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Integrating fish into irrigation infrastructure projects in Myanmar: rice-fish what if…?

Mark J. Dubois[A,I], *Michael Akester*[A], *Kimio Leemans*[A], *Shwu Jiau Teoh*[B], *Alex Stuart*[C], *Aung Myo Thant*[D], *Su Su San*[D], *Nilar Shein*[E], *Mansoor Leh*[F], *Palal Moet Moet*[G] *and Ando M. Radanielson*[H]

[A]International Center for Living Aquatic Resources – WorldFish Myanmar, Department of Fisheries Bayint Naung Road, West Gyogone, Insein Township, Yangon, 11011, Myanmar.
[B]International Center for Living Aquatic Resources – WorldFish Headquarters, Jalan Batu Maung, Batu Maung, 11960 Bayan Lepas, Penang, Malaysia.
[C]International Rice Research Institute (IRRI) – Indonesia Office, ICFORD Building, Jalan Merdeka 147, Bogor 16111, Indonesia.
[D]IRRI, Seed Division Compound, Department of Agriculture, Gyogone, Insein Road, Yangon, 11011, Myanmar.
[E]Department of Fisheries, Ministry of Agriculture, Livestock and Irrigation, Bayint Naung Road, West Gyogone, Insein Township, Yangon, 11011, Myanmar.
[F]The International Water Management Institute, IWMI South East Asia Office, c/o National Agriculture and Forestry Research Institute (NAFRI), PO Box 4199, Ban Nongviengkham, Xaythany District, Vientiane, Lao PDR.
[G]International Water Management Institute (IWMI), Irrigation Head Office, Hnin Si Road, Yankin, Yangon, 11081, Myanmar.
[H]University of Southern Queensland, Institute for Life Sciences and Environment, Centre for Sustainable Agricultural Systems, West Street, Toowoomba, Qld 4350, Australia.
[I]Corresponding author. Email: m.dubois@cgiar.org

Abstract. With rapidly increasing investment in water control infrastructure (WCI) and a recently ratified agriculture development strategy that promotes integrated farming of high-value products such as fish, agricultural production, already fundamental to Myanmar's economy, will be central to driving the countries' socioeconomic transformation. Water planners and managers have a unique opportunity to design and manage WCI to incorporate fish and, in so doing, reduce conflicts and optimise the benefits to both people and the ecosystem services upon which they depend. Results from rice–fish culture experimental trials in Myanmar's Ayeyarwady Delta are providing an evidence base for the importance of integrating fish into WCI, highlighting a range of both environmental and social benefits. By using less than 13% of paddy land area and through best management practices, existing rice productivity is sustained, alongside a 25% increase in economic returns for the same land area from fish. In addition, there are considerably more protein and micronutrients available from the fish produced in the system. Should these farming system innovations be adopted at scale, Myanmar stands to benefit from increased employment, incomes and nutritional value of farm plots (alongside associated reductions in pesticide pollution) and water use benefits.[1]

Additional keywords: landscape approach, rice–fish systems, sustainable development, water managers.

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Introduction

Myanmar is a country where rice and fish dominate diets, incomes and employment generation, and play a pivotal role in the country's cultural identity (Raitzer *et al.* 2015). The agriculture sector is the backbone of Myanmar's economy, contributing 37.8% of gross domestic product (GDP) and 25–30%

[1]The opinions expressed here belong to the authors, and do not necessarily reflect those of the Consultative Group on International Agricultural Research (CGIAR) Research Program on Fish Agri-Food Systems, Research Program on Rice (RICE) CGIAR Research Program and Water, Land, and Ecosystems (WLE) CGIAR Research Program, WorldFish, International Rice Research Institute, International Water Management Institute or CGIAR.

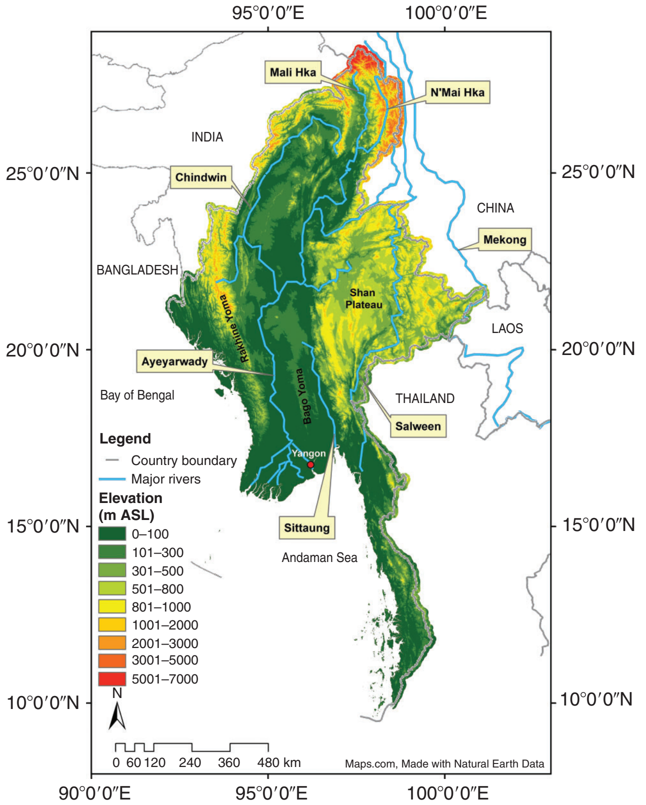

Fig. 1. Main rivers and drainage basins in Myanmar. ASL, above sea level. Reproduced with permission from Taft and Evers (2016).

of all export earnings, and employing 70% of the labour force (Food and Agriculture Organization of the United Nations 2019*a*). Rice and fisheries are the respective first and fourth largest contributors to GDP, with the fisheries sector alone contributing to incomes of up to 15 million people in the country (McCartney and Khaing 2015).

The Ayeyarwady Basin (Fig. 1), associated flood plains and the Ayeyarwady mega delta are well recognised for their rich aquatic biodiversity, with at least 388 fish species, of which half are endemic (Baran *et al.* 2017). Inland capture fisheries in Myanmar rank fourth globally, with yields estimated to be close to 1×10^6 tonnes (Mg) year^{-1}, including a 'hidden harvest' estimate (Food and Agriculture Organization of the United Nations 2019*a*).

Rice, the main staple, provides 66% of the population's daily calorie intake (80% in rural areas) and amounts to over 20% of household expenditure for low-income households (Central Statistical Organisation 2017; Myint 2018). Fish account for the largest contribution of animal protein in Myanmar diets (60%; Wilson and Wai 2013).

The combined fish production of close to 2.5×10^6 Mg from inland areas coupled with $\sim 1.5 \times 10^6$ Mg from the marine sector, less non-food use (1.5×10^6 Mg) and exports (0.570×10^6 Mg), would, in theory, provide Myanmar's 54.34 million inhabitants with 35 kg of fish per capita per annum.

However, per capita consumption data for both fish and rice can be deceptive because the figures hide the disparity of nutrient availability to the poorer sections of communities. For example, fish distribution is not even in terms of social class access and geographical location, with poorest households consuming less than one-quarter of the amount consumed by better-off households (Wilson and Wai 2013).

This paper provides a perspective on how Myanmar may be able to realise its global and national commitments to sustainable development, and provides a pathway for a growing population with more profitable, nutritious, equitable and sustainable food production systems (Willett *et al.* 2019).

Myanmar: where rice and fish dominate diets and malnutrition remains unacceptably high

Despite the contribution of rice and fish to Myanmar diets, and Myanmar's progress in fighting hunger (being 1 of only 72 countries to achieve the Millennium Development Goal of halving the proportion of hungry people by 2015; Food and Agriculture Organization of the United Nations 2019*a*), malnutrition remains extremely high, with recent studies stating that, nationally, 33–40% of children under the age of 5 years are stunted, 25–33% are underweight and 7.9–11% are wasted (Thilsted and Bose 2014; Livelihoods and Food Security Trust Fund 2015). Because of disparities in geography and income, this is even more pronounced among rural and poorer groups. With the majority calorific contribution to the Myanmar diet coming from a single food group, in this case rice, the prevalence of stunting and micronutrient deficiencies can be largely attributed to this lack of diversity in the diet. Myanmar's food systems have the potential to address national commitments under the Sustainable Development Goals (SDGs), specifically SDG 2, and support environmental sustainability (see https://www.un.org/development/desa/disabilities/envision2030-goal2.html, accessed 8 July 2019). However, unless a shift towards more integrated food production occurs, both outcomes are currently at risk. The Eat-Lancet commission states that:

> …although global food production of calories has kept pace with population growth, more than 820 million people have insufficient food and many more consume low-quality diets that cause micronutrient deficiencies. Providing a growing global population with healthy diets from sustainable food systems is an immediate challenge [Willett *et al.* 2019].

This is very much the case in the Myanmar context and, in order to deliver healthy diets for its people and to secure a sustainable food production system, a shift towards more integrated food production, diverse diets and nutrition-sensitive agriculture is urgently needed (Willett *et al.* 2019). In order for this to happen there needs to be a corresponding reform in land law and land use policy (Ministry of Agriculture, Livestock and Irrigation 2018).

Legislation–policy framework: a disabling environment?

Under the current *Farmland Act* (Pyidaungsu Hluttaw Law number 11/2012), the issuance of a land use certificate is contingent upon crop choice, principally rice, and without provision for other agricultural production systems, such as aquaculture or integrated farming systems. Unauthorised changes in land use may result in land confiscation. The law does include provision for requesting a change in land use (including crops), but the process is highly centralised (particularly for paddy lands) and expensive (it can take years to process and, in practical terms, reduces security over tenure).

The second principal legislative instrument for land management is the *Vacant, Fallow and Virgin Land Management Act* (Pyidaungsu Hluttaw Law number 10/2012). This law makes provision for land use rights over land classified as being 'vacant', 'fallow' or 'virgin'. However, these rights are only temporary and the definitions of the different land classes are unclear and do not adequately support customary rights holders who are unable to secure tenure under the *Farmland Act*. In addition, legal acquisition or illegal confiscation under the *Land Acquisition Act* (1894) enables the confiscation of land, such as in floodplain wetlands.

Several recent policies and plans have been drafted or are underway to address some of these concerns, specifically the drafting of the national land use policy (see http://extwprlegs1.fao.org/docs/pdf/mya152783.pdf, accessed 8 July 2019), the Myanmar National Water Policy (2014) (see https://www.medbox.org/mm-policies-others/myanmar-national-water-policy-burmese-version/preview?q=, in Burmese), the 2018 Multi-Stakeholder/Multi Sector National Plan of Action for Nutrition (MS-NPAN, see http://mohs.gov.mm/su/jgyv4420JG) and the Agriculture Development Strategy (ADS; Ministry of Agriculture, Livestock and Irrigation 2018). The commonalities between these policies and plans include an emphasis on resolving land issues and the promotion of greater agricultural diversity towards the delivery of water, food and nutritional security.

Myanmar in transition

Despite delivering comparatively low yields (World Bank 2018) and economic returns per unit land area (Ministry of Agriculture, Livestock and Irrigation 2018), rice cultivation accounts for 66% of Myanmar's total arable land use. However, the political and economic landscape is changing rapidly. With increasing mechanisation, out-migration from rural to urban areas and resulting rural labour shortages, Belton and Filipski (2019) ask, is Myanmar undergoing a rural transformation? With Myanmar's rapid pace of development, particularly since 2011, population increases, demographic changes, shifting land use and resource degradation, Myanmar's development interacts with and occurs in a period of unprecedented social and environmental change. Coupled with climate variability and change, increased investments in water control infrastructure, such as hydropower and irrigation, and competing land uses, the pressure on natural resources, and specifically on securing resilient food production systems, is a serious concern. Major effects of climate change will be on water and water-related services, potentially exacerbated by mitigation efforts that, in themselves, are expected to contribute to changes in hydrology. A pressing question for Myanmar and its people is how, in the face of these profound changes, can the economic, food and nutritional security of its people be ensured while retaining the ecosystem services upon which they depend?

Towards sustainable development

Delivering a productive and sustainable agriculture sector is crucial to Myanmar's commitments to the SDGs. Key issues to consider include are listed below.

1. Potential conflicts within and between SDG targets, such as those aimed at doubling production and incomes (SDG 2.3.2). Outcomes from different subsectors and their component indicators 'are not independent of each other – they interact in both positive and negative ways creating the potential for synergies and trade-offs' (Kanter *et al.* 2018). For example, to deliver on SDG 2 'End Hunger, Achieve Food Security and Improved Nutrition and Promote Sustainable Agriculture' maximising irrigation potential for single-use paddy rice may negatively affect fisheries due to the barrier effect (i.e. the effect of infrastructure on river connectivity; Conallin *et al.* 2019) and may subsequently represent a threat to meeting this SDG (Blanchard *et al.* 2017). More broadly, agricultural development needs to consider its effect on ecosystem services, such as on biodiversity, water quality, nutrient recharge and habitat provision. Resilient ecological systems support resilient social systems, with threats to ecosystem service provision threatening human well-being (Folke *et al.* 2010). This demonstrates the need to assess, track and adaptively manage these interactions within and between the agricultural and related sectors, and points to the critical role that integrated intersectoral planning has to play in coordinating Myanmar's agricultural development.
2. The importance of conducting an agricultural trade-offs analysis (Kanter *et al.* 2018) with an emphasis on understanding SDG outcome target interactions, complementarities and trade-offs. Kanter *et al.* (2018) suggests an approach to this analysis comprising four steps, namely: (1) characterising the decision setting and identifying the context-specific indicators needed to assess agricultural sustainability; (2) selecting the methods for generating indicator values across different scales; (3) deciding on the means of evaluating and communicating the trade-off options with stakeholders and decision makers; and (4) improving uptake of trade-off analysis outputs by decision makers (Kanter *et al.* 2018).
3. A robust cost–benefit analysis emphasising who or what benefits, where and in what ways and how these intersect. To use a practical example, aquaculture, one of the fastest growing food-producing sectors, accounting for ~50% of the world's fish used for food Food and Agriculture Organization of the United Nations (2019*b*), is sometimes considered a replacement for capture fisheries, yet it is important to recognise who benefits from its production (e.g. poverty and sex differences), which species are grown, what are the economic and nutritional values of these species and where they are being sold or consumed. This is clearly an issue in Myanmar, where 90% of aquaculture production comes from the Delta in macroscale privately owned systems (Belton *et al.* 2015). Thus, strategies to enhance aquaculture sector production need to take into account the existing contribution of capture fisheries and aim not to replace, but rather to complement this contribution where possible.

Strategic development of the agricultural and related sectors

As has been demonstrated, the agricultural sector is of primary importance in Myanmar's socioeconomic development and in

Table 1. Recent donor financing (2010–15) and anticipated donor investment (2016–22)
Table adapted with permission from the Agricultural and Development Strategy Investment Plan Draft 4 2017 (available at https://www.myanmarfswg.org/sites/myanmarfswg.org/files/uploads/PDF/ads_framework_version_no._4_0.pdf, accessed 1 July 2019). Note, US dollars are used throughout

Investment category and programme	2010–15 (million US$)	2016–22 (million US$)	2016–22 only (%)
Infrastructure			
New irrigation	960 504	15 086 805	5.6%
Rehab or upgrade of existing irrigation	60 212 790	248 933 737	92.5%
Agro processing	1 031 577	1 132 163	0.4%
Other investments	1 258 152	3 939 217	1.5%
Sub-total	63 463 023	269 091 922	100.0%
Sub-total as percentage of grand total	48.3%	53.9%	–

achieving the sustainable development objectives described above. Arguably the key strategic document in realising this vision is the recently endorsed agriculture development strategy (Ministry of Agriculture, Livestock and Irrigation 2018), which states that for the MoALI:

> …the key role of agriculture is to ensure food and nutrition security, climate resilience and reduced household vulnerability, ensure food safety, increase agriculture land and labor productivity and contribute to rural development and environment protection. MoALI's role has evolved from a crop agriculture focus, to one of diversification towards high value products, including livestock and fisheries, and the development of the rural non-farm sector [Ministry of Agriculture, Livestock and Irrigation 2018].

In the context of doubling agricultural production and incomes alongside an associated target of increasing irrigated land area by 5% of total potential irrigated land area (Department of Irrigation 2018), integrated farming systems can play an important role in providing increased production and incomes per unit land area:

> …thus, rather than an excessive focus on rice, there is a need to think in terms of rice-based farming systems that will encompass a range of non-paddy options depending on location [Ministry of Agriculture, Livestock and Irrigation 2018].

Key role of the MoALI

Investment in irrigation, both for rehabilitation and expansion, is expected to account for more than 50% of the total investment into the ADS for the period from 2018–19 to 2022–23, whereas fisheries will receive just 0.2% of the capital budget (Table 1). This disparity, although understandable in terms of the cost of rehabilitating, building and maintaining irrigation systems, nevertheless, from the perspective of 'diversification towards high-value products', underlines the importance of promoting multiple-use irrigation structures with institutions capable of interacting more closely to ensure cost-effective integrated food production.

Transformational change

Despite the significant contribution of irrigation infrastructure to incomes and food, poverty and malnutrition remain high. Irrigation infrastructure forms physical barriers that fragment the landscape, reducing habitat connectivity crucial for migratory fish species, which can and often do underpin the food and nutritional security of communities; the poor are often the hardest hit. It is paradoxical to suggest then, that reducing access to and availability of poor people's food and livelihood can be a 'developmental good'. It is perhaps more relevant to understand the development of one sector and its positive contributions as having trade-offs that may result in negative effects on another. The resulting conflicts between sectors and sections of the community, between, for example, farmers and fishers, can result in significant political, financial, environmental and livelihood losses. Strategies to resolve these conflicts are not always successful through traditional compensation and associated resolution efforts. However, preplanned mitigation strategies, such as incorporating multiple uses of the irrigation scheme in the design phase (e.g. for integrating fish into the full range of constructed aquatic habitats; McCartney *et al*. 2019), including wetland refuges (Fig. 2*a*, *b*), have considerable potential for 'win–win' scenarios mitigating effects and resolving conflicts.

Why integrated farming needs to be considered in water control infrastructure development

Rice–fish farming has been practiced for centuries in countries across South, East and South-east Asia. Multiple systems integrating rice and fish production exist, ranging from alternating rice and fish temporally between rainy and dry seasons to growing fish and rice concurrently but in separate areas of the paddy field to culturing fish in modified rice fields on the same plot of land at the same time. It is this latter system, also occasionally with the growing of vegetables on the bund areas and/or with poultry or livestock, that we refer to as 'integrated farming' in this paper. When rice and fish are grown together in this type of system, we refer to this as 'rice-cum-fish culture' or simply 'rice–fish' (RF). Varying levels of integration exist, with resources and nutrients flowing from one farm component to another. Integrated farming is increasingly being put forward as an alternative to intensive industrial monocropping, because of lower effects on the environment and the positive effects it can have on rural communities and their livelihoods (Tipraqsa *et al*. 2007; Murshed-e-Jahan and Pemsl 2011; Berg *et al.* 2017). In this section we describe potential benefits and constraints of integrated farming and its potential application within the Myanmar context, drawing on experience and literature from

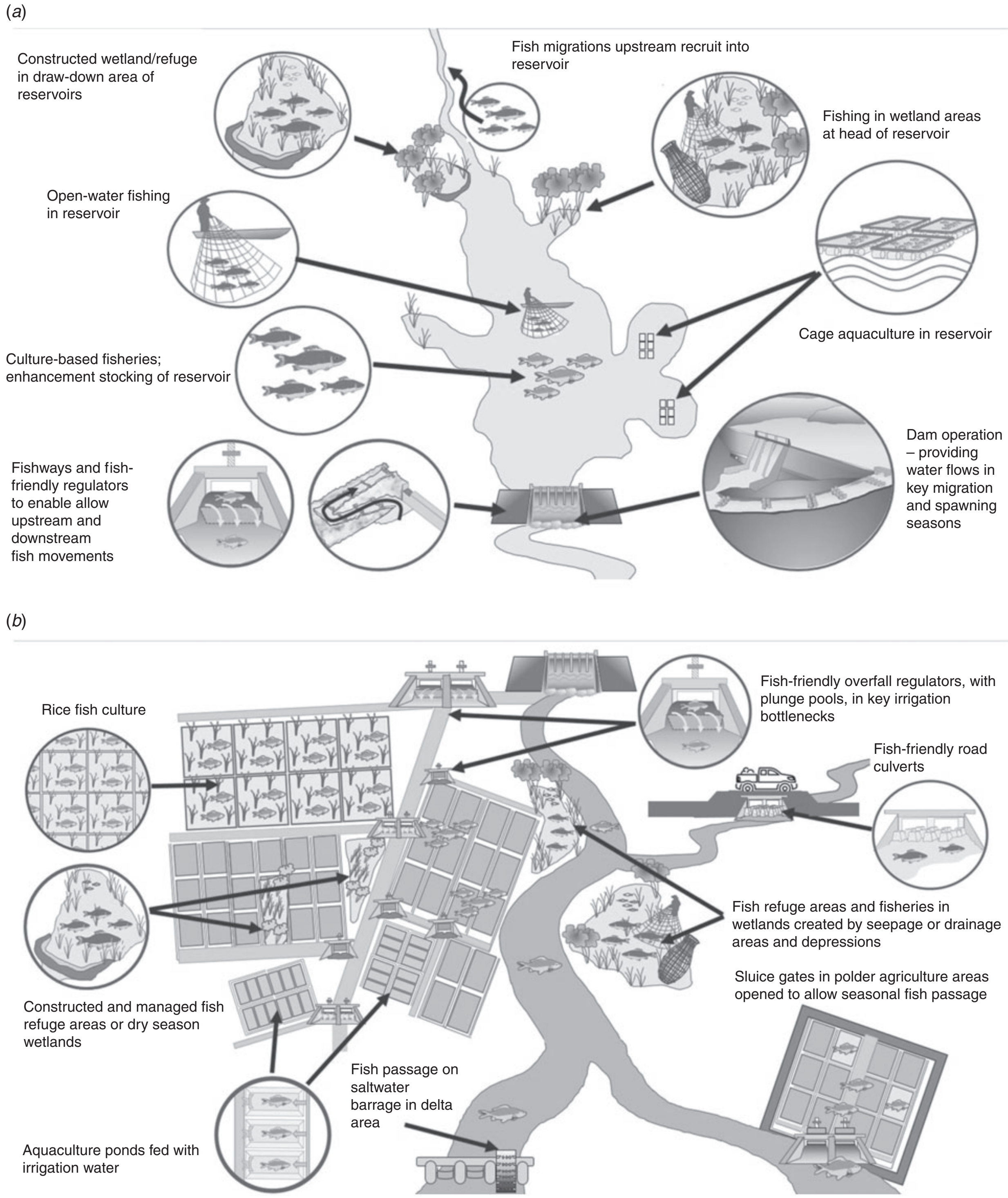

Fig. 2. Range of options to enhance fisheries in irrigation systems (*a*) upstream and (*b*) downstream of a dam. Reproduced with permission from Gregory *et al.* (2018).

other South-East Asian countries. Integrating fish into the rice field can lead to increased rice yields per unit area, as is shown in results from neighbouring countries (Halwart and Gupta 2004; Mohanty *et al.* 2004; Tipraqsa *et al.* 2007; Ahmed *et al.* 2011; Xie *et al.* 2011; Bosma *et al.* 2012; Berg and Tam 2018). A survey of 309 paired farms (RF *v.* rice monoculture) in China by Hu *et al.* (2016) found that rice yields were not negatively affected when the fish refuge size occupied no more than 10% of the surface area of the rice field, with some cases showing no yield reduction when up to a maximum of 15% of the land area was dedicated to a fish refuge. In addition, the results indicated that RF produced higher net income and had a higher production efficiency than rice monocropping.

Integrating rice and fish culture is associated with higher production efficiencies and higher incomes. Higher system efficiency can be achieved by better recycling of nutrients and waste within the system or by taking up a higher share of nutrients in the system (Halwart and Gupta 2004; Phong *et al.* 2007; Murshed-e-Jahan and Pemsl 2011; Bosma *et al.* 2012; Hu *et al.* 2016). A study by Ahmed and Garnett (2011) showed that farmers adopting integrated RF farming practices used lower amounts of fertiliser but achieved the same yields as those using higher amounts of fertiliser, but further research on this subject is needed. The lower need for fertiliser in RF systems is the result of higher nutrient availability (Ahmed and Garnett 2011). Having fish present in the rice field can improve soil fertility by increasing the availability of nitrogen and phosphorus (Huy Giap *et al.* 2005; Dugan *et al.* 2006) to the rice plant. RF systems can contribute to the recovery of soil fertility and prevent soil degradation (Lu and Li 2006).

Fish serve several different functions within the RF system, including consuming pests and weeds, recycling nutrients and oxygenating the water by burrowing for food (Lu and Li 2006; Xie *et al.* 2011; Liu *et al.* 2014). Thus, fish can be used as a component of an integrated pest management strategy (Berg 2002). This can help reduce the amount of pesticides needed, and thus the associated negative effects on the environment and on farmers' health (Berg and Tam 2018). Most importantly, in a RF system, pesticide use can have a negative effect on fish growth and survival, and thus the benefits provided by fish towards pest management provides a win–win situation.

Culturing fish in the paddy field leads not only to similar or higher yields in rice, but also to higher incomes from the associated fish yields. Studies in neighbouring countries have shown integrated RF farming to be more profitable than rice monoculture (Ahmed and Garnett 2011; Ahmed *et al.* 2011; Murshed-e-Jahan and Pemsl 2011; Saiful Islam *et al.* 2015; Hu *et al.* 2016; Berg *et al.* 2017; Berg and Tam 2018). However, integrated RF systems are more labour intensive (Halwart and Gupta 2004; Ahmed and Garnett 2011), which may lead to higher labour costs. This increased demand for labour could fall mainly to women (Halwart and Gupta 2004). Evidence from Bangladesh shows that when women are able to combine their household duties with involvement in integrated agriculture–aquaculture systems, this results in more independence and a higher social standing (Ahmed *et al.* 2007).

Integrated RF farming also increases households' food and nutrition security by providing them with a source of fish, a highly nutritious food, in addition to the small indigenous species and other aquatic animals and plants that benefit from a pesticide-free environment. Households practicing integrated farming consumed a higher proportion of fish and had higher levels of fresh fish in their diet (Nhan *et al.* 2007; Tipraqsa *et al.* 2007; Ahmed and Garnett 2011; Ahmed *et al.* 2011; Murshed-e-Jahan and Pemsl 2011; Saiful Islam *et al.* 2015). Ahmed *et al.* (2007) reported that the water from fish ponds could be used to fertilise vegetables growing on the pond dykes, further contributing positively to household nutrition.

The opinion in the academic literature on whether RF farming can contribute to improved living conditions for poorer households remains subject to debate (Tsuruta *et al.* 2011; Saiful Islam *et al.* 2015). Diversification of their livelihood strategies could ensure poor households are more able to cope with unexpected events (Phong *et al.* 2007), but less-well-off households may lack the resources required (financial capital and land ownership) to transition to RF farming.

Although the benefits of shifting from rice monoculture to integrated systems have been discussed in the preceding sections, there are several practical constraints for households willing to adopt RF systems. The main constraints that have been put forward by farmers in Bangladesh, Vietnam and Thailand are a lack of financial and human capital (Halwart and Gupta 2004; Ahmed *et al.* 2007, 2011; Nhan *et al.* 2007; Tipraqsa *et al.* 2007; Bosma *et al.* 2012; Saiful Islam *et al.* 2015), poor irrigation infrastructure and poor water quality (Halwart and Gupta 2004; Ahmed *et al.* 2007), lack of technical inputs (fish genetic material, fish feed) and extension services (Nhan *et al.* 2007; Murshed-e-Jahan and Pemsl 2011). The main reasons for households to take up RF farming as opposed to rice monoculture were to increase the efficient use of on-farm resources, income generation through aquaculture, environmental benefits and positive effects on nutrition (Nhan *et al.* 2007; Bosma *et al.* 2012). Access to irrigation systems and to credit positively influenced the adoption of RF systems in Bangladesh (Saiful Islam *et al.* 2015).

In summary, the evidence from several studies and projects conducted in South and South-east Asia (Halwart and Gupta 2004; Tipraqsa *et al.* 2007; Tsuruta *et al.* 2011; Berg and Tam 2018), demonstrate that integrated RF farming systems have the potential to maintain or increase rice production while also providing a range of associated benefits. In the context of achieving the SDGs, as well as adapting to or mitigating the effects of climate change and improving resource efficiency, converting 10% of irrigated paddy lands to integrated RF farming has transformative potential for the agri-food sector in Myanmar.

Experiences from RF experimental trials in Myanmar

To date, there are few published studies exploring the potential role of integrated RF farming systems in Myanmar. In the dry season of 2017, a replicated experiment was implemented in Maubin Township, Maubin District, Ayeyarwady region, and in Letpadan Township, Tharyarwady District, Bago Region (CGIAR Research Program on Fish Agri-Food Systems 2019). A randomised complete block design was established to compare rice only against RF (rohu and silver barb at a density of 2 fish m^{-2}) with different nitrogen treatments and rice varieties. Each plot was 225 m^2 with a 14.5- × 2- × 1.2-m fish refuge trench (occupying 13% of the plot area; Fig. 3).

The study found that although rice yields increased with higher fertiliser rates, there was no difference in rice yield between fish and no-fish treatments. In addition to the rice harvest, the average production of fish (rohu *Labeo rohita* and silver barb *Barbonymus gonionotus*) was 700 kg ha^{-1} in Maubin and 940 kg ha^{-1} in

Fig. 3. Example of plot lay out (reproduced with permission from CGIAR Research Program on Fish Agri-Food Systems 2019). Note, the fish refuge area is less than 13% of the total crop production area.

Letpadan. Compared with the rice-only system under best management practices (BMP) for N, the integrated RF system improved the gross profit margin of rice farmers by 41% in Letpadan and by 9% in Maubin. The potential benefits of introducing RF in rice-based cropping systems in Myanmar are evidently quite substantial in terms of diversified food productivity and smallholder farmer profitability, not to mention the improved resilience of having an alternative source of livelihood.

What if…?

The next section of this paper is a scenario-based step into a potential fish–agrifood system future for Myanmar. It is a perspective aimed at exploring options, specifically related to irrigation, for delivering on Myanmar's global and national commitments to doubling production and incomes, addressing food and nutritional insecurity, ending hunger and addressing rural poverty. It is borne of the question, 'What if…?'

What if potential for integrated farming in Myanmar is realised? The paper explores this through several fairly conservative scenarios in the Ayeyarwady delta based upon results from the Australian Centre for International Agricultural Research (ACIAR)-funded experimental trials and a mapping exercise conducted to determine potential areas suitable for rice-cum-fish culture. Before discussing the scenarios themselves, the following section outlines the methods and approach taken to mapping suitability and the calculations used in the scenarios.

RF suitability mapping

Through a literature review and consultations with aquaculture specialists and local experts, several key biophysical and socioeconomic determinants of RF suitability in the Delta were defined. Biophysical factors included irrigated rice growing areas, soil texture, pH and salinity, as well as land slope. Exclusion criteria included flooded, saline or brackish water areas and urban areas. Data representing these factors were collected and processed at similar resolution as input layers into a geographical information system (GIS) multicriteria evaluation (MCE) model to produce the RF suitability map (Fig. 4).

The areas estimated as suitable are likely to be an overestimate because the model has considered a fairly limited number of socioeconomic and biophysical factors. Further refinement is underway to include more social (e.g. farmer capacities and aspirations) and biophysical characteristics, as well as plans for additional stakeholder consultations and ground truthing. Alongside these refinements, the inclusion of data on access to markets and hatcheries would be considered in addition to the deep-water rice suitability map developed by Leh *et al.* (2019; see Fig. S1, available as Supplementary material to this paper) will be integrated into the spatial data layers of the map prior its use for policy planning and decision making.

Nevertheless, on choosing a sufficiently high suitability level, in this case only considering areas classified as suitable and most suitable (i.e. >60% suitability at three scenario levels: 10, 5 and 1%), the analysis remains useful and is presented in Tables 2–4.

The production figures used in the 'What if…?' scenarios are taken from the experimental trial results from one dry season in Letpadan and Maubin as described above (CGIAR Research Program on Fish Agri-Food Systems 2019). Thus, we make the assumption that the rice and fish production potential is similar across the region within the defined biophysical conditions selected for the suitability mapping and recognise that one of the main limitations for extrapolation is that it is based on experimental results from two locations only. The culture period in these trials was 115 days for both rice and fish. Fish were stocked and harvested 2 weeks after the rice was planted and harvested. To calculate the potential production and income from rice and fish for the potential suitable RF areas, the average of both trial locations was taken and then multiplied by 10% of the total suitable area. The suitable areas were defined by rice growing areas that scored 60% or higher on the suitability criteria for the suitability maps. This amounted to a total suitable land area of ~15 700 km^2 in the Ayeyarwady Delta. Gross income from rice and fish is based on farm gate prices received at the time of harvest, which were US\$2 kg^{-1} for fish in Letpadan and \$2.4 kg^{-1} for fish in Maubin, and US\$0.15 kg^{-1} for rice in Letpadan and Maubin. Net income is compared between a rice production system and a rice-cum-fish culture system, both under BMP. Net income is defined as the gross income from rice and fish production achieved during the field trials minus the total cropping season production cost. The cost of excavating the fish refuge area was not included in this calculation because we assume this to be an initial one-time cost only; thus, we also refer to net income as the gross profit margin when reporting the experimental trial results. To estimate the potential nutritional impact for human consumption, production figures were converted into edible portions. Nutrition composition tables are expressed as the nutrient value per 100-g edible portions, hence the conversion from rice and fish harvest figures. The conversion rates were determined by Bogard *et al.* (2015) for rice and fish. After converting to edible portions, the amount of protein can be calculated using the values determined in Institute of Nutrition, Mahidol University (2014) for rice and Bogard *et al.* (2017) for fish.

Under integrated RF farming with BMP, with no more than 13% of the rice field area used for a fish refuge, the mean rice production was 4.85 Mg ha^{-1} across the two field experiment

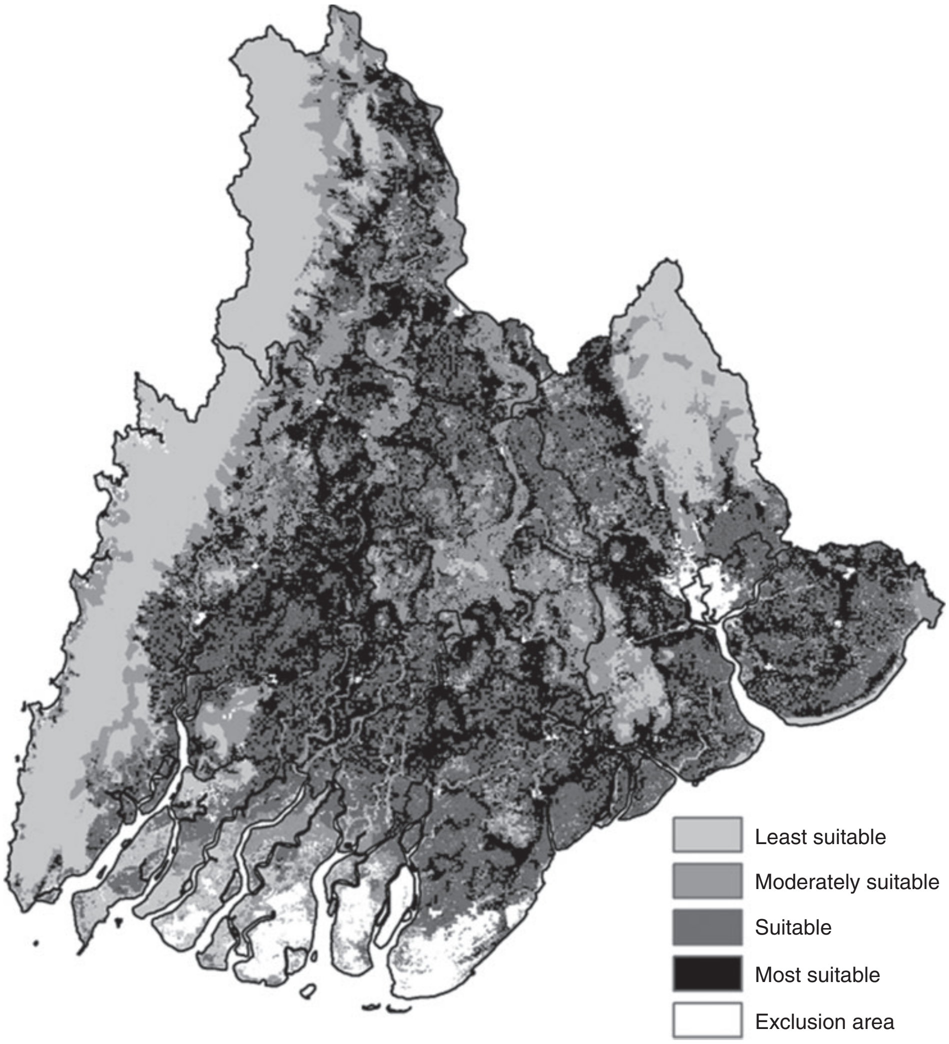

Fig. 4. Rice–fish suitability map in the Ayeyarwady Delta. Adapted from CGIAR Research Program on Fish Agri-Food Systems (2019).

Table 2. Harnessing rice–fish development potential in the Ayeyarwady Delta

The area of the 'suitable' and 'most suitable' land (>60% suitability) amounting to 15 716 km^2 is used in the analysis in Tables 3 and 4 below

Ayeyarwady Delta region	Area (km^2)				
	Least suitable	Moderately suitable	Suitable	Most suitable	Total (excluding Yangon)
District					
Hinthada	2452	1994	1006	1499	6951
Labutta	956	730	1001	403	3090
Maubin	207	1553	1343	1224	4326
Myaungmya	96	554	1034	1326	3009
Pathein	4063	2314	1814	2013	10 205
Pyapon	355	567	2000	1054	3975
Yangon	1957	2199	2646	2537	9339
Total	8128	7711	8198	7518	31 556
Combined totals	15 839		15 716		

Table 3. Three different scenarios of rice–fish system (RFS) adoption in the Ayeyarwady Delta region in Myanmar
BMP, best management practice

	Land area (km^2)	Rice production from RFS (Mg)	Fish production from RFS (Mg)	Net income from rice under BMP for N (US$)	Net income from rice + fish in RFS (US$)	Increased net income from RFS (US$)
10% scenario	1572	762 251	125 732	107 500 928	136 733 637	29 232 709
5% scenario	786	381 125	62 866	53 750 464	68 366 819	14 616 355
1% scenario	157	76 225	12 573	10 750 093	13 673 364	2 923 271

Table 4. Three different scenarios highlighting the total edible portion of rice and fish and amount of protein produced in the rice–fish system (RFS)

Scenarios	Land area (km^2)	Edible proportion of rice produced from RFS		Edible proportion of fish produced from RFS		Protein from rice produced from RFS		Protein from fish produced from RFS	
		(Mg)	(kg ha^{-1})	(Mg)	(kg ha^{-1})	(Mg)	(kg ha^{-1})	(Mg)	(kg ha^{-1})
10% scenario	1572	533 576	3395	104 358	664	36 283	231	19 828	126
5% scenario	786	266 788	1698	52 179	332	18 142	115.5	9914	63
1% scenario	157	53 358	339.5	10 436	66.4	3628	23.1	1982	12.6

locations (Table 2). Owing to the reduction in farm land area planted with rice, this was slightly lower than the rice production per unit of total farm land area achieved in rice monoculture with BMP in the experimental plots, but was similar to the rice production per unit of total farm land area achieved by neighbouring rice monocropping farmers (A. M. Stuart and N. Shein, unpubl. data). In addition, 0.8 Mg ha^{-1} fish was produced, and less fertiliser and pesticide inputs were used. When comparing rice monoculture with BMP and RF culture with BMP, there was, on average, a 25% increase in the gross profit margin of the system through the additional sales of fish.

Taking the 25% increase in gross profit margin in the 10% scenario, this would lead to a total net income of over US$268 million derived from RF systems per dry season, an increase of ~US$100 million compared with rice monocropping. The additional fish harvested from the system can be beneficial for household nutrition, providing farming households with a source of fresh fish (Table 4). Under the 10% scenario, more than an additional 1×10^5 Mg of edible portions of fish could be produced from the Ayeyarwady Delta region.

In each 100 g of raw edible fish, there is 100 kcal of energy and 19 g of protein. For rice, the ratio is approximately the reverse, that is 100 g of raw edible white rice provides a little over threefold the energy of fish, at 355 kcal, and 6.8 g of protein, amounting to a little more than one-third of the contribution from fish. Calories are not usually limiting in Myanmar diets, but protein and micronutrients often are. Thus, fish production from RF systems has the potential to greatly increase the availability of protein and micronutrients compared with monocropping of rice, notwithstanding the natural fish, particularly the small indigenous species, that may already be in the system before any fish culture systems.

In reality, this analysis is considerably more nuanced. The suitability maps can present a menu of options where, for example, in the most suitable areas high-value species may be selected for culture with the intention of selling to market as an exclusively profit-based intervention, whereas in less suitable areas local and or small indigenous species may be used (e.g. snakehead) that can be sourced locally and either kept for home consumption or sale or both. These options can address different needs, such as those more linked with nutrition and incomes.

Finally, although research in other countries has shown that the labour requirements are higher in integrated systems than for rice monoculture (Halwart and Gupta 2004; Ahmed and Garnett 2011), the increased demand for labour could potentially underpin a key aspect of Myanmar's agriculture development strategy target of slowing down rural outmigration by providing youth, who now migrate away from rural areas to look for jobs in urban areas, with a viable livelihood option.

Conclusions and ways ahead

In order to meet its commitments to global sustainable development goals and national socioeconomic development, Myanmar has endorsed several key strategic development and investment plans, in the water, agricultural and nutrition sectors. A key target is to double agricultural productivity and incomes in little more than 10 years. With the existing reliance on monocropping and the low economic returns for paddy rice cultivation, a shift in agrifood system production is increasingly being called for. Irrigated agriculture has a central role to play with a target of increasing arable land area under irrigation by 5% of total potential irrigation area, amounting to an increase of more than 0.5×10^6 ha. However, given the significant effects of irrigation expansion, specifically in terms of habitat fragmentation and river connectivity, and the resulting loss in ecosystem service provision, including effects on capture fisheries, a greater emphasis on mitigating impacts and thereby resolving conflicts will be of increasing importance. There is a significant opportunity for water planners and managers to create win–win solutions by incorporating integrated farming systems such as rice-cum-fish culture in the command area of water control infrastructure at the design phase. Although it is not suggested that these effects can simply be offset, the promotion of multiple-use irrigation infrastructure may serve to mitigate these effects by increasing water productivity per unit land area. Results from experimental trials demonstrate that by culturing fish in rice fields, rice productivity can be maintained by improved rice management practices and profitability can be almost doubled by the production of fish in the system. In addition to the increase in income per unit land area, significant benefits can also be realised through more environmentally friendly and nutrition-sensitive agriculture, with benefits to the environment and human nutrition through the more efficient use of resources, avoidance of pesticide use and increased diet diversity and nutritional security.

Myanmar has to take steps to create an enabling business and policy environmental, particularly with regard to making provision for shifting land uses from paddy to other agricultural uses to facilitate this shift, but the seeds of change appear to have been sown and, with wise use of water, Myanmar has a unique opportunity to support the well-being of a growing population and keep pace with its rapid social and environmental development.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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