import of selected agricultural machinery has been encouraged through low or negligible tariffs for over a decade, traders in Bangladesh now actively import from abroad (Table 1). In 2013, the most recent year for which GoB data is available, 112 importers imported 30,771 two-wheeled, tractor driven power tillers with an average price USD 1,135 per piece. In the same year Bangladesh imported USD2.54 million worth of spare parts and other agricultural machinery from abroad. Most imported equipment is for tillage alone, though nearly two thousand transplanters and additional implements that can be attached to two-wheeled, tractor driven power tillers for direct seeding have been imported since 2004 (GOB 2014a).

In most cases the owners of the agricultural machinery also work as service providers by renting or selling mechanized land preparation and planting operation services to other farmers (iDE 2012). As a result, even relatively small farm households have been able to access relatively affordable machinery services through custom hiring systems (iDE 2012). However, the characteristics that determine adoption and ownership of machinery – which is a crucial prerequisite for such service provision models – remain unclear. Using a large nationally representative data set, the present study characterizes farm households who invest in agricultural machinery and who provide custom services, while also identifying the civil infrastructural factors that appear to influence the ownership of agricultural machinery and provision of services in Bangladesh.

3. Data description

This study relies on two data sets made available by the Bangladesh Bureau of Statistics (BBS) housed within the Ministry of Planning, and Local Government Engineering Department (LGED), under the Ministry of Local Government, Rural Development and Cooperatives of Bangladesh. The 2008 Agricultural Census is the fourth such census in Bangladesh and was deployed in the month of May. Prior to 2008, previous censuses were conducted in 1996, 1983-84, and 1977. An additional Agriculture Sample Survey was conducted in 2005. In its broadest form, the census sought to identify the structure and characteristics of agricultural pursuits managed by household farms.

A total of 28.69 million farm households were surveyed in 2008, of which 25.35 million were from rural areas, the remainder being from urban farms. Of the sampled households 1.73 million were from Barisal, 4.88 million were from Chittagong, 9.46 million were from Dhaka, 3.43 million were from Khulna, 7.66 million were from Rajshahi and Rangpur Divisions, and 1.53 million were from Sylhet Division in the northeast. Data on farm machinery ownership focused on irrigation pumps, two-wheeled, tractor driven power tillers, and/or threshing machines. Family wealth measured by land size, pond and livestock ownership, the number of family members and gender of the household head were also documented in the present study. Using the same dataset, we also generated sub-district level information on electricity availability for agricultural machinery (mostly irrigation pumps) and the provision of formal bank loans accessed by farm households. Data on the extent of paved or gravel roads at the sub-district level were also collected from the spatial data division of LGED via institutional request.

Although the 2008 Census covered a representative sample of Bangladesh's farm households, the BBS provides access to only five percent of the entire census data, including 1,042,595 households in 64 districts in all seven divisions: Barisal, Chittagong, Dhaka, Khulna, Rajshahi, Rangpur and Sylhet. This study sought to understand the characteristics of rural farm households that invest in agricultural machinery. We therefore considered rural farm households only. As a result, we removed urban farm households from our sample resulting in 814,058 sampled households from 476 sub-Districts in 64 districts in seven divisions of Bangladesh, each of which had different machinery and other endowments (Table 2). The machinery considered included irrigation pumps, threshers and two-wheeled, tractor driven power tillers.

Table 2. Information on ownership status of the sampled agriculture machinery, land and other resources owned by rural households by division in 2008

Division	Barisal	Khulna	Dhaka	Sylhet	Chittagong	Rajshahi	Rangpur	All
Number of households	57,727	100,414	241,069	55,629	147,116	138,855	73,248	814,058
% owned of a sampled machine	0.82	6.52	2.59	1.71	3.37	4.27	2.57	3.32
% owned an irrigation pump	0.28	4.33	1.96	0.99	0.98	3.05	2.05	2.08
% owned a thresher	0.50	3.55	0.87	0.80	2.06	2.06	0.76	1.68
% owned a two-wheeled tractor driven power tiller	0.21	0.62	0.30	0.35	0.14	0.70	0.38	0.38
Land owned (acres)	0.91	0.89	0.72	1.07	0.68	0.73	0.60	0.76
% household owned a pond	58.57	25.50	13.46	34.58	45.27	8.39	7.12	23.90
Number of cows and buffalos owned	1.06	0.99	0.75	1.17	0.64	0.88	1.06	1.78

Note: Irrigation pump includes deep tubewells, shallow tubewells and low-lift pumps

Source: BBS (2010)

4. Model specification and estimation

To examine how household-level asset endowments and characteristics, and sub-district civil level infrastructure affect agricultural machinery ownership at the household level, we formulate and estimate equation 1:

$$Y_i = \alpha_0 + (HHC_i)\phi + (SUBDIS_j)\alpha + \sum_{d=1}^{6} \lambda_d (DD_d) + \xi_i \qquad (1)$$

where Y_i is a vector of dependent variables that includes a base value zero if a household did not own one of the specific sampled agricultural machineries in 2008, an irrigation pump ownership dummy that assumes a value of one if a household owned an irrigation pump, a thresher machine ownership dummy that assumes a value of two if a household owned a thresher machine in 2008 and a two-wheeled, tractor driven power tiller ownership dummy that assumes a value of three if a household owned a two-wheeled, tractor driven power tiller in 2008. Among the explanatory variables, HHC_i is a vector of independent variables that includes a gender dummy that assumes a value of one if a household head is female (zero otherwise), a dummy equal to one if the household is an owner operator who does not work as an agricultural laborer in other farms (zero otherwise), the total number of adult family members who are more than 15 years old and a dummy for farm household land size that assumes a value of one if a household owned more than 1.01 hectares of land (zero otherwise). According to the definition of the BBS (2011a), small farm households owned up to 1.01 hectares of land, medium farm households owned 1.01-3.03 hectares of land and large farm households owned more than 3.03 hectares of land. To clarify, the farm size dummy that we have included in our model is the dummy for medium and large farm households who owned more than one hectare of land. The explanatory variables also include a pond ownership dummy (one if yes, zero if no) and total number of livestock owned (only cows and buffalos) by a household. In Bangladesh pond ownership can play a major role in generating income through the provision of aquacultural resources. $SUBDIS_j$ is a vector of independent variables that includes sub-district-level information on the length of paved or gravel road in kilometres, households that operate at least one agricultural machine – most commonly irrigation pumps - using electricity (%), and the proportion of households who received formal loans from banks or formal credit agencies. To understand whether sub-district level infrastructure has different effects in terms of machinery adoption on medium and large farm households versus small farm households we also included three multiplicative dummies in which we multiplied the medium and large farm household dummy with the length of paved or gravel road at the sub-district level, the proportion of electricity connected to agricultural machinery and the proportion of credit and loan services at the sub-district level. DD_{ij} represents six division dummies for seven divisions, where Chittagong division is the base; is the scalar parameter; , and are the vectors of parameters; *i* stands for household; *j* stands for the sub-district, where the household is located; and is the random error term.

Note that the most common agricultural machine owned by farm households is an irrigation pump; however, a household can also own a thresher machine, or a two-wheeled, tractor driven power tiller (Table 2). Considering this issue, to estimate multiple machinery ownership, we applied a multinomial probit model, where we assigned value zero as the base if a sampled farmer does not own any of the sampled machines, and a value of one if a farmer owned an irrigation pump, two if a farmer owned a thresher machine, and three if a farmer owned a two-wheeled, tractor driven power tiller. Zero was applied if the answer to any of these points was no. The application of a multinomial non-linear model in explaining farmers' adoption of different agricultural technologies is not new. For example, Mottaleb et al. (2014) also applied a multinomial logit model in estimating use of hybrid and inbred rice seed by Bangladeshi farmers. Quayam and Ali (2012) also applied single equation logit model in estimating the adoption of two-wheeled, tractor driven power tillers in Bangladesh.

5. Results

On average a sampled household was endowed with 0.31 hectares of land, nearly two cows and water buffalos, and 24% owned a pond (Table 2). A total of 3.3% of the sampled farm households owned at least one of the machines of interest including irrigation pumps, threshers, and/or two-wheeled, tractor driven power tillers (Table 2). Of the 3.3%, 2.1% owned an irrigation machine, 1.7% owned a thresher and 0.38% owned a two-wheeled, tractor driven power tiller. Because of the pervasiveness of the service provision system in Bangladesh, most of these owners not only serve themselves but also serve other clients farmers on a custom hire basis. This model has been successful in generating a large number of service providers providing access to irrigation services and two-, and more recently, four-wheel tractors in select areas, in addition to post-harvest threshing and shucking services which can be found in Bangladesh (iDE 2012; Quayum and Ali 2012; Justice and Biggs 2013).

Farm households in Barisal division, however, are less likely to own the sampled agricultural machinery when compared to the national average and also to the households in other divisions (Table 2). Households in Khulna, Rajshahi and Chittagong Divisions, conversely, are more likely to own the sampled agricultural machinery than the households in other divisions. In Barisal, 0.82% households owned one or more piece of agricultural machinery. Of this group, 0.28% owned an irrigation pump, 0.50% owned a thresher, and 0.21% owned a two-wheeled, tractor driven power tiller. The cropping intensity in Barisal is typically not high (MoA and FAO 2012), owing partly to the difficulty of establishing a dry season crop where tidal flooding and salinity are concerns, and also due to farmers' lack of investment incentives where production risk is perceived (Mottaleb et al. 2013; MoA and FAO 2012). Consequently, only a few farm households invest in agricultural machinery or intensified cropping in this region, for which a logical starting point to boost cropping intensity would be to put into place measures to lower farmers' production risks as part-and-parcel of any mechanization efforts. Crop insurance schemes, stress resistant varieties and agronomic practices could be useful in this regard.

Of the total dataset, less than 4% of the households were female headed and nearly 65% of all householders are owners and operators of the machinery in question (Table 3). More than 90% are small farm holders who were endowed with less than one hectare of land. On average, a sampled household was endowed with more than three family members of which more than one was an adult who was older than 15 years (Table 3).

Table 3. Basic demographic and other characteristics of the sampled households by division in 2008

Division	Barisal	Khulna	Dhaka	Chittagong	Sylhet	Rajshahi	Rangpur	All
% female headed household	2.66	2.70	3.39	5.46	4.81	2.44	3.44	3.57
% household is an owner operator who does not work as an agriculture laborer	72.59	58.38	67.65	70.64	68.24	60.05	50.42	64.59
Total members in the family	3.27	2.81	3.09	3.78	3.99	2.81	2.76	3.18
No. of adult family members (>15 years old)	1.67	1.54	1.57	1.81	1.80	1.49	1.38	1.60
% small farm households (<1.01hectare)	90.70	89.82	92.53	93.74	88.05	91.88	93.49	91.95
% medium farm households (1.01-3.03 hectares)	8.02	8.91	6.60	9.58	5.52	7.03	5.37	6.96
% large farm households (>3.03 hectares)	1.27	1.27	0.86	2.36	0.74	1.09	1.13	1.09

Source: BBS (2010)

On average the sampled sub-districts were equipped with 164 kilometres of paved or gravel road. Nearly 62% of the sampled households operate at least one agricultural machine using electricity, primarily for irrigation pumps that require connections for deep and shallow tube well extraction in northern Bangladesh. Nearly 21% of the sampled households received loans or credit (Table 4). Sub-district civil infrastructure such as roads and the availability of electrical connections for pumping could affect the decision to purchase agricultural machineries by impacting overall operation and transaction costs. For example, the availability of electricity might inspire a household to purchase a motor pump for irrigation, as subsidized electricity can be used as an inexpensive and easy to use source of energy compared to diesel, which requires pre-season purchases of fuel and entails transaction costs for transporting fuel from the pumping station. Similarly, the extent of paved or gravel roads at the sub-district level could affect the decision to purchase a two-wheeled, tractor driven power tiller at the household level, as the extent of paved or gravel roads can expand the chance of multiple uses for a two-wheeled, tractor driven power tiller (e.g. human or goods hauling).

Table 4. Basic sub-district level information in 2008

Division	Barisal	Chittagong	Dhaka	Khulna	Rajshahi	Rangpur	Sylhet	All
Length of paved or gravel roads at the sub-district level (00 km)a	1.91	1.62	1.48	2.42	1.66	1.16	1.37	1.64
% household operating at least one sampled agriculture machine by electricity b	13.67	55.27	88.54	86.86	56.35	60.22	23.40	61.97
% household who received formal bank loans at the sub-district levelb	28.03	13.15	19.07	28.46	23.94	26.18	12.05	20.67

Sources: [a] GOB (2014a) and [b]BBS (2010)

To depict the distribution of physical assets among households with the sampled machines and households without any of the sampled machines, we developed quantitle-quantile plots illustrating the distribution of land and livestock among the sampled machine owner and non-owner households (Figures 1 and 2, respectively). In the graph, if the resulting distribution points lie roughly on a line with the sample slope then it indicates that land and livestock are evenly distributed between two groups of households. However, Figures 1 and 2 clearly show that households owning the sampled agricultural machinery also proportionally own more land (Figure 1) and livestock (cows and buffalos) than those who do not (Figure 2). Both are a logical indication of wealth status of the household.

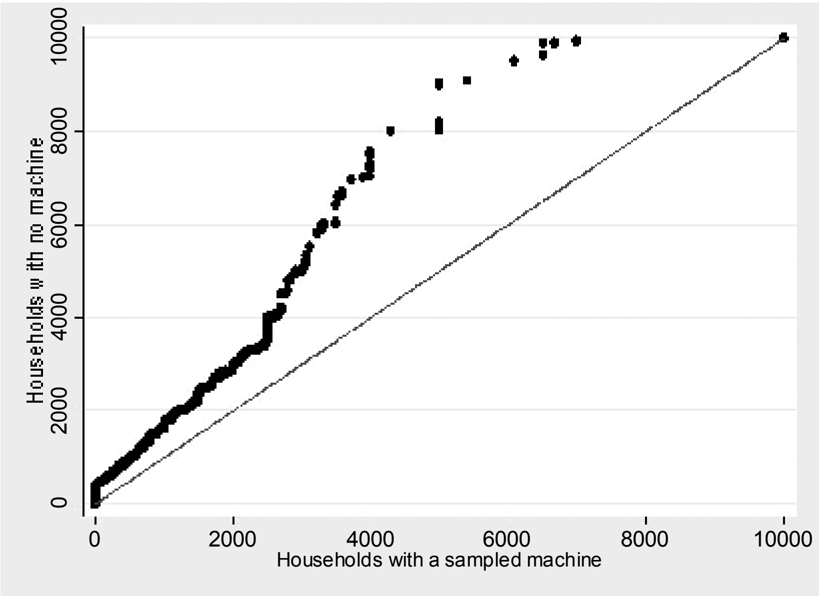


Figure 1. Distribution of land owned by the sampled rural households by ownership of agricultural machinery including irrigation pumps, threshers, or two-wheeled, tractor driven power tillers (source: BBS 2010).

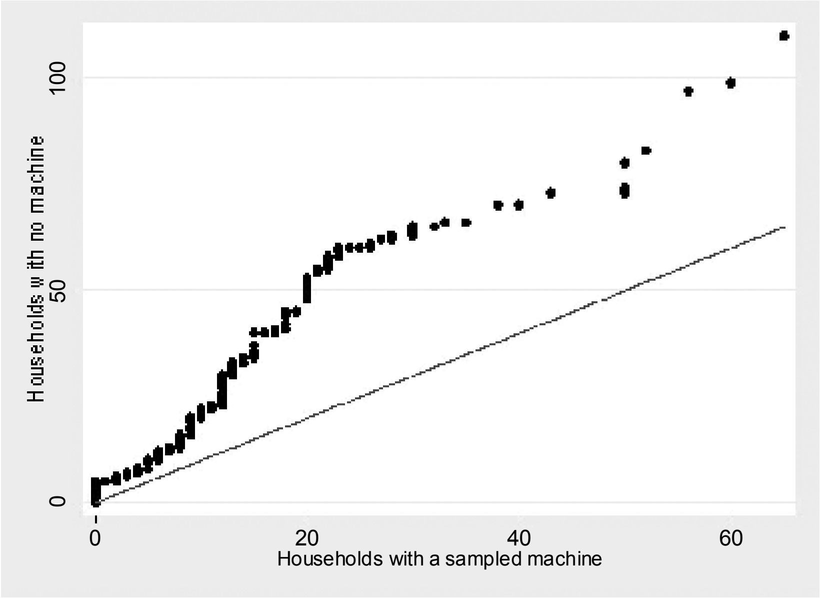


Figure 2. Distribution of cows and buffalos owned by the sampled rural households by ownership of agricultural machinery including irrigation pumps, threshers, or two-wheeled, tractor driven power tillers (source: BBS 2010).

Table 5 presents the estimated function explaining sampled agricultural machinery ownership by the sampled households in Bangladesh. All of the household level variables considered in this study were highly statistically significant with expected signs in explaining ownership of irrigation pump, thresher, and power tiller ownership at the household level. The dummies for agriculture owner operator household, the number of adult family members, the pond ownership dummy, the livestock number, and the dummy for the medium and large farm household size positively and significantly influence ownership of the sampled agricultural machinery. The marginal effects model shows that on average, an owner-operator of agricultural machinery tends to have a higher probability of having a sampled machine, ranging from between $P < 0.001$ at the lowest to $P = 0.004$ at the highest.

Conversely, the female-headed household dummy variable was negative and highly statistically significant across the estimated functions for each type of machinery ownership ($P<0.001$). This reflects convention in Bangladesh that women headed households are less likely to own productive agricultural assets than male-headed households (Table 5). The lack of machinery ownership among women is an important finding for policy planners and development organizations concerned with increasing gender equity and even development in Bangladesh, as solutions are clearly needed to boost women's access to productive assets.

While Table 5 shows positive assertion between farm size, and livestock number and the adoption of sampled agricultural machinery, a farmer may have logically used a purchased machine to derive income through service provision to invest in more on livestock and/or land after purchase, rather than before. Without longitudinal data, it is difficult to distinguish between such cause and effect in the current study, and follow up studies with a representative sub-set of the population are therefore needed. The estimated function and corresponding marginal effects nonetheless show strong correlations among physical assets and machinery ownership by a farm household. The medium and large farm household dummy (owned more than one hectare of land =1) is positive and highly statistically significant in explaining ownership of all three machines investigated. Medium and large farm households tend to have a 1 to 3% higher probability of having a sampled agricultural machine compared to a small farm household, reflecting the more resource endowed nature of larger households which tend in this case to have ownership over more productive agricultural assets than smaller households. This is an important point for development and policy planners that focus on extending use of scale-appropriate machinery to small households. Where projects seek to facilitate the commercial purchase of equipment, even at somewhat subsidized rates, our data suggest that poorer households may still not be willing to invest. As such, programs focused on machinery should seek to extend access to machinery use by small farm households through service provision models whereby those who do own machinery can sell use of the machine to those unable to purchase through custom hiring processes. Experience has shown that this is the main mechanism by which farmers at large are able to access use of irrigation pumps, threshers, and two-wheeled, tractor driven power tillers in South Asia (Justice and Biggs 2013), underscoring that not all farmers must own a machine to multiply farmers' use of mechanized services.

Among the sub-district-level variables, the length of paved or gravel roads, the percentage of agricultural households that operate at least one agricultural machine (usually irrigation pumps) using electricity, and the proportion of households who have received financial loans significantly and positively affect the ownership of irrigation pumps (*P* values ranging between 0.05 to 0.001), thresher ($P<0.001$) and two-wheeled, tractor driven power tillers (*P<0.001)* (Table 5). Thus where such services and civil infrastructure exist, systems of machinery service provision are more likely to develop. An improved transportation system can contribute to agricultural machinery adoption by reducing transactions costs. For example the transportation costs associated with use of bringing inputs, and post-harvest products to and from the farm, particularly where the two-wheeled tractors that are used to drive two-wheeled, tractor driven power tillers are used to haul materials in attachable flatbed trailers prior to or after land preparation is completed (Justice and Biggs 2013).

Table 5. Estimated functions applying a multinomial probit model explaining ownership of pumps, threshers and two-wheeled, tractor driven power tillers by farm households in Bangladesh

Name of the machine	Estimated function			Estimated function		
	Irrigation pump	Thresher	Two wheeled tractor driven power tiller	Irrigation pump	Thresher	Two wheeled tractor driven power tiller
Female-headed household dummy (yes=1)	-0.25*** (-6.38)	-0.29*** (-7.83)	-0.30*** (-3.95)	-0.003*** (-7.34)	-0.01*** (9.43)	-0.001*** (-4.77)
A dummy for household is an owner operator who does not work as an agriculture laborer	0.22*** (17.47)	0.13*** (10.32)	0.19*** (8.78)	0.004*** (17.75)	0.002*** (9.52)	0.001*** (8.23)
No. of adult family members (older than 15 years)	0.11*** (21.16)	0.14*** (21.29)	0.14*** (15.51)	0.002*** (20.34)	0.002*** (21.18)	0.001*** (14.54)
Pond ownership dummy (yes=1)	0.34*** (25.52)	0.48*** (39.42)	0.37*** (17.51)	0.006*** (20.08)	0.009*** (30.68)	0.002*** (12.55)
No. of cows and buffalos	0.10*** (33.10)	0.11*** (32.78)	0.09*** (30.00)	0.002*** (31.88)	0.002*** (31.79)	0.003*** (23.56)
Medium and large farm household dummy (>2.49 acres) yes=1	0.84*** (18.97)	0.40*** (9.07)	0.86*** (12.70)	0.03*** (11.52)	0.01*** (5.82)	0.01*** (6.54)
Length of paved or gravel road at the sub-district level (KM)	0.0002** (2.20)	0.001*** (5.99)	0.001*** (3.11)	0.000002* (1.85)	0.00001*** (5.83)	0.000001** (2.87)
% Households using electricity to run agricultural machinery at the sub-district level	0.18*** (23.82)	0.36*** (52.44)	0.18*** (13.06)	0.003*** (21.13)	0.006*** (49.30)	0.001*** (10.89)
Proportion of households receiving formal bank loans at the sub-district level	0.35*** (3.90)	0.53*** (5.59)	1.19*** (7.43)	0.01*** (3.42)	0.008*** (5.22)	0.005*** (7.21)
Length of paved or gravel roads at the sub-district level X Medium and large farm household dummy	-0.001*** (-3.18)	0.001*** (4.87)	-0.0001 (-0.32)	-0.00001*** (-3.46)	0.00001*** (5.09)	-0.0000003 (-0.39)
Proportion of household receiving formal bank loan at the sub-district level X Medium and large farm household dummy	0.531*** (3.49)	0.68*** (4.53)	0.59*** (2.81)	0.008*** (3.24)	0.01*** (4.33)	0.002** (2.45)
% households using electricity to run agricultural machinery at the sub-district level X Medium and large farm household dummy	0.01 (0.29)	0.13*** (8.54)	0.11*** (4.91)	-.0001 (-0.22)	0.002*** (8.43)	0.001*** (4.50)
Barisal division dummy	-0.89*** (-16.77)	-1.13*** (-29.06)	-0.31*** (-5.07)	-0.01*** (-34.0)	-0.01*** (-59.52)	-0.01*** (-4.65)

Table 5 cont.

Name of the machine	Estimated function			Marginal effects (dy/dx)		
	Irrigation pump	Thresher	Two wheeled tractor driven power tiller	Irrigation pump	Thresher	Two wheeled tractor driven power tiller
Khulna division dummy	0.68*** (26.40)	0.002 (0.07)	0.44*** (10.01)	0.02*** (18.17)	-0.001** (-2.68)	0.002*** (6.60)
Dhaka division dummy	0.40*** (19.91)	-0.66*** (-36.66)	0.22*** (5.71)	0.01*** (18.43)	-0.01*** (-44.45)	0.001*** (5.38)
Sylhet division dummy	-0.16*** (-4.65)	-0.72*** (-23.25)	0.17*** (3.38)	-0.002*** (-4.49)	-0.007*** (-40.81)	0.001*** (3.54)
Rajshahi division dummy	0.60*** (26.59)	-0.09*** (-4.66)	0.70*** (18.03)	0.02*** (19.62)	-0.002*** (-8.46)	0.01*** (11.58)
Rangpur division dummy	0.46*** (17.18)	-0.60*** (-20.65)	0.36*** (7.31)	0.01*** (13.47)	-0.007*** (-34.84)	0.002*** (5.46)
Constant	-4.39*** (-90.21)	-4.08*** (-92.49)	-5.41*** (-57.96)			
N	814058					
Wald chi2(54)	31267.29					
Prob > chi2	0.00					
Log pseudo likelihood	-124123.71					

Note: Numbers in parentheses are z-statistics based on standard error that allow for intragroup correlation at the household level. *Significant at the 10% level. **Significant at the 5% level. ***Significant at the 1% level

The prevalence of paved roads and highways can also enhance the flow of information, as farmers can easily visit government extension offices in the cities, discuss and exchange with each other in markets, and agricultural extension workers can easily travel to and from the office to the farm. In addition, an improved transportation system can allow households to use agricultural machinery for alternative income generating activities – as noted above, many two- and also four-wheeled tractor owners rent their machines for hauling materials before and after land preparation is done, thereby extending the use of their machines for more days of the calendar year.

Similar to our findings, Mottaleb et al. (2014) also depicted the significantly positive influence of sub-district level infrastructure such as paved or gravel roads, on the adoption of agricultural technology such as hybrid rice. They conclude that an improved transportation system can contribute to adoption of modern agricultural technology in two ways. First, the transportation costs of carrying seeds, inputs and products to and from the farm and nearest markets and cities tend to be lower in the presence of improved roads and highways. It makes investment in agricultural technology more profitable. Second, roads and highways also enhance the flow of useful information, as farmers can easily visit government extension offices in the cities and agricultural extension workers can easily travel to and from the office to the farm. Furthermore, similar to our findings, Quayum and Ali (2012) also found that credit availability can significantly and positively affect the adoption of two-wheeled, tractor driven power tillers in Bangladesh.

The multiplicative dummy in which we multiplied medium and large farm household dummy variables with sub-district level infrastructure variables further elucidates how sub-district level civil infrastructure may affect differently the adoption of agricultural machinery by households of different farm sizes. The estimated function and the corresponding marginal effects show that the length of paved or gravel road negatively and significantly affects the adoption of irrigation machines by the medium and large farm households, but positively and significantly affects the adoption of a threshers machine and has no influence on the adoption of a two-wheeled, tractor driven power tiller. By contrast, households' access to formal loans positively and significantly affects the ownership of all of the sampled machinery (*P*<0.001) by the medium and large households compared to the small ones (Table 5). Access to electricity to run agricultural machinery, however, positively and significantly (*P*<0*.001)* affects the adoption of thresher machines and two-wheeled, tractor driven power tillers by medium and large farm households compared to small farm households.

The extent of adoption of agricultural machinery in Barisal and Sylhet Divisions is low compared to Chittagong division (which is the base division in our model; Table 5). The challenges in the entire Barisal division in terms of agriculture are diverse and extreme, include poverty, and households have a low investment capacity and are averse to risk. Out-migration by agricultural laborers is also common (MoA and FAO 2012), which one might expect to positively affect agricultural machinery ownership, although it appears that farmers' sense of risk and low investment capacity, in addition to the civil infrastructural variables noted above, limit uptake of machinery. As such, adoption of machinery is comparatively low in Barisal division. Adoption is also limited in Chittagong division, though this is not necessarily surprising given that much of this region is hilly in nature, with very low groundwater tables, and remains under considerable forest cover. As such, agricultural intensification – and the potential for machinery – remains limited.

Our data suggests that GoB and donor agencies may wish to consider special programs to encourage scale-appropriate mechanization in Barisal, where farmers could be encouraged to use irrigation and rapid land preparation services to move from single to double cropping (MoA and FAO 2012) in order to spur the intensification of the agricultural sector. However, we underscore that adequate attention must also be paid to basic civil infrastructural and to the mitigation of investment risk – which could be partially ameliorated through low interest and low risk credit programs – that are likely needed in advance of efforts to develop strong agricultural machinery value chains in areas like Barisal division.

6. Conclusion and policy implications

Scale-appropriate agricultural mechanization can play an important role in enhancing labor productivity in rapidly developing agricultural economies. In select cases – for example, where farmers adopt irrigation or precision sowing and harvesting equipment is used—farmers may experience increased returns from their investment in land. Development and policy planners can benefit from information on the socioeconomic and civil infrastructural conditions that are prerequisite for rural households to purchase farm machinery, and make use of them through service provision models, thereby benefiting farmers more widely. To our knowledge, there is relatively little recent research on these issues, and no previous empirical studies employ sufficiently large scale data sets to examine household characteristics as they correlate with machinery ownership in developing nations. To fill this crucial knowledge gap we identified some of the factors that appear to facilitate or limit the ownership and adoption of common agricultural machinery in Bangladesh, including irrigation pumps, threshers, and two-wheeled, tractor driven power tillers.

Our results indicate that farm size and wealth endowment of the farm households significantly and positively affect the ownership of agricultural machinery at the household level. Households endowed with more physical asset such as land, livestock, and ponds are more likely to invest in agricultural machinery, and are thereby more likely to serve smaller-scale farmers by providing custom hiring services to help repay investments in machinery and to generate additional income. We also demonstrated that sub-district level civil infrastructure such as the availability of electricity (specifically for irrigation pumps), and the provision of paved and gravel roads, in addition to the availability of loan and credit facilities, also significantly and positively affects the ownership of agricultural machinery at the household level. These findings underscore that the provision of basic infrastructure and loan facilities in Bangladesh's rural areas is prerequisite to agricultural machinery ownership by farm households, and therefore to the development of an agricultural machinery service provision economy. This provision economy is integral to insuring that smaller and less wealthy households can benefit from access to machinery through custom hiring on an as-need basis. As such, government, donors, and development planners should place equal focus on facilitating these necessary preconditions before and/or in tandem with efforts encouraging the adoption of appropriate agricultural machinery in areas where uptake is currently limited.

Acknowledgements

This study was made possible through the support provided by the United States Agency for International Development (USAID) to the Cereal Systems Initiative for South Asia – Mechanization and Irrigation (CSISA-MI) project. The contents and opinions expressed herein are those of the author(s) and do not necessarily reflect the views of the US Agency for International Development or the United States Government and shall not be used for advertising or product endorsement purposes.

References

Ahmmed, S. 2014. Present Status, Prospects and Challenges of Mechanization in Bangladesh. In Md. Ayum Hossain, Nazmun Nahar Karim, Shoed Hassan, and Sultan Ahmed in *Use of Farm Machinery and Efficient Irrigation System Management Training Manual 2014.* Gazipur: Farm Machinery and Postharvest Process Engineering Division, Bangladesh Agricultural Research Institute (BARI).

BBS (Bangladesh Bureau of Statistics). 2010. *Census of Agriculture 2008.* Dhaka: Ministry of Planning.

BBS (Bangladesh Bureau of Statistics). 2011. *Bangladesh Bureau of Statistics 2010*. Dhaka: Ministry of Planning.

BBS (Bangladesh Bureau of Statistics). 2011a. *Census of Agriculture 2008: Zila Series Patuakhali*. Dhaka: Ministry of Planning.

Cassman, K. G., A.Dobermann, D. T. Walters, and H. Yang. 2003. Meeting Cereal Demand While Protecting Natural Resources and Improving Environmental Quality. *Annual Review of Environment and Resources,* Vol. 28: 315-358.

FAO (Food and Agriculture Organization of the United Nations). 2009. *How to Feed the World 2050.* Rome: FAO. Online: http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agr iculture.pdf

GOB (Government of Bangladesh). 1999. *National Agriculture Policy.* Dhaka: Ministry of Agriculture. Online: http://www.dae.gov.bd/Dae_Policy/NAP.pdf, accessed September 09, 2014.

GOB (Government of Bangladesh). 2014a. Automated System for Customs Data. Dhaka: National Board of Revenue (NBR).

GOB (Government of Bangladesh). 1989. *Mid Term Review of the Third Five Year Plan 1985-90.* Dhaka: Planning Commission, Ministry of Planning: 84.

GOB (Government of Bangladesh). 2014. GIS Unit. Local Government Engineering Department: Dhaka: Ministry of Local Government, Rural Development and Cooperatives.

Godfray, H. C. J., J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, C. Toulmin. 2010. Food Security: The Challenge of Feeding 9 Billion People. *Science,* Vol. 327: 812-818.

Hossain, Mahabub. 2009. The impact of shallow tubewells and boro rice on food security in Bangladesh. Washington D.C.: International Food Policy Research Institute (IFPRI). Online: http://www.ifpri.org/sites/default/files/publications/ifpridp00917.pdf, accessed December 22, 2014

Hossain, M., Lewis, D., Bose, M.L., & Chowdhury, A. (2007). Rice research, technological progress, and poverty: The Bangladesh case. In Adato, M. and Meinzen-Dick, R. (Eds.). *Agricultural research, livelihoods and poverty: Studies of economic and social impacts in six countries.* Baltimore: The Johns Hopkins University Press and International Food Policy Research Institute.

iDE (International Development Enterprises). 2012. *Commercialization of Selected Agriculture Machineries in Bangladesh.* Dhaka: International Development Enterprises (iDE). Online: http://repository.cimmyt.org/xmlui/bitstream/handle/10883/3394/98527.pdf, accessed December 15, 2014.

Justice, S. and S. Biggs. 2013. "Rural and Agricultural Mechanization in Bangladesh and Nepal: Status, Processes and Outcomes. In *Mechanization for Rural Development: A Review of Patterns and Progress from Around the World,* eds. Josef Kienzle, John E. Ashburner, and Brian G. Sims, 67-98. Rome: Plan Production and Protection Division, Food and Agriculture Organization of the United Nations (FAO).

Kienzle, J., J.E. Ashburner, and B.G. Sims 2013. *Mechanization for Rural Development: A Review of Patterns and Progress from Around the World.* Rome: Plan Production and Protection Division, Food and Agriculture Organization of the United Nations (FAO).

Krupnik, Timothy J., Santiago Santo Valle, Andrew J. McDonald, Scott Justice, Israil Hossain and Mahesh K. Gathala.2013. *Made in Bangladesh: Scale-Appropriate Machinery for Agricultural Resource Conservation.* Mexico, D.F.: International Maize and Wheat Improvement Centre (CIMMYT).

Miah, M.A.H. and N.P. Sarma (2000). Hybrid rice: progress, issues and outlook for Bangladesh. *International Rice Commission Newsletter* 49, 65–72.

MOA and FAO, 2012. Master Plan for Agricultural Development in the Southern Region of Bangladesh. Ministry of Agriculture (MoA, Government of Bangladesh) and United Nations Food and Agriculture Organization, Dhaka, Bangladesh, p. 122.

Mottaleb, K. A., S. Mohanty and A. Nelson. 2014. "Factors influencing hybrid rice adoption: a Bangladesh case". *Australian Journal of Agricultural and Resource Economics*, Vol. 58:1–17. doi: 10.1111/1467-8489.12060.

Mottaleb, K. A., S. Mohanty, H. T. K. Hoang and R. M. Rejesus. 2013. The Effects of Natural Disasters on Farm Household Income and Expenditures: A Study on Rice Farmers in Bangladesh." *Agricultural Systems* 121: 43–52.

Mueller, N. D.,M. Johnston, D. K. Ray, N. Ramankutty, J. A.Foley. 2012. Closing yield gaps through nutrient and water management. *Nature*, Vol. 490: 254-257.

Pimentel, David, and Anne Wilson. 2004. World Population, Agriculture and Malnutrition. In Population and Its Discontents, *World Watch Magazine,* Vol.17, No.5: 22-25. Online: http://www.worldwatch.org/system/files/EP175D.pdf, accessed November 26, 2014.

Quayum, M. A. and A. M. Ali. 2012. Adoption and Diffusion of Two wheeled tractor driven power tillers in Bangladesh. *Bangladesh Journal of Agricultural Research*, Vol 37, No 2: 307-325. Online: http://www.banglajol.info/bd/index.php/BJAR/article/view/11234/8209, accessed December 15, 2014.

Sison, J.F., R.W. Herdt and D. Duff. 1985. "The Effects of Small Farm Mechanization on Employment and Output in Selected Rice-Growing Areas in Nueva Ecija, Philippines." *Journal of Philippine Development,* Vol. XII, No., 1: 29-82.

Tilman, D., C. Balzer, J. Hill, and B. L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Science of the United States of America,* Vol. 108(50): 20260–20264.

UNDRO (United Nations Disaster Relief Organization). Bangladesh - Cyclone Nov 1988 UNDRO Information Reports 1-6. Online: http://reliefweb.int/report/bangladesh/bangladesh-cyclone-nov-1988-undro-information-reports-1-6, accessed on October 02, 2014.

World Bank. 2007. *Agriculture for Development, World Development Report 2008.* Washington DC: The International Bank for Reconstruction and Development / The World Bank.

World Bank. 2014. *World Development Indicators 2014: Arable land (hectares per person).* Washington DC: World Bank. Online: http://databank.worldbank.org/data/views/variableSelection/selectvariables.aspx?source=world-development-indicators#, accessed September 09, 2014.

Conference Attendees

Shelina Afroza, MoFL
Mahnaz Afsar
Rayhan Afsar
Zafar Ahmed, MoWR
Md. Masud Ahmed, Blue Gold
Zia Ahmed, CIMMYT
Nazneen Ahmed, WorldFish
Bulbul Ahmed, BARI
Masum Ahmed, Bangladesh Betar
Sultan Ahmmed, BARC
Mirja Kaizer Ahmmed, WorldFish
Md. Aktaruzzaman, BWDB
Hamida Lipi Akter, WorldFish
Shanjida Akter, WorldFish
Afroza Akter, WorldFish
Md. Jahangir Alam, MoWR
Saiful Alam, WARPO
Md. Jahangir Alam, BSMRAU
Md. Shariful Alam, MoPA
Mohammad Alamgir, WARPO
A.K.M. Abdullah Al-Amin, BAU
Mir Emdad Ali, ATN
Olivyn Angeles, IRRI
Gaur Pada Bachar, Coastal Zone Community
Mustafa Bakuluzzaman, Shushilan
Randy Barker, Cornell/IRRI
Kanteswar Barman, CCRIP, LGED
Benoy Barman, WorldFish
Alak Barman, SO
Tahmina Begum, DAE
Shawkat Begum, CIP
Jayanta Bhattacharya, PSTU-IRRI
Md. Mokter Hossain Bhuiyan, BARI
Shankar Biswas, BRAC
Jatish C. Biswas, BRRI
Panchanan Biswas, Coastal Zone Community
Mihir Biswas, Coastal Zone Community
Altaf Boyati, Coastal Zone Community
Marie-Charlotte Buisson, IWMI
Dhiman Burman, CSSRI Canning Town
Binay Kumar Chakraborty, DOF
Parvesh Kr Chandna, IRRI
Giasuddin Choudhury, Delta Plan
Afrina Choudhury, WorldFish
Mary Archana Costa, IRRI
Arijit Das, IWMI
Uzzal Das, Coastal Zone Community
Sumona Das, Blue Gold
Hasan Dastagir, New Age
Bijoy Bhusan Debnath, WorldFish
Camelia Dewan, University of London
Nepal Dey, BRAC
Golam Faruque, WorldFish
Paul Fox, IRRI
Mamun Gazi, Coastal Zone Community
Pamela George, WorldFish
T.K. Ghoshal, CIBA
ASM Golam Hafeez, BAU
Suklal Halder, Coastal Zone Community
AKM Fazlul Haque, MoFL
Joadder Md. Anowarul Haque, DoF
Sadika Haque, BAU
Alifa Haque, NSU
Md. Enamul Haque, iDE
Minam T. Haque, WorldFish
Rezaul Hasan, IWM
Rokibul Hasan, LGED
Mehedy Hasan, ETV
Md. A Hashem
Abdul Haque Hawlader, Coastal Zone Community
Md. Nazmul Hoq, BAU
A.K.M. Ariful Hoque, BARI
AFM Afzal Hossain, IWM
Md. Abul Hossain, DAE
Md. Aowlad Hossain, Blue Gold
Md. Golger Hossain, DoF
Md. Khaled Hossain, CIMMYT
Md. Mokarram Hossain, WorldFish
Md. Monowar Hossain, IWM
Md. Rifatul Hossain, DAE
Moqbul Hossain, SRDI
Mosharraf Hossain, BARI
Shahadat Hossain
Md. Kawsar Hossin

Md. Houssain, BWDB
Shamsul Huda
Liz Humphries, IRRI
Mirza Islam, BINA
Azizul Islam, Coastal Zone Community
Mahmudul Islam, Sylhet Agricultural University
Md. Kamrul Islam, WorldFish
Md. Nazrul Islam, SO
Md. Saidul Islam, Shushilan
Md Shafiqul Islam, Coastal Zone Community
Monirul Islam, BARI
Rafiqul Islam, UNB
Saiful Islam, Coastal Zone Community
Wais Kabir, FAO
Md. Pervez Kabir, KU
E. Kabir, Bangladesh Betar
Kevin T. Kamp, WorldFish
S M Kamruzzaman, Coastal Zone Community
Manjurul Karim, World Fish
Swarna Kazi, World Bank
Nandish Kenia, IWMI
Deepak Khadka, iDE
Md. Khaleduzzaman, Dutch Embassy
Sarafat Hossain Khan,CEIP, BWDB
Zahir ul Haque Khan, IWM
Abu Saleh Khan, IWM
Afroza Khanam, MoWR
Md. Mamun Khondhoker, Coastal Zone Community
Md. Humayun Kobir, Coastal Zone Community
Mir Kobir, BTV
Tim Krupnick, CIMMYT
Swapon Bhadra, BRAC
A. Latif, SB
Ed Barrett Lennard, University of Western Australia
Syed Mahbub, Naya Diganta
Barrister Anisul Islam Mahmud, MoWR
Paulceip K. Maih, IWM
Mohammed Mainuddin
Shourav Maitra
Dr. Buddheswar Maji, ICAR-CSSRI
Dr. Subhasis Mandal, CSSRI Canning Town
M. Maniruzzaman, BRRI
S.M. Abdul Mannan, FAO
Craig Meisner, WorldFish
Tofazzal Hossain Miah, BAU
Golok Mistri, Coastal Zone Community
Dilip Kr Mistri, Coastal Zone Community
Archisman Mitra, IWMI
Khaled Mohammed, DUET
Haridas Mohuta, BARI
Manoranjan Mondal, IRRI
Monoranjan Mondal, Coastal Zone Community
Dipu Moni, Coastal Zone Community
Neaz Morshed, Maasranga TV
Abdul Wahab Munshi, Coastal Zone Community
M.G. Mustafa
Golam Mustaffa, WorldFish
Nitasha Nair, IWMI
M. Niamul Naser, DU
Farhat Naz, IWMI
Syed Nicolas, IFAD
Ainun Nishat, BRAC University
Andrew Noble, WLE (IWMI)
Kasia Paprocki, Cornell University
Dr. Sanjida Parveen, Sylhet Agricultural University
Md. Shamim Parvez, WorldFish
Lutfa Parvin, World Fish
Mike Phillips, WorldFish
Ilse Pukinskis, WLE (IWMI)
Tausif Ahmed Qurashi, BRAC
Asiqur Rahaman
M. A. Rahim, BAU
Ataur Rahman
Azbina Rahman, BUET
Akhlasur Rahman, IRRI
Mahabubur Rahman, WorldFish
Md. Hadishur Rahman BAU-IRRI
Md Mahfuzur Rahman, BWDB
Md. Nazibur Rahman, BWDB
Md. Shahidur Rahman, BWDB
Mohammad Saidur Rahman, BAU
Moshiur Rahman, LGED
Musa Nurur Rahman, BWDB
Mustafizur Rahman, Coastal Zone Community
Nefaur Rahman, BAU-IRRI
Narendra Kumar Rai, Ashok Sansthan
Sohel Rana, LGED
M. Abdur Rahaman, Rana
M. Harunur Rashid, BRRI
M A Rashid, BRRI

Mike Robson, FAO
Azit Roy, Coastal Zone Community
Ruma Roy, BAU
Steven Rubinyi, World Bank
Timothy Russell, IRRI
Jayonti Saddar, Coastal Zone Community
Bidhan Sadhak, WorldFish
Nathan Sage, Office of Economic Growth, USAID
Nibir Saha, PSTU-IRRI
Jiban Krishna Saha, GIZ
PK Saha, BRRI
Panchali Saikia, IWMI
Ibrahim Saiyed
Md. Abdus Salek, Coastal Zone Community
Popy Rani Sannyashi, BAU
Sukanta Sarange, ICAR-CSSRI
Khokon K Sarker, BARI
Khaled Sarker, Prothom Alo
Md. Ruhul Amin Sarker
Gazi Abdus Sattar, Coastal Zone Community
Urs Schulthess, CIMMYT
S.M Shah-Newaz, IWM
Md. Bappy Shahriar, WorldFish
Dirk Smits, Blue Gold
Istiak Sobhan, Environment, Water Resources and Climate Change (SASDI)
South Asia Sustainable Development Department
Eyerin Sultana, WorldFish
Nazneen Sultana, LGED
Mehnaz Tabassum, WorldFish
T P Tiwari, CIMMYT
Mahmud Hasan Tuhin
T P Tuong, IRRI
Md. Ekram Ullah, Environment, Forests & Fisheries Section
Md. Hedayet Ullah, WorldFish
Samina Yasmin, CIMMYT

CPWF Ganges Partner Organizations

Bangladesh Agriculture University

Bangladesh Fisheries Research Institute

BRAC

Bangladesh Rice Research Institute

Bangladesh University of Engineering and Technology Institute of Water and Flood Management

Bangladesh Water Development Board

Indian Council of Agricultural Research—Central Institute for Brackish-Water Aquaculture-Kakdwip Research Centre

Indian Council of Agricultural Research—Central Soil Salinity Research Institute—Regiona Research Station Canning Town

Bangladesh Water Development Board

International Rice
Research Institute

International Water
Management Institute

Local Government
Engineering Department

Patuakhali Science and
Technology University

Shushilan

Socioconsult Ltd.

Soil Resource Development
Institute

WorldFish

Contact

WorldFish, Bangladesh Office
House 22B, Road 7, Block F, Banani
Dhaka 1213, Bangladesh

T: (+880-2) 881 3250
(+880-2) 881 4624
F: (+880-2) 881 1151
E: worldfish-bangladesh@cgiar.org

May 2015

CGIAR Challenge Program on
WATER & FOOD
Andes • Ganges • Limpopo • Mekong • Nile • Volta