Agronomic practices increase sunflower yield in the rabi (dry) season in clay-textured, salt-affected soils of the coastal region of Bangladesh

By

Priya Lal Chandra Paul

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Declaration

I declare that the thesis comprises results from my very own research work which has not previously been submitted for the awarded of any other degree or diploma in my name, in any university or other tertiary institution.

Priya Lal Chandra Paul

A note for style and formatting of the thesis

This thesis includes two published and two submitted papers, each of which is presented as a chapter. Regarding these cases, the formatting style follows the respective journal style.

Statement of contribution

In this thesis, the ideas for research themes, the implementation of field work, data collection and analysis, and writing up all the manuscripts were the principal responsibility of myself, the student, under the supervision of Professor Richard W Bell, Professor Edward G. Barrett-Lennard and Professor Md Enamul Kabir.

My contribution to the work and those of the co-authors were as follows:

Thesis chapter	Publication/ Chapter title	Status	Nature and % of student contribution	Nature and % of Co-author's contribution
Chapter 3	Variation in the yield of sunflower (Helianthus annuus L.) due to differing tillage systems is associated with variation in solute potential of the soil solution in a salt-affected coastal region of the Ganges Delta.	Published in Soil and Tillage Research. https://doi.org/10.1016/j.still.2019.104489	Concept, field works, data collection and analysis, prepare tables and figures and writing and compilation of the manuscript (80 %).	1. Richard W Bell: Assisted with the concept, supervised fieldwork, reviewing and editing the manuscript (10 %). 2.Edward G. Barrett-Lennard: Assisted with the concept, supervised fieldwork, reviewing and editing the manuscript (7 %). 3.Enamul Kabir: Supervised fieldwork (3%)
Chapter 4	Straw mulch and irrigation affect solute potential and sunflower yield in a heavy textured soil in the Ganges Delta.	Published in Agricultural and Water Management https://doi.org/10.1016/j.agwat.2020.106211	Concept, field works, data collection and analysis, prepare tables and figures and writing and compilation of the manuscript (80 %).	1. Richard W Bell: Assisted with the concept, supervised fieldwork, reviewing and editing the manuscript (10 %). 2.Edward G. Barrett-Lennard: Assisted with the concept, supervised fieldwork, reviewing and editing the manuscript (7 %) 3.Enamul Kabir: Supervised fieldwork (3 %)
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Student signature: Date: 05 May 2020

Priya Lal Chandra Paul

The undersigned hereby certify that the above statement correctly reflects the nature and extent of the student’s and co-author’s contributions to this work.

Signed: **Richard W Bell (Principal Supervisor)**	Date: 05 May 2020
Signed: **Edward G. Barrett-Lennard (Co-supervisor)**	Date: 05 May 2020
Signed: **Enamul Kabir (Co-supervisor)**	Date: 05 May 2020
Signed: **Donald S Gaydon**	Date: 05 May 2020

List of publications

1. **Paul,** P. L. C., Bell, R. W., Barrett-Lennard, E. G., and Kabir, E. 2020. Variation in the yield of sunflower (*Helianthus annuus* L.) due to differing tillage systems is associated with variation in solute potential of the soil solution in a salt-affected coastal region of the Ganges Delta. *Soil Tillage Res.*, 197**,** 104489. https://doi.org/10.1016/j.still.2019.104489. **(Chapter 3)**.

2. **Paul,** P. L. C., Bell, R. W., Barrett-Lennard, E. G., and Kabir, E. 2020.. Straw mulch and irrigation affect solute potential and sunflower yield in a heavy textured soil in the Ganges Delta. *Agric. Water Manage., 239, 106211*. https://doi.org/10.1016/j.agwat.2020.106211 **(Chapter 4)**.

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Conference abstracts during candidature

1. **Paul,** P. L. C., Bell, R. W., Barrett-Lennard, E. G., and Kabir, E. (2018). Establishment of Sunflower and Maize on wet soils in the salt-affected coastal region of Bangladesh.

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Oral presentation by Priya Lal Chandra Paul

2. **Paul,** P. L. C., Bell, R. W., Barrett-Lennard, E. G., and Kabir, E. (2019). Dynamics of soil water content and salinity in the Ganges Delta: effects of rice straw mulch.

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Abstract

Agriculture in the coastal zone of Bangladesh is threatened by a range of abiotic stresses, including salinity, waterlogging and drought. Rice is generally grown in the wet (kharif) season, but soils lie fallow in the dry (rabi) season. This thesis was framed around the opportunity to increase the intensity of cropping in this region by shortening the rice-growing phase in the kharif (by planting short-season rice varieties) so that high-value adapted crops can be grown in the rabi season. Prior to this research, the best methods for the timely establishment and management of rabi crops on the poorly structured clay soils were unknown. Common soil constraints and requirements during the rabi season in the coastal zone of Bangladesh include the need to: rapidly decompose the mass of rice straw from the end of the kharif season, sow as early as possible to maximise growing season duration while avoiding extreme waterlogging effects at the end of the (rice) kharif season, and then maintain soil moisture and high solute potentials in a drying salinity-prone soil environment. A range of field experiments was conducted in the three rabi cropping seasons of 2016-17, 2017-18 and 2018-19. The research was in four theme areas with experiments conducted in three of these themes over two consecutive years. Using sunflower as a model crop, rabi cropping was possible provided: (a) soils received appropriate tillage (theme 1), (b) soils had application of surface mulches to maintain high soil solute potentials (theme 2), and (c) crops were sown early in the rabi season, but after waterlogging had abated (theme 3). In experiments in theme 4, it was shown that mulches decreased soil resistance and cracking, and improved root growth.

Experiments examined in Theme 1 showed that intensive soil disturbance such as bed planting, double pass shallow tillage, and single pass shallow tillage maintained higher soil water content and soil solute potential in the surface soil (0-15 cm depth) than less disturbance soil such as zero tillage, narrow strip tillage and wide strip tillage. The highest yields (19 % and 10 % improvements in 2016-17 and 2017-18, respectively) were associated with the tillage

treatments involving greatest soil disturbance, the bed planting and double pass treatments in 2016-17, and the single pass shallow tillage treatment in 2017-18. The benefits of intensive soil disturbance were mostly due to increases in soil water content and increases in solute potential in surface soil layers, leading to higher water uptake by plants.

Experiments in Theme 2 found that rice straw mulches and irrigation increased soil water content, reduced soil salinity, and increased solute potentials. The substantially higher solute potential of the soil solution with the rice straw mulch at 0-7 and 7-15 cm (-644 and -588 kPa in 2017, and -649 and -558 kPa in 2018) than with no-mulch (-925 and -728 kPa in 2017, and -801 and -641 kPa in 2018) was associated with increased sunflower yield (26 % and 16 % in 2017 and 2018, respectively). The rice straw mulch also increased grain and biomass water productivity by 26-32 % in the first season and 16 % in the second season relative to the no-mulch treatment.

Experiments in Theme 3 showed that early sowing before 15 December was associated with larger heads, more seeds per head, heavier seed, and higher grain yields (3.5 – 4 t ha^{-1}) except in the second year when sowing on 25 November was affected by waterlogging because of heavy rainfall. Data collected across both seasons showed that early sowing before 15 December tended to have higher soil water content, lower soil salinity, and, therefore higher solute potential than later sowings. For late sowing after 15 December, the lower yield was also associated with higher temperatures. However, the main driver of yield determination was $EC_{1:5}$ and, to a lesser extent, to temperature in both years.

Experiments in Theme 4 demonstrated that rice straw mulch at 5 and 10 t ha^{-1} increased mean root dry weight, total root length, and root length density at 0-20 cm soil depth, but there was higher total root length at 60-80 cm with the no-mulch treatment. Rice straw mulch significantly reduced crack volume, cross-sectional area, crack length density, depth and width by 84-91 %, 63-69 %, 57-70 %, 42-52 %, and 42 %, respectively, relative to the no-mulch. With increased soil water content at 0-30 cm under the straw mulch, there was decreased average soil resistance by 77 %, 49 % and 28 % at 0-7, 7-15 and 15-30 cm depths, respectively, compared to the no-mulch. Overall, for wet-clay saline soil, soil and crop management treatments that enabled early sowing also enhanced the establishment and yield of sunflower due to increased soil water availability in the upper root zone, especially by increasing soil water solute potential. Increased soil water, in turn, decreased soil resistance and cracking. I conclude that early establishment leads to higher yield by enabling sunflower to escape soil surface dryness and salinity and heat stress in the later part of the growing season. Although sunflower is a promising rabi crop for Southern Bangladesh, only few farmers grow it due to a lack of proper agronomic practices to manage soil constraints. The current findings, therefore, would help to expand sunflower cultivation across the salt-affected coastal region of Bangladesh.

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List of Abbreviations

Agro-ecological zone	AEZ
Ammonium acetate	NH_4OAc
Analysis of variance	ANOVA
Approximately	~
Bed planting	BP
Bicarbonate	HCO_3
Bulk density	BD
Calcium chloride	$CaCl_2$
Calcium sulphate dehydrate	$CaSO_4 . 2H_2O$
Carbonate	CO_3^{2-}
Centimetre	cm
Centimoles per kilogram	cmol kg ^{1}
Change in soil water	ΔW
Crack cross-sectional area	$(\overline{X})$
Crack depth	D
Crack length per unit area	L_A
Crack volume	V_A
Crack width	W
Crop factor	K_c
Crop water requirement	ET_{crop}
Cubic metre	m^{-3}
Days after sowing	DAS
deciSiemens per metre	dS m^{-1}
Degree centigrade	^0C
Degree centigrade per year	^0C $year^{-1}$
Double pass shallow tillage	DP

Drainage	D
Dry weight	DW
Electrical conductivity of saturated paste extract	EC_e
Electrical conductivity of 1:5 soil water suspension	$EC_{1:5}$
Electrical conductivity of water	EC_w
Exchangeable sodium percentage	ESP
Fresh weight	FW
Germ per kilogram	g kg^{-1}
gram	g
Gram per cubic centimetre	gm cm^{-3}
Gravitational potential	φ_g
Greater than	>
Hectare	ha
Irrigation	I
Kilo newton	KN
Kilo pascal	kPa
Kilogram per hectare	Kg ha^{-1}
Kilo-gram per hectare per millimetre	kg ha^{-1} mm^{-1}
Kilometre	Km
Kilometre per square metre	Km^2
Least significance difference	LSD
Less than	<
Magnesium chloride	$MgCl_2$
Magnesium sulphate	$MgSO_4$
Manganese oxides	MnO_2
Maximum temperature	T_{max}
Matric Potential	Ψ_m
Mega pascal	MPa
Megagram per cubic metre	Mg m^{-3}
Metre	m
Milligram per kilogram	mg kg^{-1}
Milligram per litre	mg l^{-1}
Millilitre	mL
Millimetre	mm
Millimhos per centimetre	mhos cm^{-1}
Millimole per metre square per second	mmol m^{-2} s^{-1}
Millimoles per litre	mM
Million per hectare	Mha
Minimum temperature	T_{min}
Moderately saline	MS
Moderately tolerant	MT
Narrow strip tillage	NST
Newton per centimetre	N cm^{-2}
Nitrate	NO_3^-
Nitrite	NO_2^-
Nitrous oxides	N_2O
No-mulch	NM
Not significant	NS

Osmotic potential	Ψ_0
Pan coefficient	K_p
Pan evaporation	E_p
Percentage	%
Pressure potential	φ_p
Probability	*P*
Rainfall	P
Regression coefficient	r^2
Relative water content	RWC
Relative yield	Y_r
Residual sodium carbonate	RSC
Rice residue	RR
Rice straw	RS
Root dry weight	RDW
Root length density	RLD
Runoff	R
Sensitive	S
Single pass shallow tillage	SPST
Sodium adsorption ratio	SAR
Sodium chloride	NaCl
Soil water content	SWC
Solute potential	SP
Solute potential	Ψ_s
Specific root length	SRL
Square metre	m^2
Statistical Tools for Agricultural Research	STAR
Stomatal conductance	SC
Sulphate	SO_4^{2-}
Tolerant	T
Tonne per hectare	t ha^{-1}
Total cation concentration	TCC
Total dissolved salts	TDS
Total potential	Ψ_t
Total root length	TRL
Total water use	TWU
Turgid weight	TW
Versatile Multi-crop Planter	VMP
Water productivity	WP
Weight per weight	w/w
Wide strip tillage	WST
Zero tillage	ZT

List of Botanical Names

Sunflower	*Helianthus annus* L.
Maize	*Zea mays* L.
Mungbean	*Vigna radiata* L. R. Wilczek
Sesame	*Sesamum indicum*
Rice	*Oryza sativa L.*
Cotton	*Gossypium hirsutum L.*
Wheat	*Triticum aestivum* L.

Definition of Terms

A range of terms are used throughout this thesis. Their meanings are defined here.

In Bangladesh, there are two main growing seasons in which a range of crops are grown. These are broadly classified as:

1. **Khraif season:** Kharif crops are grown in the summer and harvested in the late summer or early winter (May to October).
2. **Rabi season**: Rabi crops are grown in winter and harvested in the spring or early summer (November to April).

Sometimes words are used to describe both the crop and season simultaneously. Included here are:

Boro: Boro refers to rice planted in the winter season in December/January and harvested in April/May.

Aus: Aus refers to rice planted from the pre-kharif season in March/April and harvested in July/August.

Aman: Aman refers to rice planted in the wet season in July/August and harvested in November/December.

Dibbling: Dibbling is a no-tillage technique used to sow non-rice seeds in wet soil (mostly saturated) without soil puddling. Seeds are dropped into open holes without subsequent soil covering.

Soil salinity: The concentration of dissolved salts present in the soil solution.

Solute potential: Solute potential is a component of total water potential. Solute potential decreases when the amount of solute increases in the soil solution. It is expressed as a negative value.

Waterlogging: Soil saturation after rainfall or irrigation is referred to here as waterlogging.

Inundation: Standing water after rainfall or irrigation is referred to here as inundation.

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Dedication

This dissertation is dedicated to my parents whose blessings have always been my strength

Chapter 1

General Introduction

1 General Introduction

1.1 Rationale

Among the agro-ecological zones of Bangladesh, the coastal region is the most fragile and least productive because of cyclones, storm surges, flooding, land erosion, soil and water salinity, and waterlogging. This area comprises ~32 % of the net cultivable land of Bangladesh (Mainuddin et al., 2013; PDO-ICZMP, 2006), and almost 1.1 Mha of cultivable land is compromised by different levels of soil salinity (SRDI, 2010). Topographically, the coastal area has an elevation ~2-3 metres above sea level (Khanom, 2016), and is connected with many rivers and canals; as a consequence, tidal flooding through these rivers and creeks inundates the soil increasing salinity in the soil, particularly during the dry season (Haque, 2006; Khan et al., 2015). In addition, both monsoon rain (~1,800 mm annually) and seawater surges delay flood water drainage, which results in prolonged waterlogging during maturation and after the harvest of rice. Large areas of land remain fallow in the dry season (January-May) because of poor drainage, lack of freshwater for irrigation, and soil salinity (Mondal et al., 2015a), and cropping intensity is much lower (below 150 %) than the country's average (Mainuddin et al., 2014).

Some studies have shown that there is ~700,000-800,000 ha of land underutilized during the dry season in Southern Bangladesh (Mainuddin et al., 2013; Schulthess et al., 2015). The land characteristics and hydrology of the coastal zone of Bangladesh can be divided into three categories depending on the degree of water salinity: low salinity (where water salinity (EC_w) is less than 1.0 dS m^{-1}); medium salinity (EC_w values vary 2 - 10 dS m^{-1}), and high salinity ($EC_w > 10$ dS m^{-1}) (Khan et al., 2015; Mondal et al., 2015a). Agricultural production is impeded by medium and high salinity levels depending on environmental and hydrological circumstances. The presence of substantial amounts of soluble salts in the root zone of the crops grown in these areas hinders plant growth and reduces yields (Mondal et al., 2001; Miah et al., 2004; Shrivastava and Kumar, 2015). In the dry season, the highest soil salinity (EC_e) varies from 5 to 12 dS m^{-1} at 0-15 cm, and pH level is 7.7-8.0, which indicates that soils are slightly alkaline (Mondal et al., 2001). Other research has reported that delta saline soils contain very low organic matter (1.2-2.7 %), and have widespread deficiencies of P and Zn, but the soils are rich in K (Saleque et al., 2010).

In the medium saline area of the south-west coastal zone in Bangladesh, farmers traditionally mostly grow low-yielding and long duration traditional rice varieties (‘aman’) in the wet season during July to December, which may be followed by a low input, low yielding rabi (dry season) crops such as sesame and mungbean in March to June (Mainuddin et al., 2014; Mondal et al., 2015a). The use of late-maturing traditional rice varieties and the lack of timely drainage together result in the late establishment of traditional rabi crops such as sesame and mungbean because the soil is too wet to cultivate until February. Late rabi crop establishment, in turn, results in crop damage or complete failure due to high salinity (in both the irrigation water and soil) and waterlogging from early kharif rains prior to harvest (Mondal et al., 2015a). The inability to achieve early crop establishment also prevents the cultivation of high yielding and high-value rabi crops such as maize, sunflower, mustard, and wheat. River water in this salt-affected region remains suitable for irrigation from July to January. Both water and soil salinity start to increase from February, and this continues up to May-June. However, freshwater for strategic irrigation for rabi crops can be stored in ponds and canals inside the polders prior to the river water becoming too saline.

There is strong potential to increase the diversity and productivity of rabi crops in this region if crops can be established in a timely manner to allow for the better use of residual soil water after the monsoon season, together with a couple of supplementary irrigations (Bell et al., 2019). Achieving this requires the growth of earlier maturing aman rice varieties and drainage shortly prior to rice harvest (if the lands are still flooded). Reduced tillage technologies could be applied to enable the early establishment of rabi crops into the moist soil as soon as possible after the rice harvest, and the use of surface mulch could help to conserve soil moisture and reduce salt accumulation on the surface. It is postulated here that minimum and reduced tillage, rice straw mulch, surface residue retention and novel cropping patterns offer considerable potential for the coastal zone that would help to enhance crop use of soil water with low salinity and avoid the most severe effects of soil salinity and soil cracking. However, suitable machinery is needed to assist in early crop establishment, together with appropriate agronomic management in combination with reduced tillage and mulching. The feasibility of the early establishment of high yielding and high-value rabi crops such as sunflower and maize into the moist soil by dibbling have been tested during the dry season on a small scale (Mondal et al., 2015a; Rahman et al., 2015). However, the impacts of zero tilled dibbling and mechanized crop establishment on soil profile water and salinity, osmotic potential of soil solutions, soil compaction and cracking, root growth and distribution have not previously been determined. Therefore, the present study was undertaken with sunflower to test the following hypotheses and objectives.

1.2 Underlying hypotheses

i) Establishing sunflower with zero tillage and dibbling will enable the early planting of rabi crops into wet soils; this will maximise access to stored residual non-saline soil water and facilitate escape from increasing salinity hazard later in the growing season, thereby increasing crop yield.

ii) Reducing soil disturbance (through the use of minimum and reduced tillage) will decrease soil dryness and salinity, improve soil physical properties, and therefore increase sunflower growth and yield.

iii) Application of a rice straw mulch (~ 5 t ha^{-1}) to the soil surface will increase surface soil water availability, reduce salt accumulation in the surface soil and rootzone and reduce soil cracking, thereby improving root growth and yield of sunflower.

These hypotheses were tested in a sequence of four field experiments, each conducted over two years except the fourth one.

1.3 Specific objectives

i) Determine the impacts of different tillage systems on sunflower establishment and yield, soil water availability and salinity **(Chapter -3)**

ii) Quantify the effects of rice straw mulch and minimum tillage on soil profile water and salinity dynamics, and sunflower productivity under soil water depletion **(Chapter-4)**

iii) Effects of early sowing of sunflower establishment and subsequent growth and yield **(Chapter-5).**

iv) Determine the impacts of different mulch levels and irrigation water regimes on soil compaction and cracking and sunflower root distribution, and yield **(Chapter-6).**

1.4 References

Bell, R., Mainuddin, M., Barrett-Lennard, E., Sarangi, S., Maniruzzaman, M., Brahmachari, K., Sarker, K., Burman, D., Gaydon, D., Kirby, J., Glover, M., Rashid, H., Sahidul, M., Khan, I., Kabir, M., Rahman, M., and Hossain, M. B. (2019). Cropping Systems Intensification in the Coastal Zone of the Ganges Delta: Opportunities and Risks. *J. Indian Soc. Coastal Agric. Res.* **37**, 153-161.

Haque, S. (2006). Salinity problems and crop production in coastal regions of Bangladesh. *Pak. J. Bot.* **38**, 1359-1365.

Khan, Z., Kamal, F., Khan, N., Khan, S., and Khan, M. (2015). Present surface water resources of the Ganges coastal zone in Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF,GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into

Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo. Sri-Lanka: CGIAR Challenge Program on Water and Food (CPWF).

Khanom, T. (2016). Effect of salinity on food security in the context of interior coast of Bangladesh. *Ocean Coast Manage.* **130**, 205-212.

Mainuddin, M., Kirby, M., Chowdhury, R., Sanjida, L., Sarker, M., and Shah-Newaz, S. (2014). Bangladesh integrated water resources assessment supplementary report: land use, crop production and irrigation demand. *CSIRO: Australia*.

Mainuddin, M., Rawson, H., Poulton, P., Ali, R., Roth, C., Islam, K., Saifuzzaman, M., Rahman, M., Quader, M., and Shah-Newaz, S. (2013). Scoping study to assess constraints and opportunities for future research into intensification of cropping systems in Southern Bangladesh. *ACIAR Report. Australia*.

Miah, M. Y., Mannan, M., Quddus, K., Mahmud, M., and Baida, T. (2004). Salinity on cultivable land and its effects on crops. *Pak. J. Biol. Sci.* **7**, 1322-1326.

Mondal, M., Paul, P., Humphreys, E., Tuong, T., Ritu, S., Rashid, M., Humphreys, E., Buisson, M., Pukinskis, I., and Phillips, M. (2015a). Opportunities for cropping system intensification in the coastal zone of Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF), 342-360.

Mondal, M. K., Bhuiyan, S. I., and Franco, D. T. (2001). Soil salinity reduction and prediction of salt dynamics in the coastal ricelands of Bangladesh. *Agric. Water Manage.* **47**, 9-23.

PDO-ICZMP (2006). Program development office for integrated Coastal zone management plan. Draft coastal development strategy, water resources planning organization, ministry of water resources Bangladesh.

Rahman, M., Amin, M., Mondal, M., and Humphreys, E. (2015). Rabi crop establishment methods for increasing land productivity in the coastal zone of Bangladesh. Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices Conference Proceedings. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF),504.

Saleque, M., Uddin, M., Salam, M., Ismail, A., and Haefele, S. (2010). 11 Soil Characteristics of Saline and Non-saline Deltas of Bangladesh. *Tropical Deltas and Coastal Zones*, 144.

Schulthess, U., Krupnik, T., Ahmed, Z., and McDonald, A. (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?In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo. SriLanka: CGIAR Challenge Program on Water and Food (CPWF). p542.

Shrivastava, P., and Kumar, R. (2015). Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi J. Biol. Sci.* **22**, 123-131.

SRDI (2010). Soil Resources Development Institute.“Saline soils of Bangladesh.” SRMAF project, Ministry of Agriculture, Govt. of Bangladesh. Dhaka: SFSDP-SRDI Publicationproject, Ministry of Agriculture, Govt. of Bangladesh. Dhaka: SFSDP-SRDI Publication.

Chapter 2

Review of Literature

2 Review of literature

2.1 Introduction

The coastal zone environment of Bangladesh is represented geographically by river deltas, mangrove swamps, salt marshes and estuaries, where tidal and riverine flooding and varying salinity levels affect agriculture and livelihoods. Many coastal zones around the globe are being impacted by reduced freshwater inflow from upstream, increased siltation, climate change and inappropriate planning and management. For example, in Bangladesh, extensive areas of land in the coastal zones are characterized by multiple problems such as waterlogging and flooding, various degrees of water and soil salinity, and poorly structured soils; these lead to unfavourable soil-water-plant relationships and growing threats to crop production. Recent studies have found that drainage congestion and salinity are the main constraints to the growth of crops during the dry season (Mondal et al., 2015b). However, local hydrology and climate, land types, natural disasters (cyclones and storm surges), and the limited knowledge of cropping and management options are also associated with low agriculture productivity. This literature review focuses on the local hydrology and climates in the Ganges coastal zone, scope and constraints for cropping system intensification, salt-affected soils and their classification, the effects of salt on soil properties, the effects of shallow water tables on salinization and what management options are available to grow crops in such adverse conditions. The review focusses on research gaps in how to achieve success early establishment of rabi season crops on wet soils with a shallow saline water table; this is seen as a key step to enabling sunflower to escape from soil surface dryness, salinity and heat stress in the latter part of the growing season

2.2 Geography and climates in the Ganges coastal zone

2.2.1 Geography

The Ganges delta, the largest river delta in the world (www.scienceclarified.com/landforms/Basins-to-Dunes/Delta.html#b), is situated mostly in Bangladesh but also spreads into India. The floodplain of the Ganges delta is influenced by three great rivers: the Ganges, Brahmaputra and Meghna, which discharge (annual runoff of 1200-1500 billion m^{-3}) into the Bay of Bengal (Khan et al., 2015; van der Most, 2009). The total area of the Ganges river basin is ~ 09 Mha, which covers parts of Bangladesh, India, Nepal, and Tibet (Murshed et al., 2019). The coastal zone of Bangladesh can be categorized into three distinct areas: the western, central, and eastern areas, which cover ~27,150 km^2, 12,040 km^2, and 8010 km^2, respectively (Ahmed et al., 2018) (Fig. 2.1). Based on exposure to the Bay of Bengal, the coastal area can also be divided into the interior and exterior coastal zones (PDO-ICZMP, 2006). Agricultural land in the Ganges delta is generally protected by earthen embankments called polders (Bell et al., 2019). In the late 1960s and early 1970s, 139 polders were built to protect agricultural land and livelihoods from tidal inundation and seawater intrusion (Khan et al., 2015). Fig. 2.2 shows a typical polder view in the coastal zone of Bangladesh.

Fig. 2.1. Coastal zone of Bangladesh showing western, central and eastern (Source: Ahmed et al., 2018)

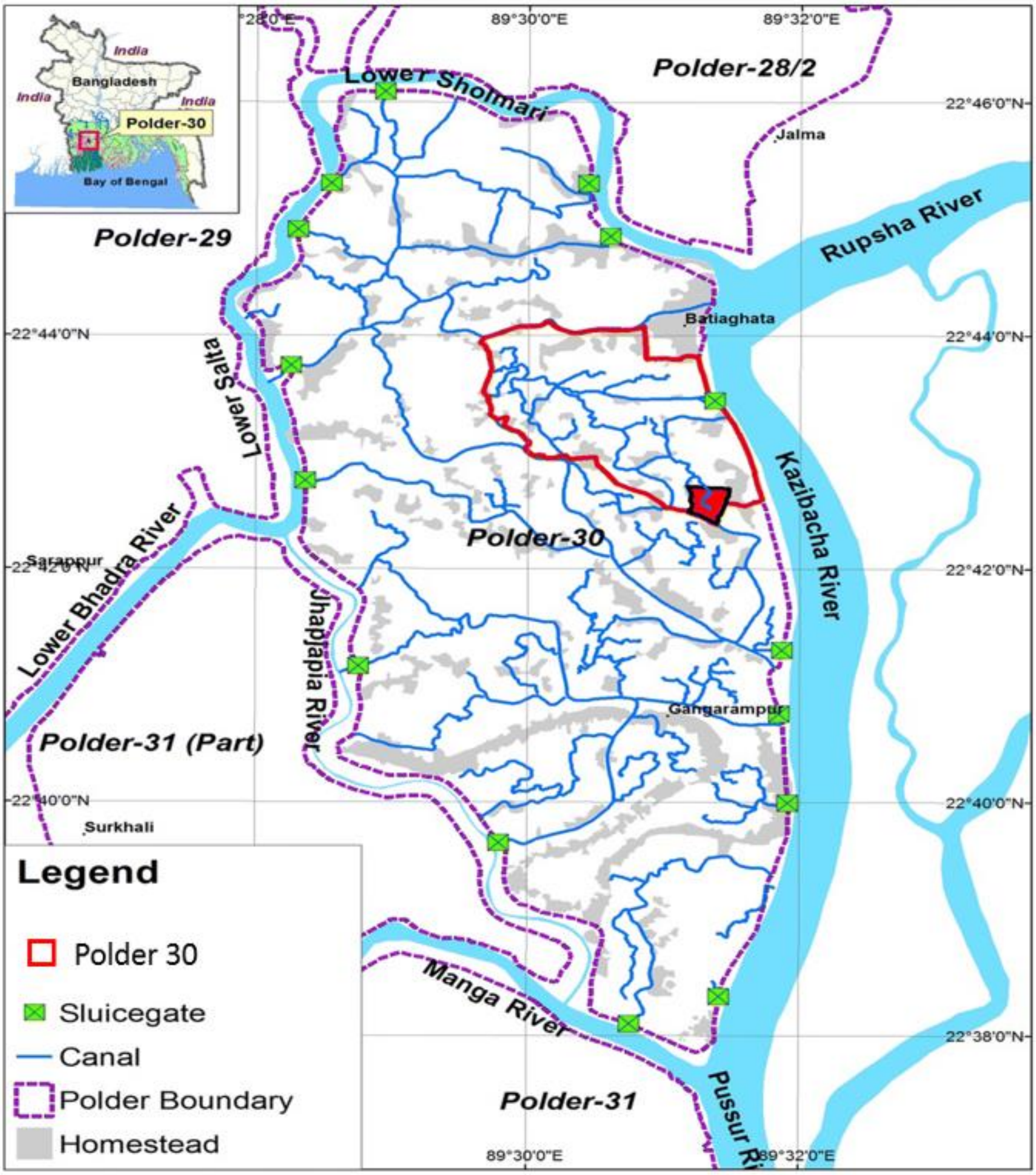

Fig. 2.2. Plan view of a typical polder in the coastal zone of Bangladesh (Yadav et al., 2019)

Polders are generally surrounded by river water, which may vary from fresh in the upper zone (Northern coastal zone) to saline in a lower zone (close to the Bay of Bengal) (Mainuddin et al., 2019). The water and soil salinity within low-lying polders show both seasonal and spatial variation. Salinity remains low during the monsoon season (July-November) and high in the dry season (December-June). The surface water salinity in the south-east is very low < 1 dS m^{-1}, but in the south-west region, it exceeds 4 dS m^{-1} in January, reaching a maximum of about 20 dS m^{-1} in May. Fig. 2.3 shows the variation in the EC_w of river water at a typical location in the area (Mondal et al., 2015a). This area has an elevation of ~2-3 m above sea level and has a shallow groundwater table. Groundwater salinity in this area varies with aquifer depth. The shallow aquifer (~30-50 m deep) has EC_w values ranging from 2.5 to 3.5 dS m^{-1} in March to May, while the deeper aquifer (~150 m deep) has EC_w values greater than 4 dS m^{-1} (Bell et al., 2019).

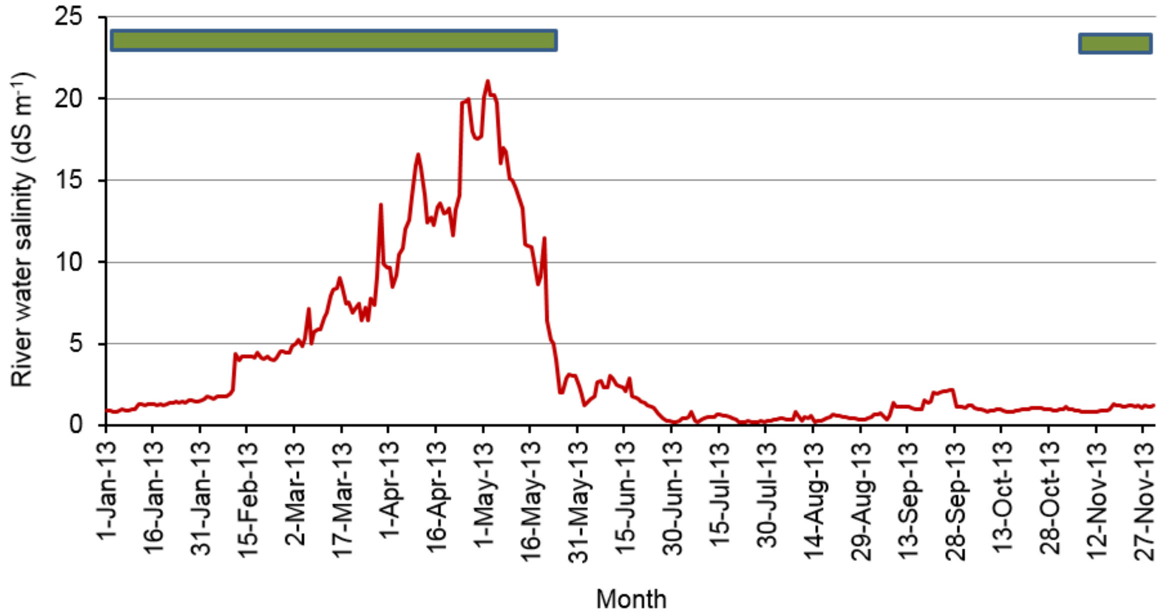

Fig. 2.3. River water salinity in Batiaghata, Khulna Bangladesh (Mondal et al., 2015a). The green bars indicate the duration of the rabi season in Bangladesh.

2.2.2 Climate

This area has a subtropical monsoonal climate. The annual rainfall is ~1,800 mm, and ~ 80 % of this occurs in the monsoon season (July to October). Although conditions are generally more humid with higher temperatures in the summer (March-June) and drier with cooler temperatures in the winter (December-February), long-term weather data also show significant variation across the coastal zone (Yu et al., 2019). There is a decreasing trend in rainfall from east to west in the western and south coastal regions, and from north to south in the north-east region. More than 200 mm rainfall (monthly average) occurred in May to October, and the amount was always higher in the east (e.g., Patuakhali) than that in the west (e.g., Khulna) (Fig. 2.4). Since the 1960s, maximum rainfall over a 5-day period has been increasing (Yu et al., 2019). This rainfall is beneficial for overall crop production (Bell et al., 2019) as heavy rainfall in the monsoon season dilutes and washes out the available salt in the soil, decreases water salinity (less than 1.0 dS m^{-1}), and improves the favourability of the wet season for rice cultivation. In the dry season, increased rainfall is useful to crop production by mitigating salt and drought stress. However, recent studies have shown that a few heavy events of rain often occur in the dry season (November to April), which can interfere with early crop establishment or cause crop damage (Bell et al., 2019). In November, there can be > 20 mm rainfall events in 50 % of years and > 50 mm in 25 % of years, but in December and January, rainfall > 20 mm is unlikely. Similarly, the probability of heavy rainfall may increase by 25-65 % and 5-30 % for > 20 mm and > 50 mm events, respectively, from February to April. These heavy rainfall events in the dry season can create waterlogging, which interacts with salinity in the root-zone to jeopardise crop growth and survival (Barrett-Lennard, 2003).

The temperature in the coastal zone has shown an increasing trend over the last 40 years (0.04 ^{0}C $year^{-1}$) (Yu et al., 2019), although the west region tends to be warmer than the east (Mondal et al., 2015a). Long-term temperature data showed that the maximum and minimum temperature in the west region (e.g., Khulna) varied from 25 and 35 ^{0}C and 12 and 26 ^{0}C, respectively, and in the east region (e.g., Patuakhali) varied from 25 and 33 ^{0}C and 13 and 26 ^{0}C, respectively (Fig. 2.5).

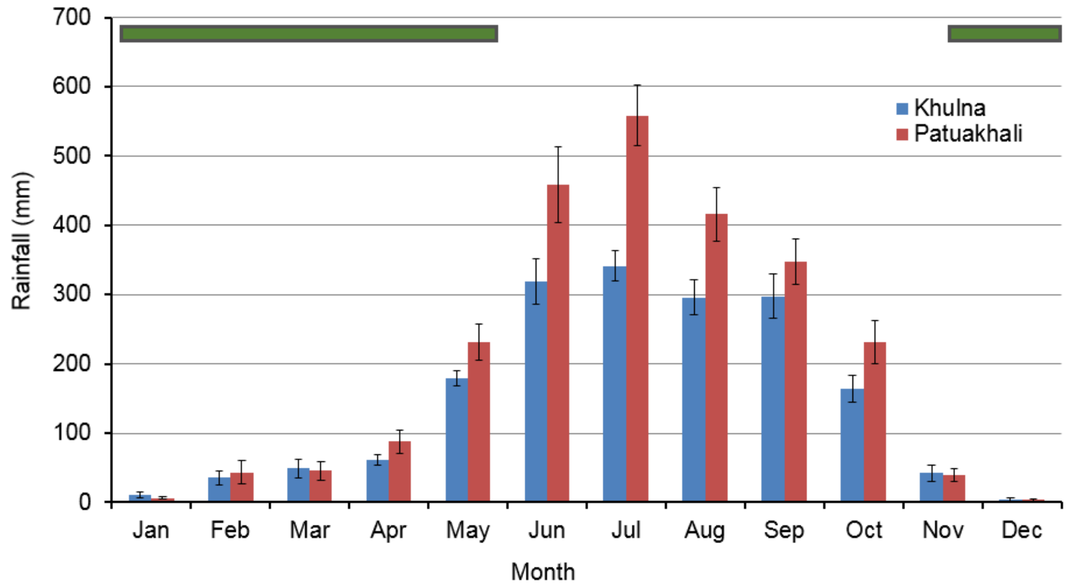

Fig. 2.4. Monthly average rainfall (1985-2010) of Khulna (in the west) and Patuakhali (in the east) in Bangladesh. Error bars indicate the standard error of 26 monthly values (Mondal et al., 2015a). The green bars indicate the duration of the rabi season in Bangladesh.

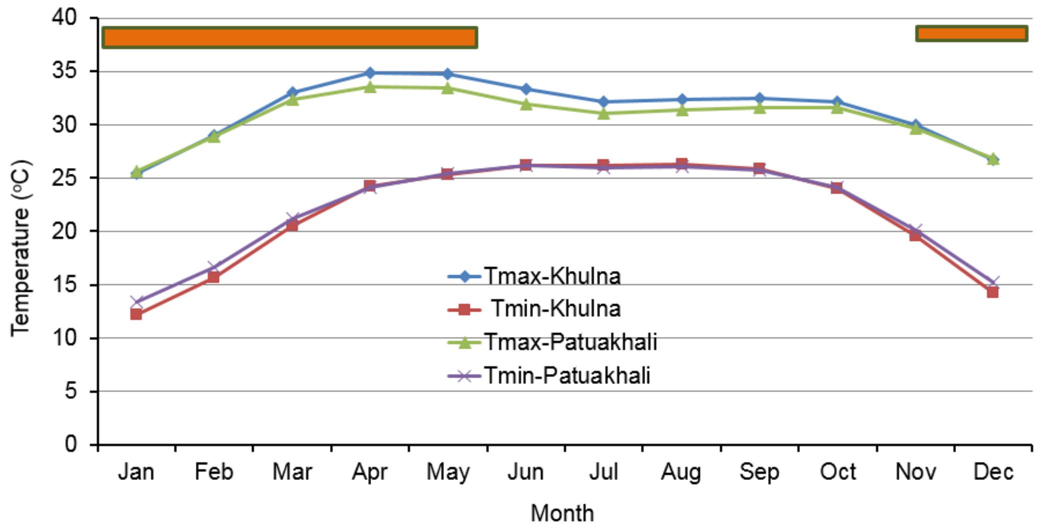

Fig. 2.5. Monthly average maximum and minimum temperature (1985-2010) of Khulna (in the west) and Patuakhali (in the east) in Bangladesh (Mondal et al., 2015a). Orange bars indicate the duration of the rabi season in Bangladesh.

2.3 Existing cropping systems and scope for cropping system intensification

In the Ganges coastal zone, farmers mostly grow long duration low yielding traditional wet (kharif) season rice from July/August to December/January, which gives a typical yield of ~2.0-2.5 t ha^{-1} (Mainuddin et al., 2019; Mondal et al., 2015a). A few farmers grow non-rice crops, such as sesame and mungbean in the dry (rabi) season (Nov-April), but these are often damaged by salinity and drought due to a lack of freshwater irrigation and waterlogging by post and pre-monsoon rain. Although there has been a substantial increase in the number of improved rice and non-rice varieties (short to medium duration and stress-tolerant) released over the decades, farmers are still reluctant to use these varieties due to their lack of knowledge and appropriate technologies to reduce the risk of changing their cropping practices. Increase cropping system intensification is possible if short to medium duration high yielding rice can be established early in the wet season (July). The early planting of modern rice would allow 15-30 days advance in harvesting (November), which could open up options for early establishment of high-value rabi crops in the dry season, and facilitate avoidance of salinity, drought and waterlogging stress during the growing season. Fig.2.6 shows the scope for dry season crop establishment on the one hand and constraints for the implementation of this on the other. Research is necessary to develop agronomic management technologies to overcome these constraints and improve the crop productivity of coastal zones. The following sections of the review focus on the constraints and research gaps that are relevant to cropping systems intensification in the Ganges delta coastal zone.

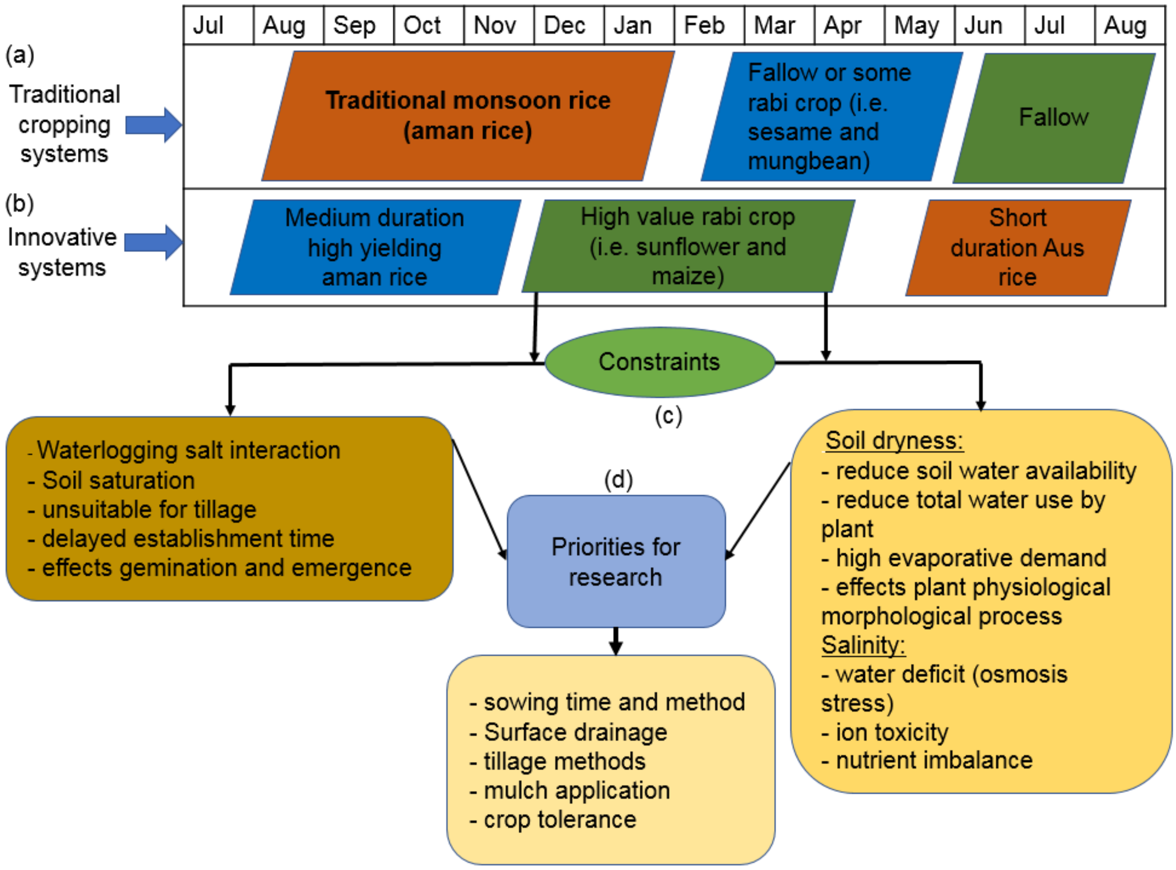

Fig. 2.6. Proposed conceptual diagram of opportunities for dry season crop establishment in the coastal -zone of Bangladesh showing: (a) the calendar for traditional cropping systems, (b) the proposed calendar for the new innovative cropping systems, (c) the constraints likely to impact on the adoption of the new cropping systems, and (d) the priorities for research.

2.4 Abiotic constraints for rabi crop establishment

2.4.1 Waterlogging

Large areas of land in the coastal zones are flooded due to combined effects of monsoon rainfall and tidal influence, which lead to prolonged waterlogging (saturation of the soil) and water stagnation because of siltation in the river, low infiltration, shallow water tables and poorly structured soils (Ghassemi et al., 1995; Ismail and Tuong, 2009). About one and three million ha of land are annually affected by waterlogging in Bangladesh and India, respectively (Ismail and Tuong, 2009). In the coastal zone of Bangladesh, waterlogging is a soil condition which is specifically selected for by farmers, and it is even enhanced in the wet (kharif) season through soil management practices (puddling). This is done to preserve irrigation water, enhance rice production, and reduce the impacts of weeds. The side effect is that during the dry (rabi) season the waterlogging, which naturally occurs in these soils, can be severely detrimental to any attempted dryland crop production. Due to the tendency to waterlogging, many of these areas are therefore left fallow during the dry season. Waterlogging of soils is important abiotic stress that affects plant growth and productivity (Jackson and Colmer, 2005). One of the major concerns of waterlogged soil is element (Mn, Fe, Na, Al and B) toxicities, which cause damage to the plant shoots (Ponnamperuma FN, 1984; Setter et al., 2009). Waterlogged soils develop hypoxia (low concentration of oxygen) due to the low solubility of oxygen in water (0.28 mol m^{-3} at 20 ^{0}C) (Qureshi and Barrett-Lennard, 1998), low diffusivity rates of oxygen in water-filled pores (Grable, 1966), and the rapid depletion of dissolved oxygen by the respiration of soil bacteria and plant roots (Armstrong and Drew, 2002). In the absence of oxygen, many elements, including plant nutrients in soils, can be chemically reduced by micro-organisms. At successively lower redox potentials, nitrate (NO_3^-) is reduced to nitrite (NO_2^-), nitrous oxide (N_2O) and nitrogen gas (N_2), in the process, referred to as denitrification. Other electron acceptors are manganese oxides (MnO_2) and iron (Fe^+), which are reduced to Mn^{2+} and Fe^{2+}, respectively, and may accumulate to toxic concentrations with prolonged waterlogging (George et al., 2012).

Many winter crops such as vegetables, pulses, and oilseed species cannot adapt to prolonged waterlogging and consequently suffer from plant cell injury over this period because oxygen deficiency strongly restricts ion uptake by roots and ion transport to the shoot. Wilting, chlorosis and leaf senescence are common plant symptoms in flooded soils (Drew, 1990). Numerous studies found that waterlogging reduced plant height, plant density, and yield (Dickin and Wright, 2008; Jiang et al., 2008; Stieger and Feller, 1994). However, the overall effects of waterlogging on crop growth and yield depend on waterlogging duration and stage of crop development.

Studies showed that waterlogging under saline conditions can have more damaging impacts on crop growth and yield than waterlogging alone (Singh, 2015). Barrett-Lennard (2003) reviewed the interaction between hypoxia and salinity in relation to ion movement, growth, and survival status of plants. He showed that plant growth is hindered by the combined effect of waterlogging and salinity because of increased Na^+ and Cl^- concentrations in the shoot. Another study has reported that the combined impact of waterlogging and salinity decreased wheat yield because of reducing grain weight and spike length (Saqib et al., 2004). A combination of flooding and salinity is substantially more harmful to bald-cypress seedlings than the effect of either single stress (Allen et al., 1996; Conner, 1994). When the plant roots are in waterlogged conditions and suffer from oxygen deficiency, tolerance mechanisms to adapt to this stress include developing aerenchyma in the root cortex, shoot elongation and the creation of adventitious roots (George et al., 2012). In addition, plant roots under submergence situations release ethylene into the soil, which has a positive effect on root growth and plant morphology. Research suggests that an increase in ethylene concentration in the root tissue can enhance aerenchyma formation through cell wall separation or cell wall collapse in the cortex, which can help to facilitate oxygen movement from shoots to roots (George et al., 2012).

2.4.2 Salinity

2.4.2.1 Salt affected soils and constraints

Salinity of agricultural land is a serious issue for crop production in many parts of the world. The majority of tropical coastal zone soils are affected by different degrees of salinity occurring together with other abiotic stresses such as alkalinity, acidity, high organic matter content in peat soils and nutrient imbalance, which cause low agricultural productivity in these areas (Ismail and Tuong, 2009). The main causes of salt build-up in soils are the intrusion of seawater or brackish water flow, the use of saline irrigation water, the accumulation of salts at the soil surface through capillary rise from shallow groundwater, poor drainage, and changing climate (Michael, 1978). Fig. 2.7 shows the process of salinization through seawater intrusion.

Rengasamy (2006) identified three major processes that cause saline land in the world. These are: (i) groundwater associated salinity, (ii) non-groundwater associated salinity, and (iii) irrigation water associated salinity (Fig. 2.8).

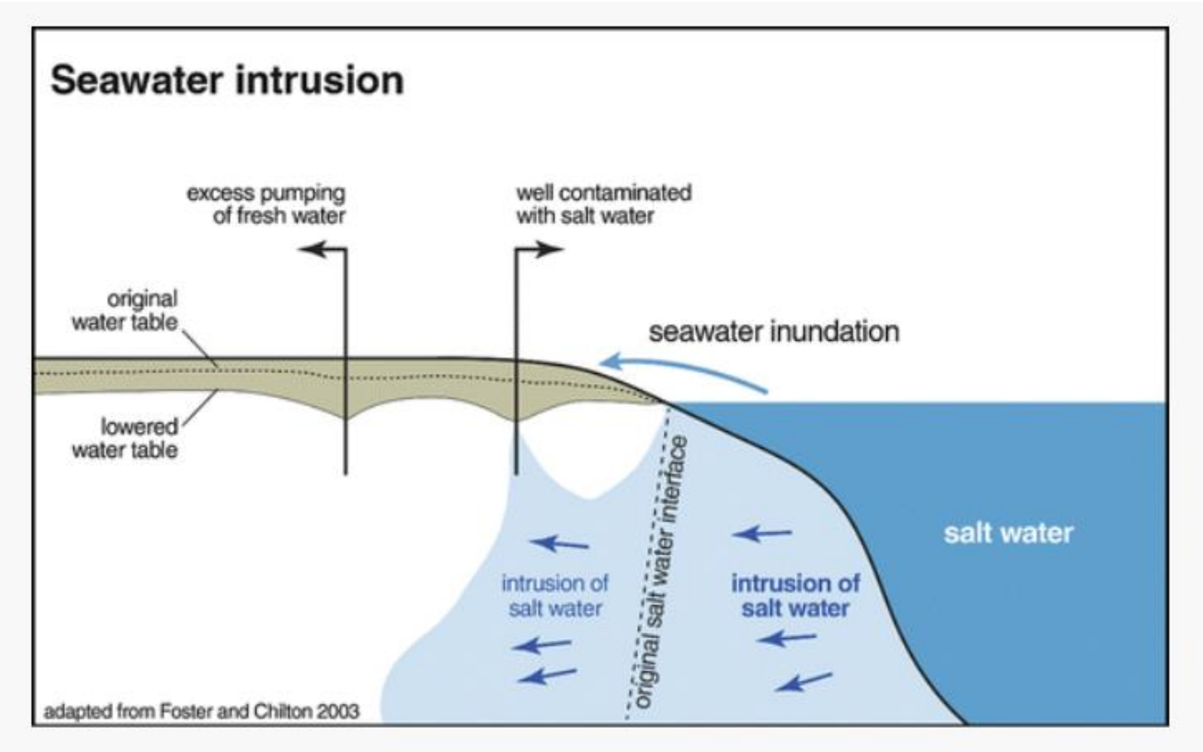

Fig. 2.7. Salinization of coastal soil and aquifers due to saltwater intrusion from the sea (Greene et al., 2016)

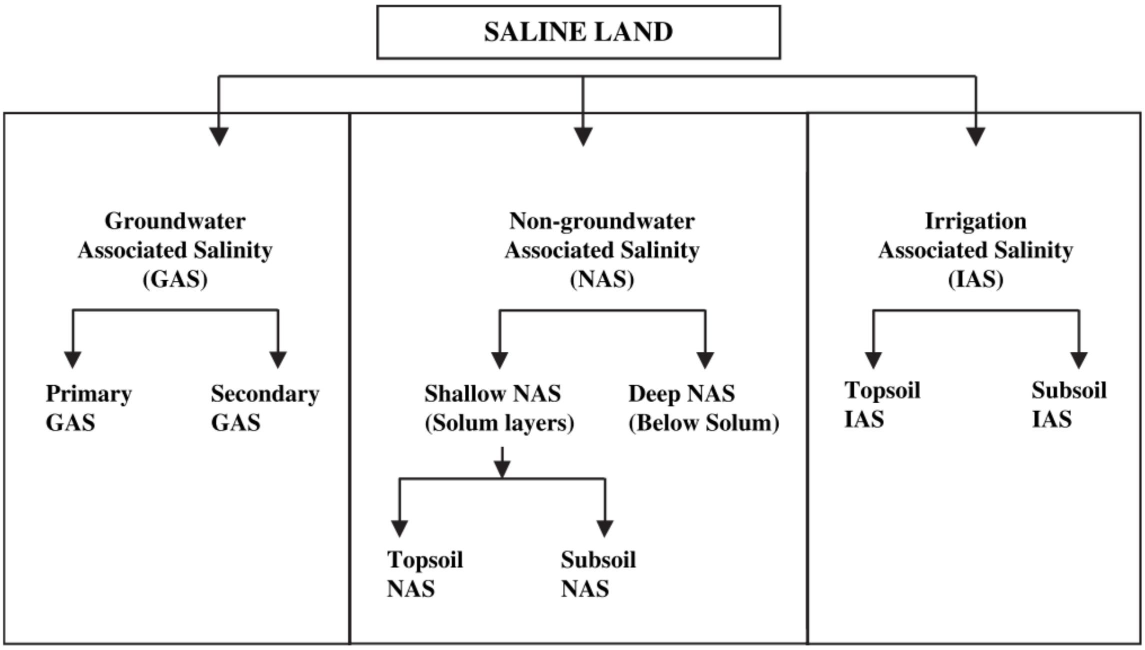

Fig. 2.8. Major types of salinity in world soils based on salinization processes (Rengasamy, 2006)

2.4.2.2 Salinity hazard

Salinity causes high concentrations of soluble salts (soil salinization) in irrigation water or soil that accumulates in the crop root zone and causes yield reduction (George et al., 2012). The main cations in salt-affected soils are Na^+, Ca^+, and Mg^+. The main anions are Cl^-, SO_4^{2-}, and HCO_3^-, CO_3^{2-} particularly at a higher level of pH (Wallender and Tanji, 2011). Plant growth in salt-affected soils is hindered for the three main reasons: water deficit (osmosis stress); ion toxicity (excessive uptake mainly Na^+ and Cl^+); and nutrient imbalance in the internal mechanism of plants (Munns and Tester, 2008; Parihar et al., 2015). Plant response to salinity and their adaption mechanism is shown in Fig. 2.9. The dynamics of soluble salts in the soil water are influenced by, on the one hand, root water extraction by plants for transpiration and water, which evaporates from the soil surface, and on the other hand, soil water replenishment by irrigation and rainfall. However, the soluble salts move freely in the soil profile because of chemical dispersion and ion mobility (Wallender and Tanji, 1990). When the upward movement of salt in the soil water through the capillary rise and evaporation exceeds the downward movement by leaching (irrigation or rainfall), then the salt will accumulate in the root zone. Fig. 2.10 shows the typical soil processes leading to salt accumulation in the root zones (Rengasamy, 2006).

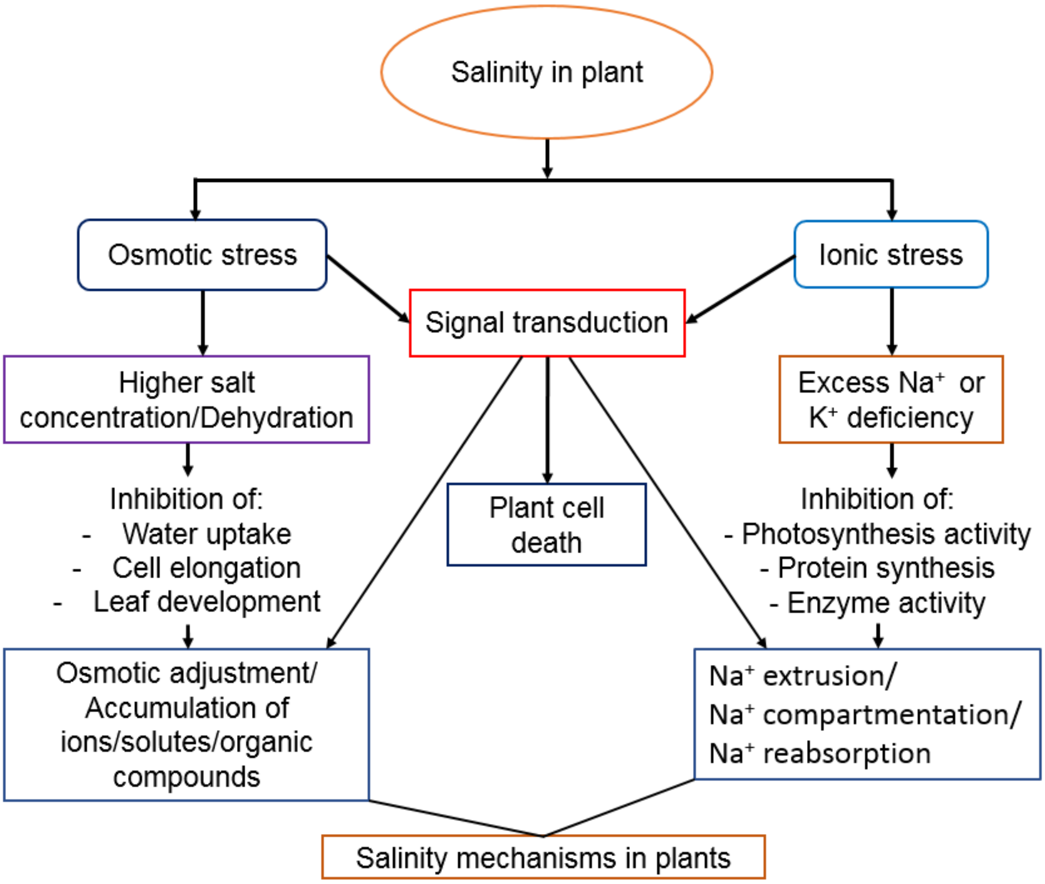

Fig. 2.9. Plant response to salinity effects and adaptation processes. Extracted from Munns and Tester (2008) and Zhu (2002).

The simplest way to measure the total concentration of dissolved salts in irrigation water or soil solution is by the determination of electrical conductivity (EC) (Richards, 1954). Measuring EC is a convenient method for estimating total soluble salts, and it has been widely accepted to analyse water quality with regards to salinity hazard (Wallender and Tanji, 1990).

According to Richards (1954), the EC of a salt solution increases at the rate of around 2 percent for each degree centigrade increases in temperature, and EC values are always expressed at a standard temperature of 25 degree centigrade. For the purposes of this thesis, the standard unit of EC is deciSiemens per meter (dS m^{-1}), with seawater having an EC of ~55 dS m^{-1}. With respect to other units: 1 dS m^{-1} is equal to 1 milliSiemens cm^{-1} or 1 mmhos cm^{-1} (Wallender et al., 2011).

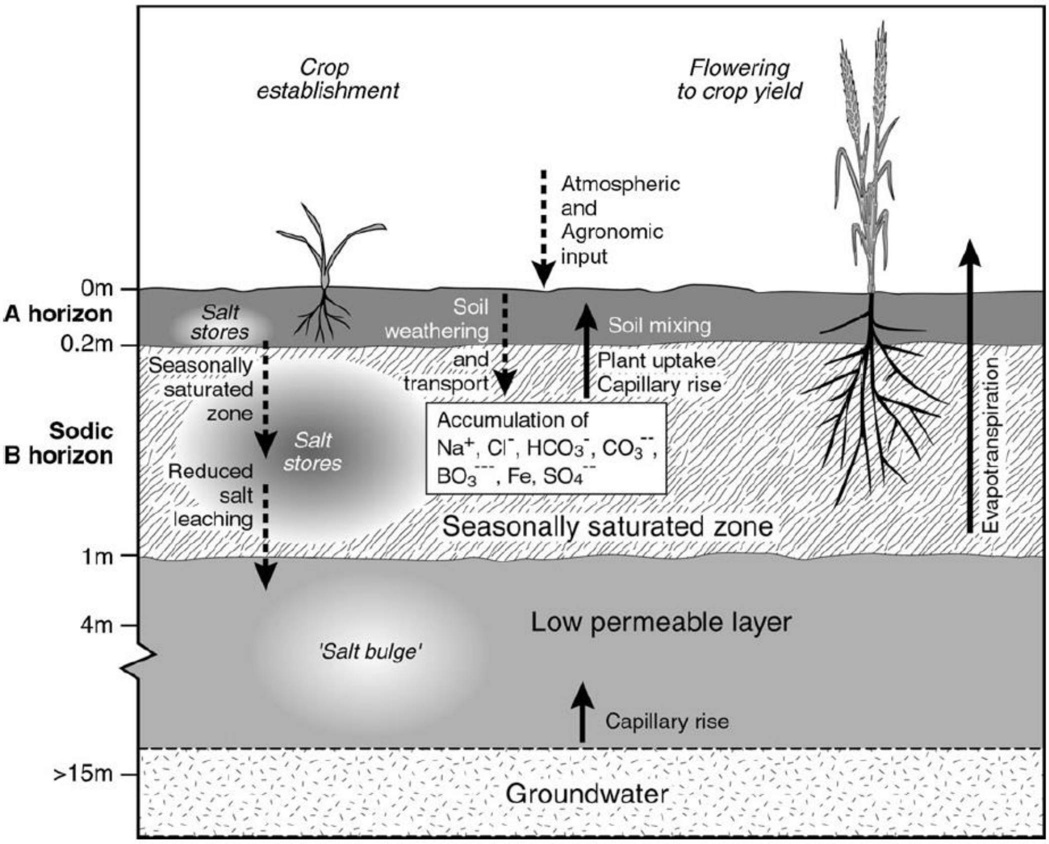

Fig. 2.10. Soil processes and salt accumulation in the root zone layers (source:(Rengasamy, 2006)).

The electrical conductivity of soil saturated extracts (EC_e) is widely used to measure the concentration of salts in the soil solutions. However, this method is tedious when there are lots of samples taken. The electrical conductivity of a 1: 5 soil: water suspension is a faster method to measure the concentration of salt. Many conversion factors are used for converting $EC_{1:5}$ to

EC_e. Based on different soil texture and saturation percentage, Slavich and Petterson (1993) proposed the conversion factors in Table 2.1 for converting $EC_{1:5}$ values to EC_e values.

Table 2.1. Conversion factors to estimate EC_e from $EC_{1:5}$ and saturated paste water contents (Θ_{SP}) for soils of different texture grade classed by clay percentage (Slavich and Petterson, 1993)

Texture class	Clay (%)	Θ_{SP} range (kg kg^{-1})	Range of conversion factor	Mid-range of conversion factor
Sand, Loamy sand, Clayey sand	<10	<0.2	>17.6	22.7
Sandy loam, Fine sandy loam, Light sandy clay loam	10-20	0.2-0.41	17.6-9.9	13.8
Loam, Loam fine sandy, Silt loam, Sandy clay loam	20-30	0.41-0.46	9.9-9.0	9.5
Clay loam, Silty clay loam, Fine sandy clay loam, Sandy clay, Silty clay, Light clay, Light medium clay	30-45	0.46-0.53	9.0-8.2	8.6
Medium clay	45-55	0.53-0.72	8.2-6.7	7.5
Heavy clay	>55	>0.72	<6.7	5.8

2.4.2.3 Sodicity hazard

Sodicity problems occur in soil when soluble salts are leached out of the soil, but exchangeable sodium (Na^+) is retained on soil cation exchange sites (Rengasamy, 2002). An excessive proportion of Na^+ in soil relative to calcium and magnesium cause soil swelling and dispersion when soils are wet, which may result in soil structural collapse (George et al., 2012; Horneck et al., 2007). Dispersion of sodic soil during rain or irrigation disintegrates the aggregates and clogs the soil pore space, which leads to reduced air and water movement within the soil (Rengasamy and Olsson, 1991). The restricted water movement in sodic soils promotes waterlogging. Poor structural stability of sodic soil means that there is a narrow range between soil being too wet or too dry (Brady et al., 2008).

There are two common methods of measuring sodicity. Firstly, sodium adsorption ratio (SAR) describes the concentration of the Na^+ relative to the calcium and magnesium ions in the soil water extract, as follows (Richards, 1954):

$$SAR = Na^+ / \sqrt{(Ca^{2+} + Mg^{2+})},$$

Where the values of Na, Ca, and Mg are the concentrations of sodium, calcium, and magnesium ions in milliequivalents per litre.

Secondly, the exchangeable sodium percentage (ESP) can be used for measuring sodicity. ESP is measured by the ratio of the amount of exchangeable Na^+ to the sum of all exchangeable cations or effective cation exchange capacity (CEC) (Abrol et al., 1988):

$$ESP = (\text{Exchangeable } Na^+ / CEC_{eff}) \times 100$$

Where CEC_{eff} is the sum of exchangeable Ca^{2+}, Mg^{2+}, K^+, and Na^+.

Measuring ESP is tedious and time-consuming and subject to errors. SAR is more widely used than ESP because of its easier measurement. However, ESP can be calculated from SAR by the following equation (Richards, 1954).

$$ESP = 1.475\,(SAR)/(1 + 1.0147\,SAR)$$

2.5 Classification of salt-affected soil

A soil is considered saline (saline soil) if the ECe is over 4 dSm^{-1} at 25 ^0C, and ESP is less than 15 and SAR <13-15 (Richards, 1954). Most plant species are adversely affected when EC_e is greater than 4 dS m^{-1} (George et al., 2012). However, many factors such as soil texture, water content and formation of salts, climatic conditions and groundwater table can influence soil salinization. On the other hand, non-saline alkali or sodic soils are those which ESP above 15 and EC_e is less than 4 dS m^{-1} at 25 ^{0}C and SAR > 13-15 (Brady, 1990). Though the soluble salts in non-saline alkali or sodic soil are relatively low, the composition of these soils is different from saline and normal soils (Richards, 1954). The common anions of these soils are mainly chloride, sulphate, bicarbonate with smaller amounts of carbonate. Plant growth in this soil is interfered with mostly by a high level of pH and bicarbonate. Another soil type is saline-alkali, or saline-sodic soils that have EC_e above 4 dS $m^{-1,}$ and their ESP is greater than 15 with SAR > 13-15 (Richards, 1954). These types of soils can be formed by both salinization and alkalization. Horneck et al. (2007) summarized the properties of the salt-affected soils, including their soil physical condition using the criteria in Table 2.2.

Rengasamy (2010) categorized the salt-affected soil (saline, sodic and saline-sodic) based on the possible effects of salts on plants and soil properties (Fig. 2.11). He also mentioned that the presence of different ions in the soil solution determines whether toxicity, deficiency or ion-imbalance due to other elements (e.g., B, K, N, P) also impede plant growth on salt-affected soils.

Table 2.2. Classification of salt-affected soil based on soil conditions (Horneck et al., 2007).

Salt affected soil classification	Electrical conductivity of saturation pest extract (EC_e)	Sodium absorption ratio (SAR)	Exchangeable sodium percentage (ESP)	Typical soil physical condition (Soil structure)
None	< 4	< 13	< 15	Flocculated
Saline	> 4	< 13	< 15	Flocculated
Sodic	< 4	> 13	> 15	Dispersed
Saline-sodic	> 4	> 13	> 15	flocculated

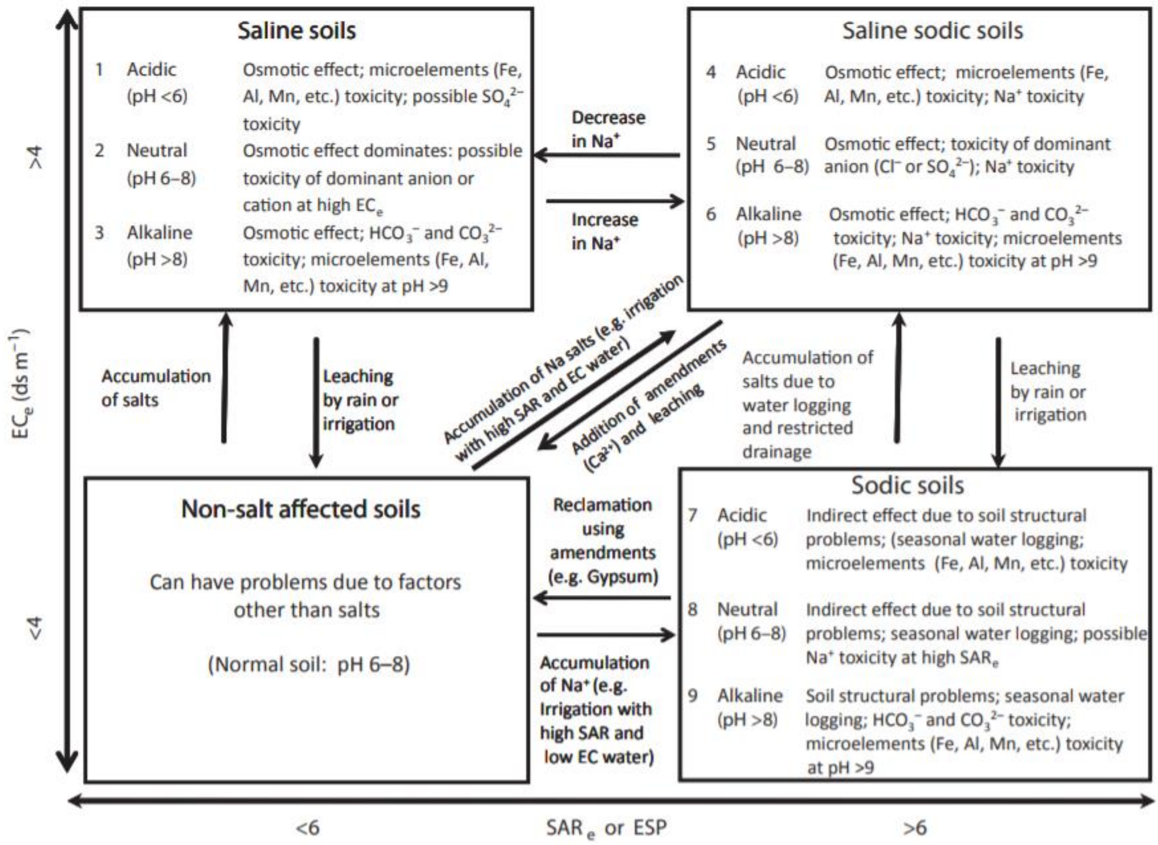

Fig. 2.11. Categories of salt-affected soils based on sodium adsorption ratio (SARe) and electrical conductivity (EC_e) measured in soil saturation extract and pH1:5 measured in soil water suspension and possible mechanisms of impact on plants; source (Rengasamy, 2010).

Abrol et al. (1988) highlighted that plant responses to salt stress differ widely, and the rating of salt tolerance of plants is determined by the yield loss in saline soil when compared with yields on the non-saline soils. They proposed the soil salinity classes based on EC_e values and crop response in Table 2.3.

Table 2.3. Soil salinity classes and crop growth (Abrol et al., 1988).

Soil salinity class	Electrical conductivity of the saturation extract (dS m^{-1})	Effect on crop plants
Non-saline	0-2	Salinity effects negligible
Slightly saline	2-4	Yields of sensitive crops may be restricted
Moderately saline	4-8	Yields of many crops are restricted
Strongly saline	8-16	Only tolerant crops yield satisfactory
Very strongly saline	> 16	Only a few very tolerant crops yield satisfactory

2.6 Effects of salts on soil properties

Irrigation water can improve or damage soil properties as irrigation water always contains a certain quantity of dissolved salts. However, the effects depend on the type and amount of salts and their management, soil texture, and hydrology (Warrence et al., 2002). Both concentrations of soluble salts and exchangeable cations of soils can affect soil properties simultaneously. For example, an excess of exchangeable Na affects the soil physical properties more than the chemical properties (Mondal, 1997). As discussed above, an increase of ESP causes the swelling and dispersion of clay particles, which results in clogging of soil pores, a reduction in soil permeability, reduced hydraulic conductivity and surface crusting (Frenkel et al., 1978; Pearson and Bauder, 2006; Rowell et al., 1969). Occasionally, a high level of salt concentration in the soil solution can have a flocculating effect on soil, which enhances clay particle aggregation (Warrence et al., 2002). The benefits of soil aggregation are more permeability, higher infiltration, better soil aeration, root penetration and growth (Hanson et al., 1999; McNeal, 1968). Soil flocculation is usually enhanced when the salinity of soil solutions was greater than 1.5 dS $m^{-1,}$ or irrigation water salinity was more than 0.5 dS m^{-1} (Hanson et al., 1999).

2.6.1 Bulk density

Bulk density can be defined as the weight of dry soil per unit of volume (both solids and pores) and is generally expressed in Mg cm^{-3} or g cm^{-3}. It is an important soil physical property that is related to the water holding capacity of the soil, plant nutrient availability, and soil microorganism activity. Higher sodium percentage in a soil solution can decrease soil structural stability, which causes the loss of macroporosity, and increases bulk density (Rengasamy and Olsson, 1991). High bulk density indicates low soil porosity and high soil strength, which may cause restrictions to root penetration and proliferation. Low porosity also inhibits the movement of air and water through the soil. However, clay-textured soils usually have a lower bulk density than coarse-textured soils (Daddow and Warrington, 1983). Sunflower root elongation can be stopped at a bulk density of 1.75 g cm^{-3} and 1.46 to 1.63 g cm^{-3} for sandy and clay soils, respectively (Daddow and Warrington, 1983).

2.6.2 Infiltration

The movement of water from the soil surface into the soil is called infiltration, and the depth of water entering the soil profile per unit of time is called the infiltration rate. Infiltration can be affected by both the salinity and the SAR of water. High SAR of irrigation water may clog soil pores and impede water flow into the soil due to swelling and dispersion of clay particles (Ayers and Westcot, 1985; Hanson et al., 1999). However, the infiltration rate can be influenced by soil texture and the capacity of salt leached into the soil. The disruption of infiltration may hamper crop establishment and can restrict water availability for seedling growth (Bauder and Brock, 2001). Agassi et al. (1981) evaluated the effect of water with different levels of EC and varying soil ESP on infiltration rates, and they found that the infiltration rate was 16 mm h^{-1} when EC of applied water was 5.6 dS m^{-1} with soil ESP of 10 but decreased to 10 mm h^{-1} when EC of water was 5.6 dS m^{-1} with soil ESP of 13.6. They also reported that increasing EC of water may favour higher infiltration and improve soil aggregation because of flocculating effects, but reverse results may occur if ESP of soil solution is increased.

2.6.3 Hydraulic conductivity

Hydraulic conductivity which is a measure of the rate at which water flows through the soil is important in the management of irrigated agriculture and especially on saline-alkali soil due to loss of soil structure (dispersion and coagulation) when these soils are wet (Levy et al., 1999; McNeal, 1968). Usually, a well-structured soil contains an abundance of macropores and possibly additional fine cracks and fissures that maintain continuous water flow through the soil profile (Warrence et al., 2002). Soil with high Na percentage can disperse soil colloids, and the subsequent loss of soil structure can decrease the rate of water movement through the soil. However, the degree of soil dispersion will depend on soil type and clay mineralogy. Water with a low concentration of Na either increases hydraulic conductivity, or there is no significant effect, whereas a high proportion of Na in water can reduce hydraulic conductivity significantly (Shalhevet, 1994). The detrimental effect of higher sodium percentage can be reduced with increasing total soluble salts. Singh et al. (2011) mentioned that the soil, which had a higher concentration of sodium, reduced the hydraulic conductivity of the soil during leaching. Rao and Mathew (1995) also pointed out that the influence of exchangeable cations on hydraulic conductivity was related to dispersion and deflocculation of clay particles.

2.6.4 Crust and crack formation

The factors responsible for surface crusting are: (i) physical slaking due to raindrops and irrigation, and puddling and wetting the soil at zero tension, and (ii) chemical dispersion caused by high exchangeable Na^+ and EC of water (Agassi et al., 1981; Hardy et al., 1983). A surface crust causes poor infiltration and crop establishment because it forms a strong barrier to germination and emergence of seedlings, and it seals the soil surface and slows water movement into the soil. In salt-affected areas, rainfed paddy fields often have substantial amounts of salt accumulate in the dry season, which can develop into salt crusts on the soil surface through evaporation processes (Grünberger et al., 2008).

Heavy clay soils become soft, muddy and swell when they wet, but soils tend to shrink and for vertical cracks if they dry. Cracking is an issue for soil and water management in heavy clay-textured soil in the salt-affected coastal region of Bangladesh. In the dry period, the high clay content of soils associated with widespread cracking leads to soil shrinkage because of the rapid movement of water through macropores (Harris and Catt, 1999). This shrinkage phenomenon limits seedling emergence and root elongation. Crack development in the soils decrease water and fertilizer use efficiency because of irrigation water movement through these cracks down the soil profile (Tuong et al., 1996). Cracking may increase the leaching of nitrate, phosphorus, and pesticides, which increase the risk of contamination of surface and groundwater (Harris and Catt, 1999; Smaling and Bouma, 1992). Proper soil and agronomic management practices such as tillage, drainage, mulching, and crop rotation can improve soil leading to successful crop cultivation. A study conducted by Bandyopadhyay et al. (2003) reported that sub-soiling (30 cm deep by chisel plough) in the soybean - linseed cropping system significantly decreased crack parameters such as the width, depth, length and surface area by 12.5, 10, 5 and 12%, respectively, relative to the conventional tillage, while crack width, depth and volume increased with no-tillage in the soybean - wheat system relative to the conventional tillage.

2.7 Soil moisture retention and movement

Soil water retention and movement are determined by soil pore space and pore-size distribution, which are controlled by soil texture and structure (Nimmo, 2004). Water moves in both saturated and unsaturated soil due to hydraulic and water potential gradients, respectively. In the saturated condition, all pore spaces are filled with water, where water movement is predominantly in the horizontal direction. In the unsaturated condition, soil pore spaces are filled with both air and water, and water flow is mainly in a vertical direction (Hillel, 2008). In the field, many activities such as the transport of water, solutes and nutrients to roots, and the drainage of water from the root zone occur through soil-water interactions under unsaturated conditions. The amount of water retained in the soil and its uptake by plants is controlled by soil water potential. Total soil water potential has four components (Kirkham, 2014):

$$\Psi_t = \Psi_g + \Psi_0 + \Psi_p + \Psi_m$$

Where Ψ_t = total water potential (in a unit of bar or MPa)

Ψ_g = gravitational potential

Ψ_0 = osmotic or solute potential

Ψ_p = pressure potential

Ψ_m = matric or capillary potential

Soil water content is at field capacity after drainage of gravitational water, which usually occurs two to three days after the soil has been wetted through irrigation or rainfall (Jabro et al., 2009). Field capacity is widely recognized as the upper limit of soil water, which optimise available for plant use, with adequate aeration. At field capacity, soil water is retained in the soil against gravitational force by matric potential (Jabro et al., 2009). Plants can take up water from the soil (10-50 %) at water content above the field capacity (de Jong van Lier, 2017). There is a convention that the soil water tension (matric potential) at field capacity is -33 kPa or -1/3 bars (Hanks and Ashcroft, 1980; Jabro et al., 2009; Jury et al., 1991). However, this value can be influenced by soil texture and structure, clay percentage, and organic matter (Jabro et al., 2009). A permanent wilting point occurs when the soil water potential is below root water potential so that the water flow for transpiration is stopped. At the wilting point, water is tightly held by soil particles at a matric potential of about -15 bars or 1500 kPa (Li et al., 2019). Plant available water is usually considered to be the soil water content between field capacity and permanent wilting point. Table 2.4 shows the range of soil water holding capacity in different soil types.

Table 2.4. Range of available water holding capacity in different soil types (http://eagri.org/eagri50/AGRO103/lec03.pdf; verified 28 March 2020).

Soil type	Soil water content (%, w/w)		Depth of available water
	Field capacity	Permanent wilting point	cm per meter depth of soil
Find sand	3-5	1-3	2-4
Sandy loam	5-15	3-8	4-11
Silt loam	12-18	6-10	6-13
Clay loam	15-30	7-16	10-18
Clay	25-40	12-20	16-30

The presence of solutes in the soil solution determines the solute potential. Increasing salts in the soil decrease the solute potential of the soil solutions (osmotic stress), which limits water uptake by plants, resulting in reduced growth and yield (Chowdhury et al., 2011; Setia and Marschner, 2013; Steppuhn et al., 2005). The solute potential can be calculated by its relationship to the electrical conductivity of soil using the following formula (Richards, 1954).

$$\Psi_0 = - 0.36\ EC_e$$

Where Ψ_0 = osmotic potential in bars,

EC_e = electric conductivity of saturated soil in dS m^{-1}

Lower osmotic potential in the soil solution decreases the availability of water to plants because of the decrease in total soil water potential. Thus, as the soil dries, the salt concentration in the solution rises, which further reduces both the matric and the osmotic potential. As a result, to maintain water uptake from saline soil, plants must osmotically adjust. “This is done either by taking up salts and compartmentalizing them within plant tissue or synthesizing organic solutes” (Sheldon et al., 2017). The capacity for osmotic adjustment varies among plant species and cultivars. Halophytes (highly salt tolerance plants) osmotically adjust by storing salt in plant tissue, while glycophytes (tolerate only low salinity) exclude salt from the root but may synthesise organic solute for an osmotic adjustment (Sheldon et al., 2017).

2.8 Shallow groundwater table and salinization

In general, higher concentrations of soluble salts are found in groundwater than in surface water. Groundwater can contain salt concentrations ranging from less than 25 mg L^{-1} to greater than 300,000 mg L^{-1} depending on the source of groundwater, its movement, and hydrologic cycles (Todd and Mays, 2005). Shallow saline groundwater is a primary cause of soil salinity. In coastal areas, the water table is often very high (Mondal et al., 2015a), and water moves up by capillary rise and soil water loss by evaporation can cause salts to accumulate at or near the soil surface and/or in the crop root zone (Rasheed et al., 1989; Salama et al., 1999). The rate of evaporation is controlled by soil texture, the presence of salt in the soil, depth of the water table, and climatic conditions (Hanson et al., 1999; Li et al., 2013). Ibrakhimov et al. (2007) mentioned that the presence of shallow saline groundwater can deposit around 3.5 - 14 t of salts ha^{-1} in the upper soil layer annually. According to Michael (1978), when the water table is 1.5 m or greater below the soil surface, salt accumulation in the soil profile due to capillary rise is minimal. Hanson et al. (1999) stated that from a water table below 0.76 m, the upward flow is at 0.01 m per day in clay loam soil, and the rate of upward flow can be minimized if the water table is lower. In the south-west of Western Australia in a Mediterranean climate, the critical depth of shallow water at which salinity can restrict plant development varied from 1.5 - 2 m depending on plant species (Nulsen, 1981). In this report, he also indicated that the critical depth to saline groundwater is shallower in dryland conditions than for irrigated land where it varied between 1.0 and 6.0 m.

2.9 Management options to alleviate soil constraints in the coastal zones

The coastal region of Bangladesh is highly vulnerable to waterlogging, salinity, tidal effects, and in addition, natural calamity (cyclones and storm surges) can reduce or even curtail the ability of the land to produce high yielding crops. Soil and water salinity are reported to be the main constraints to the intensification of crop production in this area (Haque, 2006), and the spread of salinity in this region is growing each year because of poor soil and water management. Some techniques like soil reclamation and amendments are not cost-effective (Abrol et al., 1988). In the following section, I review alternative techniques such as tillage practices, agronomic management and more efficient water use that could be appropriate to reduce the adverse impacts of salinity for crop production. Increasing drainage, salt leaching and the use of more salt-tolerant plants can be effective to avoid the adverse impacts of long term salt accumulation, but other cultural practices such as land levelling, method of irrigation, planting and fertilizer application could be significant as means of dealing with possible short term or interim increases in salinity (Ayers and Westcot, 1985; Mandal et al., 2019).

2.9.1 Drainage

In the low-lying salt-affected coastal zones, drainage congestion is a serious problem because of land topography, intensive rainfall, shallow groundwater, faulty irrigation systems, and poor cultivation practices. In the salt-affected Ganges delta, slow drainage, intense rainfall events and the presence of groundwater close to the surface can cause waterlogging during the dry season, which impedes normal crop cultivation. Surface water stagnation in saline soil reduces aeration around the root zone, decreases nutrient availability, and increases the movement of Na^+ and Cl^- to plant leaves, resulting in lower crop yields (Barrett-Lennard, 1986; Barrett-Lennard, 2003). One of the key approaches to remove excess water from the land is drainage (Manik et al., 2019; Singh, 2018). Drainage is used in many parts of the world to alleviate the adverse effects of waterlogging and control salinity (Valipour, 2014). One effective and simple way to mitigate waterlogging is surface drainage (Valipour, 2014). Land grading to flatten the soil surface and achieve a shallow slope can eliminate surplus water from the field. Abrol et al. (1988) mentioned that in clay-textured soil, a V-shaped open field ditch (30-45 cm deep) can discharge field water very quickly after heavy rainfall. Another solution to reclaim areas affected by waterlogging and salinity on a long-term basis is to install sub-surface drainage. The many types of sub-surface drainage include open ditches, the use of the buried perforated pipe, the use of mole or buried tile drainage, and groundwater pumping. In many countries, sub-surface drainage is implemented to control root zone waterlogging and salinity and improving crop yields (Nijland et al., 2005; Ritzema et al., 2008; Sharma et al., 2000). Jha and Koga (1995) found that the implementation of mole drainage under clay soil in Thailand improved infiltration, hydraulic conductivity, aeration, and lowered the EC. Tiwari and Goel (2017) reviewed and summarized the guidelines for sub-surface drainage to ameliorate the problems from waterlogging and saline soil in many climatic conditions. They mentioned that depending on the soil texture, drainage spacing should be 100-150 m for light-textured soils, 50-100 m for medium-textured soils, and 30-50 m for heavy-textured soils when drainage depth was greater than 1.2 m.

2.9.2 Tillage

Tillage plays a major role in agricultural crop production. Over the years, different types of tilling, including deep plowing with mouldboard disk and sub-soil plow, have been used to alter the soil and improve adverse soil conditions. The benefits of tillage are: it can loosen a compact soil and prepare a seedbed for germination or seedling placement at the proper depth, it can increase the availability of soil nutrients and water, and it can incorporate crop residues, which controls weeds and maintain soil organic matter levels (Hobbs et al., 2008). Loosening soils by tillage surrounding the seed decreases the soil resistance and improves seed soil-contact and movement of air and water, which increases initial root and shoot growth (Mohanty et al., 2006; Schjønning and Rasmussen, 2000; Tapela and Colvin, 2002). Since the 1970s, conventional tillage practice involving intensive soil disturbance has been changing to the minimum or reduced tillage in global agriculture practice (Derpsch et al., 2010). The benefits and disadvantages of conventional tillage, minimum tillage, and reduced tillage have been recorded in many studies in different environments and soil conditions (Triplett and Dick, 2008). Intensive tillage can decrease soil strength and bulk density and increase soil porosity and infiltration and soil water content (Minhas, 1996; Xue et al., 2018). Other studies reported that intensive tillage of soil is usually related to inefficient irrigation practice and removal of soil residue. It can disperse soil aggregates and increase the groundwater level, which may cause higher evaporation and soil salinization (Devkota et al., 2015). On the other hand, minimum tillage can improve aggregate stability and improve water holding capacity, optimize seed and fertilizer placement while decreasing fuel and labour requirement, and advancing the sowing time for rabi crops (Haque et al., 2017; Hobbs et al., 2008). Even for smallholder farms, planters are now available for minimum disturbance of soil by practicing zero tillage, strip tillage, bed planting, and single pass shallow tillage, which are suitable for both dry and wet soils (Haque et al., 2017).

Many scientists across the world have recommended the use of deep plowing and sub-soiling to reduce salinity hazard (Ayers and Westcot, 1985; Hamdy, 2005). Deep cultivation helps to break surface crusts and hardpans reduces soil compaction and improves soil physical condition, all of which are likely to increase soil water storage capacity and control salt accumulation in the soil (Ayers and Westcot, 1985; Gajri et al., 1997; Hartmann et al., 2008). However, Devkota et al. (2015) showed that soil salinity was reduced by 32 and 22 % in the top 10 cm and 90 cm of the soil profile under reduced tillage (permanent bed planting) with crop residue retained compared to conventional tillage. Bakker et al. (2010) conducted an experiment in the waterlogging and saline areas in the Mediterranean climate of Western Australia, and they found that waterlogging was significantly reduced in the top-soil with a permanent raised bed, whereas there was a little change of salinity of the subsoil clay.

2.9.3 Soil cover or mulch

Different mulching techniques such as rice straw, crop residues, and live crops (growing cowpea or grass pea) can be used to cover the soil, which is an effective technology for conserving soil moisture, improving soil quality, decreasing soil bulk density, and boosting crop productivity (Balwinder et al., 2011; Hobbs et al., 2007; Ji and Unger, 2001; Zhao et al., 2014). In the late 1960's, Benz et al. (1967) found that using rice straw mulch in bare soil was an effective means of reducing soil evaporation and root zone salinity. In saline soil, mulching can improve salt leaching and reduce ESP, resulting in an increase in land productivity (Hamdy, 2005). Kumar and Goh (1999) showed that residues from cultivated crops have substantial positive effects on soil physical properties, nitrogen dynamics, soil water and crop yield. Pang et al. (2010) evaluated the effect of brackish water irrigation and straw mulching on soil salinity and crop yield, and the result showed that salt content in 100 cm depth of soil was decreased with mulch treatment relative to non-mulch treatment. Bezborodov et al. (2010) conducted an experiment on the effect of mulching and different level of saline water on soil salinity and sodicity dynamics as well as yield and crop water productivity. They found that salinity decreased significantly in the upper 0.15 m depth of soil with mulching, and the combination of mulching and water quality enhanced crop yield and water productivity.

Numerous studies on the effects of various types of mulches on the soil physical and chemical properties are summarized in Table 2.5.

Table 2.5. Effects of mulch on soil physical and chemical properties.

Parameters	Indicator	Mulch types	References
Soil physical properties	Increased soil water content	Rice straw (4 t ha^{-1}), maize stover (3 t ha^{-1}), Plastic film, rice husk	(Montenegro et al., 2013),(Gicheru et al., 2004),(Xiukang et al., 2015),(Chakraborty et al., 2008)
	Improved Infiltration	Elephant grass, wheat straw	(Adekalu et al., 2007),(Mannering and Meyer, 1963)
	Reduced Runoff	Hardwood compost, corn residue	(Bakr et al., 2015),(Findeling et al., 2003)
	Enhanced water use efficiency	Plastic mulch, wheat straw, farmyard manure and rice straw	(Mahajan et al., 2007), (Wang et al., 2015a),(Abd El-Mageed et al., 2016)
	Improved soil structure	Wheat straw (0,8 and 16 t ha^{-1})	(Blanco-Canqui and Lal, 2007)
	Stabled soil aggregates	Straw mulch	(Tindall et al., 1991)
Soil chemical properties	Decreased electrical conductivity	Polythene, farmyard manure and rice straw, wheat straw. Plastic mulch	(Abd El-Mageed et al., 2016), (Bezborodov et al., 2010), (Haque et al., 2018)
	Increased soil organic carbon	Plastic mulch, rice straw mulch	(Luo et al., 2015), (Wang et al., 2015b)

2.9.4 Cultural practice

2.9.4.1 Crop establishment

Many dryland crops are sensitive to salinity at germination and early seedling stages (Bernstein, 1975; Yadav et al., 2011), and become more salinity tolerant with development through the vegetative, reproductive, and grain-filling stages (Katerji et al., 1994). By contrast, rice can be strongly affected by salinity stress during flowering (Leland and Eugene, 1999).

Failure to achieve an acceptable plant population is a serious problem in a saline environment. Application of pre-sowing irrigation with fresh water can remove surface salts through leaching, which will help to improve germination and crop establishment (Minhas et al., 1998). Seed priming is another strategy to enhance germination and emergence rate as well as improve seedling vigour and crop development and yield in the saline soils (Ashraf and Foolad, 2005; Paparella et al., 2015). Seed priming involves a pre-sowing hydration treatment that keeps the seeds in a specific solution for a certain period; there is then a dehydration process. Ibrahim (2016) reviewed the different seed priming technologies to alleviate salinity hazard in germinating seeds. Using polyethylene glycol 6000 (−2 bar) and hydro-priming for sunflower (Moghanibashi et al., 2013), choline chloride (0, 5 and 10 mM) for 24 h for wheat (Salama et al., 2011) and salicylic acid (25 ppm) and NaCl (−10 bar) for maize (Tabatabaei, 2014) all improved germination rate and seedling growth. Mondal et al. (2015a) showed that the early establishment of rabi crops avoided salinity in the seedbed and improved germination rate because the seedlings escaped initial salt injury. Rashid et al. (2014) found that early dibbled sunflowers in the coastal zone of Bangladesh avoided the risk of pre-monsoon rainfall and gave significantly higher yield. Planting on a raised bed can improve crop stands by mitigating waterlogging and salinity. However, planting the seeds at the centre of the single row raised bed can result in poor germination because of the influencing from two wetting fronts from the furrows, which deposits more salt in the centre of the bed (Leland and Eugene, 1999). Modification of the shape of the seed beds and double-row raised bed (alternative furrows) could be effective to avoid salt accumulation (Hamdy, 2005). Another technique involves the placement of seeds at the bottom of the ridges on both edges of the furrows where the zone is less saline and saline water irrigation in alternative rows can improve crop establishment (Minhas et al., 1998). Lower plant density and wide row spacing often causes lower yields in saline areas. Keren et al. (1983) conducted an experiment in saline conditions and found that cotton yield increased significantly when increasing the number of plants per unit area by decreasing the row spacing. Minhas et al. (1998) recommended using 20-30 % extra seed to achieve a higher plant density and higher yield under saline irrigation conditions.

2.9.4.2 Crop cultivars

The selection of crop species is an important consideration in saline agriculture. Within most species, some crop cultivars have a greater ability to withstand the effects of root zone salinity. However, there is a negative correlation between crop yield and salinity. The desirable characteristics of selecting salt-tolerant cultivars are: (i) high economic value, (ii) tolerance to salinity, (iii) ability to tolerate saline irrigation water, and (iv) a good fit in the crop rotation (Hamdy, 2005). Plant's response to salinity can be influenced by environmental factors. Leland and Eugene (1999) reported that many crops produced higher yields in cool and humid coastal environments compared to the same crops in hot or dry environments (desert climate). Crop responses to salinity differ over a wide range from highly tolerant to extremely sensitive. Barley and cotton are considered highly salt-tolerant crops (Leland and Eugene, 1999), while wheat and sunflower are considered moderately salt-tolerant (Katerji et al., 2003). Based on the threshold level of salinity and yield slope parameters associated with an increase in EC_e, Maas and Hoffman (1977) categorized crops as sensitive, moderately sensitive, moderately tolerant and tolerant (see Fig. 2.12).

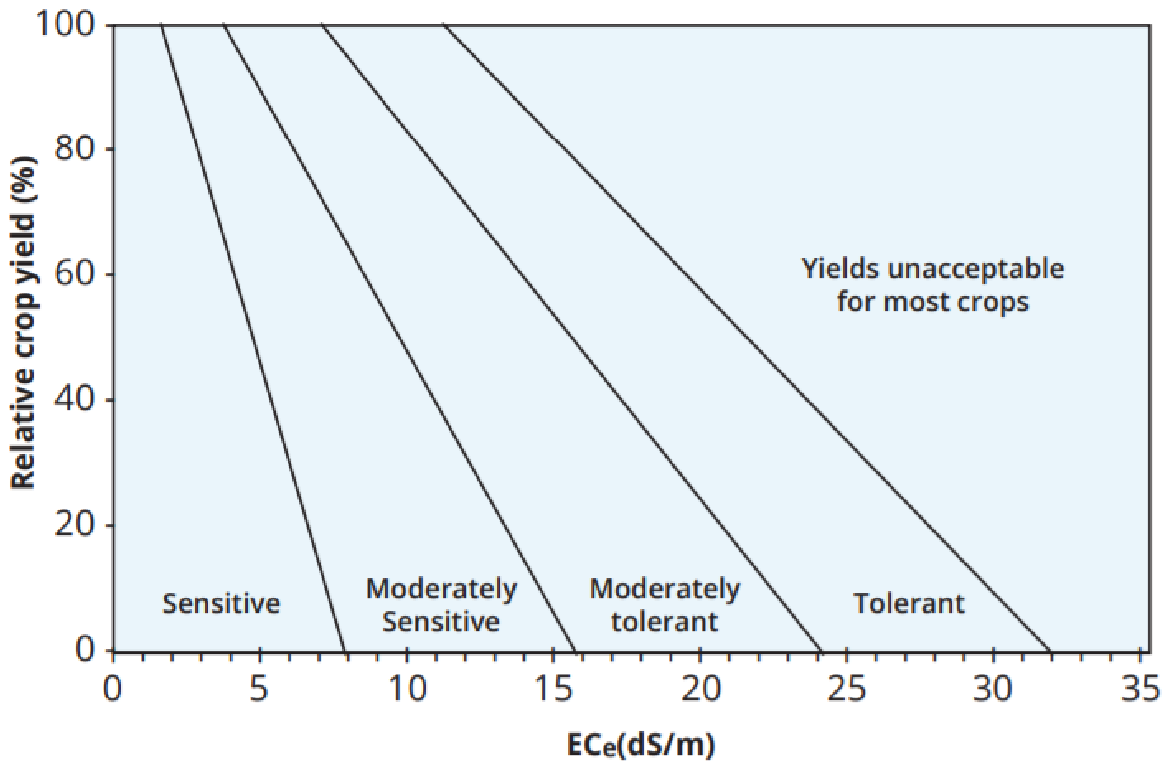

Fig. 2.12. Division for classifying crop tolerance to salinity (Maas and Hoffman, 1977).

Katerji et al. (2003) mentioned that crop behaviour under saline conditions differs with salinity level, soil type and climatic conditions. A recent study in the salt-affected Ganges delta showed that with proper soil and agronomic management, some cultivars such as sunflower, maize, wheat, and potato could be grown with satisfactory yield in the dry season (Bell et al., 2019; Mainuddin et al., 2019; Mondal et al., 2015a).

In this thesis, sunflower was used as a model crop for the salt-affected coastal zone of Bangladesh. Sunflower is cultivated on around 21 Mha of land across 60 countries (Seiler and Gulya Jr, 2010), and it is the fifth-largest oilseed crop in the world after soybean, rapeseed, cottonseeds and groundnuts (FAOSTAT, 2018). It can be grown widely and is considered a well-adapted crop in temperate and subtropical climates (De La Vega and Hall, 2002). Major growing areas of sunflower are Ukraine, the Russian Federation, Argentina, Europe and Turkey

(FAOSTAT, 2018). Its importance and growing area are increasing because it is a valuable source of edible vegetable oil with high polyunsaturated fatty acid content (about 90% linoleic and oleic acids) and no cholesterol (González-Pérez and Vereijken, 2007). With an advanced breeding progress, sunflower has been made into a highly adaptable, efficient crop in different stress conditions. It is considered to be a drought-tolerant crop because of its efficient use of soil water through a deep root system (up to 2 m) (Rauf, 2008; Sadras et al., 1989; Seiler, 1994). It is also classed as a moderately salt-tolerant crop based on water stress day index classification (Katerji et al., 2003) and its tolerance to salinity (Francois, 1996). Sunflower is also often considered as an eco-friendly and diversified crop as it needs a lower amount of nitrogen (56 kg ha^{-1}), a small quantity of irrigation water (~ 50 mm), small amounts of pesticide and insecticide (Debaeke et al., 2017), and it can be grown with minimum soil disturbance and with other cereal crops in inter-cropping systems (Jones and Sieving, 2006). Temperature may influence sunflower emergence, growth and yield (Chimenti et al., 2001). It can be tolerant to both low and high temperatures (ranges 10 -26 ^{0}C) (Harris et al., 1978) but is more favoured by low temperature (GRDC, 2017). Low temperatures (< 25 ^{0}C) may delay and reduce germination and emergence (Gay et al., 1991), while high temperatures (> 30 ^{0}C) during bud formation and flowering depress seed number, grain size and yield (Chimenti et al., 2001; Rondanini et al., 2006).

Minhas et al. (2020) reviewed the tolerance to salinity of common agricultural crops (Table 2.6) based on the equation developed by Maas and Hoffman (1977) (linear equation 1) and van Genuchten et al. (1984) (non-linear equation 2).

$$Y_r = 100 - b\,(EC_e - EC_{e\ threshold}) \qquad (1)$$

$$Y_r = \frac{100}{1+\left(\frac{EC_e}{EC_{e50}}\right)P_{Yr}} \qquad (2)$$

Where Y_r is relative yield (ratio of the actual and maximum yield), EC_e is the time averaged of soil saturated paste extract, $EC_{e\ threshold}$ is the threshold salinity (dS m^{-1}), b is the yield reduction rate per unit increase in EC_e (% per dS m^{-1}), P_{Yr} is the empirical parameters and ECe_{50} is the ECe at which the yield is reduced by 50%.

Table 2.6. Salt tolerance of selected agricultural crops grown in Southern Bangladesh (after Minhas et.al., 2020).

Crop		$EC_{e\ threshold}$ (dS m^{-1})	$EC_{e\ 50}$ (dS m^{-1})	B (% / dS m^{-1})	Rating
Small vegetables					
Cabbage	*Brassica oleracea* L. (Capitata group)	1.0-1.8	7.0	9.8-14.0	MS
Cauliflower	*Brassica oleracea* L. (Botrytis group)	1.5-1.8	-	6.2-14.4	MS
Lettuce	*Lactuca sativa* L.	1.3-1.7	5.1	12.0-13.0	MS
Onion	*Allium cepa* L	1.2	4.3	16.0	S
Radish	*Raphanus sativus* L	1.2-2.0	5.0	7.6-13.0	MS
Vegetables - Solanum Family (Solanaceae)					
Egg Plant	*Solanum melongena* L.	1.1	-	6.9	MS
Pepper	*Capsicum annuum* L	1.5-1.7	5.1	12.0-14.0	MS
Tomato	*Lycopersicon esculentum* L.	0.9-2.5	7.6	9.0-9.9	MS
Vegetables Cucumber Family (Cucurbitaceae)					
Cucumber	*Cucumis sativus* L.	1.1-2.5	6.3	7.0-13.0	MS
Melon	*Cucumis melo* L.	1.0	-	8.4	MS
Pumpkin, winter	*Cucurbita moschata Poir*	1.2	-	13.0	MS
Squash, Zucchini	*Cucurbita pepo* L.var *melopepo* (L.) Alef.	4.7-4.9	10.0	10.0-10.5	MT
Squash (scallop)	*Cucurbita pepo* L.var *melopepo* (L.) Alef	3.2	6.3	16.0	MS
Watermelon	*Citrullus lanatus* (Thunb.) Matsum. & Nakai	-	-	-	MS
Roots and tuber					
Carrot	*Daucus carota* L.	1.0	4.6	14.0	S
Garlic	*Allium sativum* L.	3.9	-	14.3	MS
Potato	*Solanum tuberosum* L.	1.7	5.9	12.0	MS
Sweet potato	*Ipomoea batatas* (L.) Lam	1.5-2.5	6.0	10.0-11.0	MS
Legumes (Leguminosae)					
Bean	*Phaseolus vulgaris* L.	1.0	3.6	19.0	S
Bean, mung	*Vigna radiata* (L.) R. Wilcz.	1.8	-	20.7	S
Cowpea	*Vigna unguiculata* (L.) Walp.	4.9	9.1	12.0	MT
Groundnut (Peanut)	*Arachis hypogaea* L.	3.2	4.9	29.0	MS
Pea	*Pisum sativum* L.	1.5-3.4	-	10.6-14.0	S/MS
Soybean	*Glycine max* (L.) Merrill	5.0	7.5	20.0	MT
Oil crops					
Rapeseed	*Brassica sp*.L.	9.7-11.0	-	13-14	T

Safflower	*Carthamus tinctorius* L.	-	-	-	MT
Sunflower	*Helianthus annuus* L.	4.8	-	5.0	MT
Cereals					
Barley	*Hordeum vulgare* L.	8.0	18.0	5.0	T
Maize	*Zea mays* L.	1.7	5.9	12.0	MS
Maize, sweet	*Zea mays* L.	1.7	5.9	12.0	MS
Millet	*Setaria italica* (L.) Beauvois	-			MS
Rice	*Oryza sativa* L.	3.0	7.2	12.0	S
Wheat	*riticum aestivum* L.	6.0	13.0	7.1	MT
Wheat, semidwarf	*Triticum aestivum* L.	6.0 8.6		3.0	T
Tropical Fruits and Trees					
Banana	*Musa acuminata* Colla	-	-	-	MS
Coconut	*Cocos nucifera* L.	-	-	-	MT
Pineapple	*Ananas comosus* (L.) Merrill	-	-	-	
Fruit trees					
Avocado	*Persea americana* Mill.	-	-	-	S
Citrus (Orange)	*Citrus sinensis* (L.) Osbeck	1.3-1.7	4.8	13.1-16.0	S
Citrus (Lemon)	*Citrus limon* (L.) Burm. f.	1.5	-	12.8	S
Citrus (Lime)	*Citrus aurantiifolia* (Christm.)	-	-	-	S
Citrus (Pummelo)	*Citrus maxima* (Burm.)	-	-	-	S
Pomegranate	*Punica granatum* L.	-	-	-	MT
Guava	*Psidium guajava* L.	4.7	-	9.8	MT

EC_e threshold is the EC_e value above which yield begins to decrease; EC_e 50 is the EC_e value at which crop yield is reduced by 50%; B is the rate of reduction in yield per unit increase in EC_e; S-sensitive; MS-moderately sensitive; T-tolerant; MT- moderately tolerant.

2.10 Water management

In salt-affected areas of Bangladesh, the availability of freshwater during the dry season is limited by the high river and groundwater salinity. Therefore, proper water and crop management are vital to minimise the effects of salt stress on crop growth and development. Irrigation with saline water can cause salt accumulation in the soil, which results in lower crop yield than the non-saline condition. Therefore, some strategies are needed for crop cultivation with saline water. Irrigation water that is high in carbonates and bi-carbonates (alkali water) results in precipitation of Ca and Mg, and thus tends to increase soil pH and the sodium saturation of soils (Minhas et al., 1998; Sharma and Minhas, 2005). One way to control root zone salinity while using saline irrigation water is the conjunctive use of saline with freshwater (Murad et al., 2018). Blending and cyclic modes of application are commonly used for the multi-quality irrigation water to improve agricultural productivity in many parts of the world

(Gawad et al., 2005; Oster, 1994; Qadir and Oster, 2004). Blending can be used by mixing two or more water sources to obtain a certain level of salinity for a specific crop. The effectiveness of this method depends on crop types, salinity level, soil type, climate, and the relative volumes of the two water supplies (Grattan et al., 2009; Minhas et al., 2020; Sharma and Minhas, 2005). Experiments have been conducted by Flowers et al. (2005) in Egypt and Syria with blended (fresh and saline water at different ratios) and cyclic water (freshwater at a sensitive stage and saline water at the tolerant stage) application for tomato cultivation; they found that tomato yield was higher with fresh and saline water blended, but fruits were heaviest when grown with 100 % fresh water application. Shalhevet (1994) reviewed that the used of blended water (saline drainage water: 9 dS m^{-1} and canal water: 0.75 dS m^{-1}) in cotton cultivation and reported it reduced the yield by 36 % compared to the yield with freshwater applied but applying fresh water at the seedling stage with blended water for the remainder of the season resulted in only a 20 % yield reduction. He concluded that the mixing of highly saline water with non-saline water is a questionable practice because using blended water has a significant negative effect on yield. Ayers and Westcot (1985) claimed that this method usually does not minimize total salt load but can offer an alternative to the cultivation of crops. They also suggested that good quality of water should be applied at the early stage of the growing season, and mixing blended water may be supplied at a later stage when the crop is less sensitive to salinity. Rhoades (1992) and (Hanson et al., 1999) suggested that the irrigation practice of cycling has many advantages over the blending method. Numerous studies have shown that yields were higher in different cyclic modes than the yields with blended water (Minhas et al., 1998). For the cyclic strategy, it has been advocated that low salinity (<1.0 dS m^{-1}) water should be applied in early growth, particularly at germination and early seedling growth (most crops are sensitive at these stages), with more saline water being applied at later stages when plants can tolerant higher salinity (Naresh et al., 1993; Rhoades, 1992). Mondal (1997) highlighted that application of one irrigation with saline water followed by two irrigations with fresh canal water increased the crop yield significantly when compared to yield after saline water alone. The benefits of cyclic water use is also provided by many experiments (Chauhan et al., 2007; Minhas et al., 2007). In these experiments, it was concluded that if two water sources are available, the preferred option is to use non-saline water during the initial and sensitive stage and the use of saline water should be delayed to the later stages of growth when the plants are often more tolerant to salt.

2.11 Utilization of rainwater

In many salt-affected areas, agricultural production is hampered due to freshwater scarcity. For example, in the Ganges coastal region of Bangladesh, river water salinity is < 1 dS m^{-1} during the monsoon (June-November), but during the dry season, salinity starts to increase from December and reaches at the peak in April-May (> 20 dS m^{-1}) when late-sown rabi crops are flowering or close to maturity stage. The high water salinity during the later part of the growing season restricts water availability for plants, which may reduce the final yield of a crop. Therefore, rainwater harvesting or freshwater storage can be an alternative option for maintaining satisfactory water quality to irrigate crops according to water demand. Utilization of rainwater could have potential in the management of saline water and soil used for long term crop productivity and sustainability. In many areas, rainwater utilization efficiency is at about 20-30 %, but if this efficiency increases by only 10 %, many water shortage areas can be alleviated (Gupta, 2002). In the south-west coastal region of Bangladesh, there are many internal canals and creeks connected with the river. There is potential to harvest rainwater for irrigation in this area as monsoon season rainfall is over 1,500 mm, and natural reservoirs are suitable to store this water. Irrigation in the dry season can contribute to the removal of soluble salts from the crop root zone by leaching, which can help for the reclamation of agricultural land and increase the cropping area. The rainwater stored in small reservoirs or mini ponds or natural canals could be used to profitably irrigate dry season crops in the coastal saline area, thereby increasing crop yield (Molla et al., 2010). A mini pond covering 3-5 % of farmland surface area can be used to store run-off or flood water during monsoon for irrigating dry season crops and increasing yield (Bruins et al., 1986; Velasco-Muñoz et al., 2019).

2.12 Fertilizer management

Adding optimum amounts of essential minerals to soils improves crop growth and ensures long term fertility management of soils. In the salt-affected soils, the common problems are excessive salinity and sodicity, poor soil structure, high soil pH and low organic matter, which cause nutrient imbalance and reduce nutrient uptake for plants and decrease fertilizer use efficiency (Ismail and Tuong, 2009). Alternatively, growing and incorporating green manure crops (Dhaincha: *Sesbania aculeata*) into the soil has many benefits (MacRae and Mehuys, 1985; Mandal et al., 2003). It increases soil organic matter and soil permeability, and it releases carbon dioxide and organic acids during decomposition (Hamdy, 2005). In addition, by lowering the soil pH and liberating Ca by solubilisation of $CaCO_3$, exchangeable Na is replaced by Ca and Mg, which helps to reduce the ESP (Mondal, 1997). In many saline soils, the elements K and Ca are deficient, and fertiliser supplements of these may be required (Saleque et al., 2010). Minhas et al. (1998) suggested that using phosphorus fertilizer above the recommended level can reduce the adverse effects of salinity, particularly if saline water is dominated by chlorides compared to sulphates. Abrol et al. (1988) remarked that the application of high P-fertilizer in saline soil alleviates salt injury symptoms on crops and increases yields. Many studies have recommended the use of gypsum ($CaSO_4.2H_2O$) into the soil, which could eliminate the adverse effects of saline water and ameliorate the sodic-saline soils. Gypsum is usually low in cost, available, easy to apply and appropriate for agronomic purposes (Ayers and Westcot, 1985; Qadir et al., 2006). The application of gypsum to sodic-saline soils helps to increase the electrolyte concentration of soil solution and exchangeable

Ca^{2+} on the cation exchange, which helps to remove Na^{+} from the root zone, thereby increasing soil infiltration and hydraulic conductivity and reducing soil swelling and dispersion (Oster, 1982; Qadir et al., 2001; Shainberg et al., 1989).

2.13 Conclusions

The major constraints for agricultural development in the coastal areas are high soil and water salinity, as the coastal zone is the interface between freshwater and saline water environments. In addition, the coastal zone experiences waterlogging and water stress from drought, scarcity of freshwater for irrigation, poorly structured soil, shallow groundwater, climatic and natural disasters. Successful crop production during the rabi (dry) season will need to minimise the impacts of residual waterlogging from the preceding kharif season, overcome the tendency of these soils to waterlog during the rabi season, and enhance tolerance or avoidance of high salinity which occurs from February onwards. The above review of literature has identified several promising approaches such as surface drainage, crop establishment by dibbling, straw mulch application, practicing deep tillage, and using salt-tolerant cultivars. Soil covered by straw mulch has performed well in maintaining soil water availability, salinity reduction, and improved crop yield, but for dry season crop establishment in wet soil, its role remains unclear. Similarly, the performance of mechanized tillage (a range of soil disturbance) in wet, clay-textured soil needs to be investigated. Finally, it is not clear whether the early establishment of sunflowers in the coastal zone of the Ganges delta will achieve the highest yield potential. Overall, there are still limited information on the environmental constraints of waterlogging, salinity and/or drought-related to crop production in the Ganges coastal zone. Therefore, it is imperative to initiate a research program for developing new technologies and management practices for dry (rabi) season cropping in this unfavourable area.

2.14 References

Abd El-Mageed, T. A., Semida, W. M., and Abd El-Wahed, M. H. (2016). Effect of mulching on plant water status, soil salinity and yield of squash under summer-fall deficit irrigation in salt affected soil. *Agric. Water Manage.* **173**, 1-12.

Abrol, I., Yadav, J. S. P., and Massoud, F. (1988). "Salt-affected soils and their management. Food and Agriculture Organization. Soils bulletin 39."

Adekalu, K., Olorunfemi, I., and Osunbitan, J. (2007). Grass mulching effect on infiltration, surface runoff and soil loss of three agricultural soils in Nigeria. *Bioresour. Technol.* **98**, 912-917.

Agassi, M., Shainberg, I., and Morin, J. (1981). Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation 1. *Soil Sci. Soc. Am. J.* **45**, 848-851.

Ahmed, A., Drake, F., Nawaz, R., and Woulds, C. (2018). Where is the coast? Monitoring coastal land dynamics in Bangladesh: An integrated management approach using GIS and remote sensing techniques. *Ocean Coast. Manage.* **151**, 10-24.

Allen, J. A., Pezeshki, S. R., and Chambers, J. L. (1996). Interaction of flooding and salinity stress on baldcypress (Taxodium distichum). *Tree Physiol.* **16**, 307-313.

Armstrong, W., and Drew, M. C. (2002). Root growth and metabolism under oxygen deficiency. *In* "Plant roots", pp. 1139-1187. CRC Press.

Ashraf, M., and Foolad, M. R. (2005). Pre-sowing seed treatment—A shotgun approach to improve germination, plant growth, and crop yield under saline and non-saline conditions. *Adv. Agron.* **88**, 223-271.

Ayers, R. S., and Westcot, D. W. (1985). "Water quality for agriculture," Food and Agriculture Organization of the United Nations Rome, Italy.

Bakker, D. M., Hamilton, G. J., Hetherington, R., and Spann, C. (2010). Salinity dynamics and the potential for improvement of waterlogged and saline land in a Mediterranean climate using permanent raised beds. *Soil Tillage Res.* **110**, 8-24.

Bakr, N., Elbana, T. A., Arceneaux, A. E., Zhu, Y., Weindorf, D. C., and Selim, H. M. (2015). Runoff and water quality from highway hillsides: Influence compost/mulch. *Soil Tillage Res.* **150**, 158-170.

Balwinder, S., Eberbach, P. L., Humphreys, E., and Kukal, S. S. (2011). The effect of rice straw mulch on evapotranspiration, transpiration and soil evaporation of irrigated wheat in Punjab, India. *Agric. Water Manage.* **98**, 1847-1855.

Bandyopadhyay, K. K., Mohanty, M., Painuli, D. K., Misra, A. K., Hati, K. M., Mandal, K. G., Ghosh, P. K., Chaudhary, R. S., and Acharya, C. L. (2003). Influence of tillage practices and nutrient management on crack parameters in a Vertisol of central India. *Soil Tillage Res.* **71**, 133-142.

Barrett-Lennard, E. (1986). Wheat growth on saline waterlogged soils. *Journal of the Department of Agriculture (WA)* **27**, 118-119.

Barrett-Lennard, E. G. (2003). The interaction between waterlogging and salinity in higher plants: causes, consequences and implications. *Plant Soil* **253**, 35-54.

Bauder, J., and Brock, T. (2001). Irrigation water quality, soil amendment, and crop effects on sodium leaching. *Arid. Land Res. Manage.* **15**, 101-113.

Bell, R., Mainuddin, M., Barrett-Lennard, E., Sarangi, S., Maniruzzaman, M., Brahmachari, K., Sarker, K., Burman, D., Gaydon, D., Kirby, J., Glover, M., Rashid, H., Sahidul, M., Khan, I., Kabir, M., Rahman, M., and Hossain, M. B. (2019). Cropping Systems Intensification in the Coastal Zone of the Ganges Delta: Opportunities and Risks. *J. Indian Soc. Coastal Agric. Res.* **37**, 153-161.

Benz, L., Sandoval, F., and Willis, W. (1967). Soil-salinity changes with fallow and a straw mulch on fallow. *Soil Sci.* **104**, 63-68.

Bernstein, L. (1975). Effects of salinity and sodicity on plant growth. *Annu. Rev. Phytopathol.* **13**, 295-312.

Bezborodov, G. A., Shadmanov, D. K., Mirhashimov, R. T., Yuldashev, T., Qureshi, A. S., Noble, A. D., and Qadir, M. (2010). Mulching and water quality effects on soil salinity and sodicity dynamics and cotton productivity in Central Asia. *Agric. Ecosyst. Environ.* **138**, 95-102.

Blanco-Canqui, H., and Lal, R. (2007). Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. *Soil Tillage Res.* **95**, 240-254.

Brady, N. C. (1990). "The Nature and Properties of Soils, Tenth Edition. Macmillan Publishing Company, New York."

Brady, N. C., Weil, R. R., and Weil, R. R. (2008). "The nature and properties of soils," Prentice Hall Upper Saddle River, NJ.

Bruins, H., Evenari, M., and Nessler, U. (1986). Rainwater-harvesting agriculture for food production in arid zones: the challenge of the African famine. *Appl. Geogr.* **6**, 13-32.

Chakraborty, D., Nagarajan, S., Aggarwal, P., Gupta, V., Tomar, R., Garg, R., Sahoo, R., Sarkar, A., Chopra, U. K., and Sarma, K. S. (2008). Effect of mulching on soil and plant water status, and the growth and yield of wheat (Triticum aestivum L.) in a semi-arid environment. *Agric. water Manage.* **95**, 1323-1334.

Chauhan, S., Chauhan, C., and Minhas, P. (2007). Effect of cyclic use and blending of alkali and good quality waters on soil properties, yield and quality of potato, sunflower and Sesbania. *Irrig. Sci.* **26**, 81-89.

Chimenti, C. A., Hall, A. J., and Sol López, M. (2001). Embryo-growth rate and duration in sunflower as affected by temperature. *Field Crops Res.* **69**, 81-88.

Chowdhury, N., Marschner, P., and Burns, R. (2011). Response of microbial activity and community structure to decreasing soil osmotic and matric potential. *Plant Soil* **344**, 241-254.

Conner, W. H. (1994). The effect of salinity and waterlogging on growth and survival of baldcypress and Chinese tallow seedlings. *J. Coastal Res.*, 1045-1049.

Daddow, R. L., and Warrington, G. (1983). "Growth-limiting soil bulk densities as influenced by soil texture," Watershed Systems Development Group, USDA Forest Service.

de Jong van Lier, Q. (2017). Field capacity, a valid upper limit of crop available water? *Agric. Water Manage.* **193**, 214-220.

De La Vega, A. J., and Hall, A. J. (2002). Effects of planting date, genotype, and their interactions on sunflower yield: I. Determinants of oil-corrected grain yield. *Crop Sci.* **42**, 1191-1201.

Debaeke, P., Bedoussac, L., Bonnet, C., Bret-Mestries, E., Seassau, C., Gavaland, A., Raffaillac, D., Tribouillois, H., Véricel, G., and Justes, E. (2017). Sunflower crop: Environmental-friendly and agroecological. *OCL - Oilseeds and fats, Crops and Lipids* **24**, D304.

Derpsch, R., Friedrich, T., Kassam, A., and Hongwen, L. (2010). Current status of adoption of no-till farming in the world and some of its main benefits. *Int. J. Agric. Biol. Eng.* **3**, 1-25.

Devkota, M., Devkota, K. P., Martius, C., Gupta, R. K., McDonald, A. J., and Lamers, J. P. A. (2015). Managing soil salinity with permanent bed planting in irrigated production systems in Central Asia. *Agric. Ecosyst. Environ.* **202**, 90-97.

Dickin, E., and Wright, D. (2008). The effects of winter waterlogging and summer drought on the growth and yield of winter wheat (Triticum aestivum L.). *Eur. J. Agron.* **28**, 234-244.

Drew, M. (1990). Sensing soil oxygen. *Plant Cell Environ.* **13**, 681-693.

FAOSTAT (2018). Food and Agricultural Organigation of the United Nations, Rome, Italy.

Findeling, A., Ruy, S., and Scopel, E. (2003). Modeling the effects of a partial residue mulch on runoff using a physically based approach. *J. Hydrol.* **275**, 49-66.

Flowers, T., Ragab, R., Malash, N., Gawad, G. A., Cuartero, J., and Arslan, A. (2005). Sustainable strategies for irrigation in salt-prone Mediterranean: SALTMED. *Agric. Water Manage.* **78**, 3-14.

Francois, L. E. (1996). Salinity effects on four sunflower hybrids. *Agron. J.* **88**, 215-219.

Frenkel, H., Goertzen, J., and Rhoades, J. (1978). Effects of clay type and content, exchangeable sodium percentage, and electrolyte concentration on clay dispersion and soil hydraulic conductivity 1. *Soil Sci. Soc. Am. J.* **42**, 32-39.

Gajri, P. R., Gill, K. S., Chaudhary, M. R., and Singh, R. (1997). Irrigation of sunflower (Helianthus annuus) in relation to tillage and mulching. *Agric. Water Manage.* **34**, 149-160.

Gawad, G. A., Arslan, A., Gaihbe, A., and Kadouri, F. (2005). The effects of saline irrigation water management and salt tolerant tomato varieties on sustainable production of tomato in Syria (1999–2002). *Agric. Water Manage.* **78**, 39-53.

Gay, C., Corbineau, F., and Côme, D. (1991). Effects of temperature and oxygen on seed germination and seedling growth in sunflower (Helianthus annuus L.). *Environ. Exp. Bot.* **31**, 193-200.

George, E., Horst, W. J., and Neumann, E. (2012). Adaptation of plants to adverse chemical soil conditions. *In* "Marschner's mineral nutrition of higher plants", pp. 409-472. Elsevier.

Ghassemi, F., Jakeman, A. J., and Nix, H. A. (1995). "Salinisation of land and water resources: human causes, extent, management and case studies," CAB international.

Gicheru, P., Gachene, C., Mbuvi, J., and Mare, E. (2004). Effects of soil management practices and tillage systems on surface soil water conservation and crust formation on a sandy loam in semi-arid Kenya. *Soil Tillage Res.* **75**, 173-184.

González-Pérez, S., and Vereijken, J. M. (2007). Sunflower proteins: overview of their physicochemical, structural and functional properties. *J. Sci. Food Agric.* **87**, 2173-2191.

Grable, A. R. (1966). Soil aeration and plant growth. *In* "Adv. Agron.", Vol. 18, pp. 57-106. Elsevier.

Grattan, S. R., Oster, J. D., Benes, S., and Kaffka, S. (2009). Use of saline drainage waters for irrigation. *Agricultural Salinity Assessment and Management, 2nd ed.; Wallender, WW, Tanji, KK, Eds*, 687-719.

GRDC (2017). Sunflower: Plant growth and physiology. *Grains Research and Development Corporation, Northern, Western Australia, Australia*.

Greene, R., Timms, W., Rengasamy, P., Arshad, M., and Cresswell, R. (2016). Soil and Aquifer Salinization: Toward an Integrated Approach for Salinity Management of Groundwater. *In* "Integrated Groundwater Management: Concepts, Approaches and Challenges" (A. J. Jakeman, O. Barreteau, R. J. Hunt, J.-D. Rinaudo and A. Ross, eds.), pp. 377-412. Springer International Publishing, Cham.

Grünberger, O., Macaigne, P., Michelot, J.-L., Hartmann, C., and Sukchan, S. (2008). Salt crust development in paddy fields owing to soil evaporation and drainage: Contribution of chloride and deuterium profile analysis. *J. Hydrol.* **348**, 110-123.

Gupta, S. (2002). Meeting challenge of the water shortage: Rainwater conservation in land reclamation programs. *In* "12th ISCO Conference", pp. 446-451.

Hamdy, A. (2005). Saline irrigation management for a sustainable use. In: Hamdy A. (ed.), EI Gamal F. (ed), Lamadddalena N. (ed), Bogliotti C. (ed), Guelloubi R. (ed.). *Non-conventional water use. WASAMED project. Bari : CHIEAM. 3-42*

Hanks, R., and Ashcroft, G. (1980). Applied Soil Physics, Springer-Verlag. *New York.*

Hanson, B., Grattan, S. R., and Fulton, A. (1999). "Agricultural salinity and drainage," University of California Irrigation Program, University of California, Davis.

Haque, M. A., Jahiruddin, M., and Clarke, D. (2018). Effect of plastic mulch on crop yield and land degradation in south coastal saline soils of Bangladesh. *Int. Soil Water Conserv. Res.* **6**, 317-324.

Haque, M. E., Islam, A. K. M. S., Hossain, M. M., Bell, R. W., and Sayre, K. D. (2017). An innovative versatile multi-crop planter for crop establishment using two-wheel tractors. *Agric. Mech. Asia Afr. Lat. Am, 48, pp.33-37.*

Haque, S. (2006). Salinity problems and crop production in coastal regions of Bangladesh. *Pak. J. Bot.* **38**, 1359-1365.

Hardy, N., Shainberg, I., Gal, M., and Keren, R. (1983). The effect of water quality and storm sequence upon infiltration rate and crust formation. *J. Soil Sci.* **34**, 665-676.

Harris, G., and Catt, J. (1999). Overview of the studies on the cracking clay soil at Brimstone Farm, UK. *Soil Use Manag.* **15**, 233-239.

Harris, H., McWilliam, J., and Mason, W. (1978). Influence of temperature on oil content and composition of sunflower seed. *Aust. J. Agric. Res.* **29**, 1203-1212.

Hartmann, C., Poss, R., Noble, A. D., Jongskul, A., Bourdon, E., Brunet, D., and Lesturgez, G. (2008). Subsoil improvement in a tropical coarse textured soil: effect of deep-ripping and slotting. *Soil Tillage Res.* **99**, 245-253.

Hillel, D. (2008). 7. - SOIL-WATER DYNAMICS. *In* "Soil in the Environment" (D. Hillel, ed.), pp. 91-101. Academic Press, San Diego.

Hobbs, P. R., Sayre, K., and Gupta, R. (2007). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 543-555.

Hobbs, P. R., Sayre, K., and Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. Phil. Trans. R. Soc. B363: 543–555. http://doi.org/10.1098/rstb.2007.2169.

Horneck, D. A., Ellsworth, J. W., Hopkins, B. G., Sullivan, D. M., and Stevens, R. G. (2007). Managing salt-affected soils for crop production. https://ir.library.oregonstate.edu/concern/administrative_report_or_publications/pr76f371k.

Ibrahim, E. A. (2016). Seed priming to alleviate salinity stress in germinating seeds. *J. Plant Physiol.* **192**, 38-46.

Ibrakhimov, M., Khamzina, A., Forkutsa, I., Paluasheva, G., Lamers, J., Tischbein, B., Vlek, P., and Martius, C. (2007). Groundwater table and salinity: Spatial and temporal distribution and influence on soil salinization in Khorezm region (Uzbekistan, Aral Sea Basin). *Irrig. Drain.* **21**, 219-236.

Ismail, A., and Tuong, T. (2009). Brackish water coastal zones of the monsoon tropics: challenges and opportunities. In: Haefele SM, Ismail AM, (eds). Natural resource management for poverty reduction and environmental sustainability in fragile rice-based systems. Limited Proceedings No. 15. Los Baños (Philippines): International Rice Research Institute. 113-121.

Jabro, J., Evans, R., Kim, Y., and Iversen, W. (2009). Estimating in situ soil–water retention and field water capacity in two contrasting soil textures. *Irrig. Sci.* **27**, 223-229.

Jackson, M., and Colmer, T. (2005). Response and adaptation by plants to flooding stress. *Ann. Bot.* **96**, 501-505.

Jha, M. K., and Koga, K. (1995). Mole drainage: Prospective drainage solution to Bangkok clay soils. *Agric. Water Manage.* **28**, 253-270.

Ji, S., and Unger, P. W. (2001). Soil Water Accumulation under Different Precipitation, Potential Evaporation, and Straw Mulch Conditions. *Soil Sci. Soc. Am. J.* **65**, 442.

Jiang, D., Fan, X., Dai, T., and Cao, W. (2008). Nitrogen fertiliser rate and post-anthesis waterlogging effects on carbohydrate and nitrogen dynamics in wheat. *Plant Soil* **304**, 301-314.

Jones, G. A., and Sieving, K. E. (2006). Intercropping sunflower in organic vegetables to augment bird predators of arthropods. *Agric. Ecosyst. Environ.* **117**, 171-177.

Jury, W., Gardner, W. R., and Gardner, W. H. (1991). Soil Physics, John Wiley & Sons. *Inc. New York*.

Katerji, N., van Hoorn, J. W., Hamdy, A., Karam, F., and Mastrorilli, M. (1994). Effect of salinity on emergence and on water stress and early seedling growth of sunflower and maize. *Agric. Water Manage.* **26**, 81-91.

Katerji, N., van Hoorn, J. W., Hamdy, A., and Mastrorilli, M. (2003). Salinity effect on crop development and yield, analysis of salt tolerance according to several classification methods. *Agric. Water Manage.* **62**, 37-66.

Keren, R., Meiri, A., and Kalo, Y. (1983). Plant spacing effect on yield of cotton irrigated with saline waters. *Plant Soil* **74**, 461-465.

Khan, Z., Kamal, F., Khan, N., Khan, S., and Khan, M. (2015). Present surface water resources of the Ganges coastal zone in Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF,GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo. Sri-Lanka: CGIAR Challenge Program on Water and Food (CPWF).

Kirkham, M. B. (2014). "Principles of soil and plant water relations," Academic Press.

Kumar, K., and Goh, K. (1999). Crop residues and management practices: effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. *In* "Advance in Aagronomy", Vol. 68, pp. 197-319. Elsevier.

Leland, E., and Eugene, V. (1999). Crop response and management of salt-affected soils. *Handbook of Plant and Crop Stress* **169**.

Levy, G., Rosenthal, A., Tarchitzky, J., Shainberg, I., and Chen, Y. (1999). Soil hydraulic conductivity changes caused by irrigation with reclaimed waste water. *J. Environ. Qual.* **28**, 1658-1664.

Li, X., Chang, S. X., and Salifu, K. F. (2013). Soil texture and layering effects on water and salt dynamics in the presence of a water table: a review. *Environ. Rev.* **22**, 41-50.

Li, X., Shao, M. a., and Zhao, C. (2019). Estimating the field capacity and permanent wilting point at the regional scale for the Hexi Corridor in China using a state-space modeling approach. *J. Soils Sediments* **19**, 3805-3816.

Luo, S., Zhu, L., Liu, J., Bu, L., Yue, S., Shen, Y., and Li, S. (2015). Sensitivity of soil organic carbon stocks and fractions to soil surface mulching in semiarid farmland. *Europ. J. Soil Biol.* **67**, 35-42.

Maas, E. V., and Hoffman, G. J. (1977). Crop salt tolerance–current assessment. *J. Irrig. Drain. Div.* **103**, 115-134.

MacRae, R. J., and Mehuys, G. R. (1985). The Effect of Green Manuring on the Physical Properties of Temperate-Area Soils. pp. 71-94. Springer New York.

Mahajan, G., Sharda, R., Kumar, A., and Singh, K. (2007). Effect of plastic mulch on economizing irrigation water and weed control in baby corn sown by different methods. *Afr. J. Agric. Res.* **2**, 19-26.

Mainuddin, M., Bell, R., Gaydon, D., Kirby, J., Barrett-Lennard, E., Glover, M., Razzaque Akanda, M., Maji, B., Ali, M. A., and Brahmachari, K. (2019). An overview of the Ganges coastal zone: climate, hydrology, land use, and vulnerability. *J. Indian Soc. Coastal Agric. Res.* **37**, 1-11.

Mandal, U. K., Burman, D., Bhardwaj, A., Nayak, D. B., Samui, A., Mullick, S., Mahanta, K., Lama, T., Maji, B., and Mandal, S. (2019). Waterlogging and coastal salinity management through land shaping and cropping intensification in climatically vulnerable Indian Sundarbans. *Agric. Water Manage.* **216**, 12-26.

Mandal, U. K., Singh, G., Victor, U., and Sharma, K. (2003). Green manuring: its effect on soil properties and crop growth under rice–wheat cropping system. *Eur. J. Agron.* **19**, 225-237.

Manik, S. N., Pengilley, G., Dean, G., Field, B., Shabala, S., and Zhou, M. (2019). Soil and crop management practices to minimize the impact of waterlogging on crop productivity. *Front. Plant Sci.* **10**.

Mannering, J., and Meyer, L. (1963). The Effects of Various Rates of Surface Mulch on Infiltration and Erosion 1. *Soil Sci. Soc. Am. J.* **27**, 84-86.

McNeal, B. (1968). Prediction of the Effect of Mixed-Salt Solutions on Soil Hydraulic Conductivity 1. *Soil Sci. Soc. Am. J.* **32**, 190-193.

Michael, A. M. (1978). "Irrigation: theory and practice," Vikas publishing house, New Delhi.

Minhas, P. (1996). Saline water management for irrigation in India. *Agric. Water Manag.* **30**, 1-24.

Minhas, P., Dubey, S., and Sharma, D. (2007). Comparative affects of blending, intera/inter-seasonal cyclic uses of alkali and good quality waters on soil properties and yields of paddy and wheat. *Agric. Water Manage.* **87**, 83-90.

Minhas, P., Ramos, T. B., Ben-Gal, A., and Pereira, L. S. (2020). Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues. *Agric. Water Manage.* **227**, 105832.

Minhas, P., Sharma, O., and Patil, S. (1998). "25 years of research on management of salt-affected soils and use of saline water in agriculture," Central Soil Salinity Research Institute Karnal,, India.

Moghanibashi, M., Karimmojeni, H., and Nikneshan, P. (2013). Seed treatment to overcome drought and salt stress during germination of sunflower (Helianthus annuus L.). *J. Agrobiol.* **30**, 89-96.

Mohanty, M., Painuli, D. K., Misra, A. K., Bandyopadhyaya, K. K., and Ghosh, P. K. (2006). Estimating impact of puddling, tillage and residue management on wheat (Triticum aestivum, L.) seedling emergence and growth in a rice–wheat system using nonlinear regression models. *Soil Tillage Res.* **87**, 119-130.

Molla, H. R., M. A. Rashid, M. A. Latf Shah, and M.A. Rashid (2010). Assessment of farm reservoir for crop production in the coastal area at Sonagazi, Feni Bangladesh. Bangladesh Rice Research Institute Annual Report 2009-10.

Mondal, M., Paul, P., Humphreys, E., Tuong, T., Ritu, S., Rashid, M., Humphreys, E., Buisson, M., Pukinskis, I., and Phillips, M. (2015a). Opportunities for cropping system intensification in the coastal zone of Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF), 342-360.

Mondal, M. K. (1997). Management of soil and water resources for higher productivity of coastal saline ricelands in Bangladesh. PhD dissertation, University of the Philippines Los Banos.

Mondal, M. K., Saha, N., Ritu, S., Paul, P., Sharifullah, A., Humphreys, E., Tuong, T., and Rashid, M. (2015b). Optimum sowing window for boro cultivation in the coastal zone of Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF), 342-360.

Montenegro, A. d. A., Abrantes, J., De Lima, J., Singh, V., and Santos, T. (2013). Impact of mulching on soil and water dynamics under intermittent simulated rainfall. *Catena* **109**, 139-149.

Munns, R., and Tester, M. (2008). Mechanisms of salinity tolerance. *Annu. Rev. Plant Biol.* **59**, 651-681.

Murad, K. F. I., Hossain, A., Fakir, O. A., Biswas, S. K., Sarker, K. K., Rannu, R. P., and Timsina, J. (2018). Conjunctive use of saline and fresh water increases the productivity of maize in saline coastal region of Bangladesh. *Agric. Water Manage.* **204**, 262-270.

Murshed, S. B., Rahman, M. R., and Kaluarachchi, J. J. (2019). Changes in Hydrology of the Ganges Delta of Bangladesh and Corresponding Impacts on Water Resources. *J. Am. Water Resour. As.* **55**, 800-823.

Naresh, R., Minhas, P., Goyal, A., Chauhan, C., and Gupta, R. (1993). Production potential of cyclic irrigation and mixing of saline and canal water in Indian mustard (Brassica juncea) and pearl millet (Pennisetum typhoides) rotation. *Arid. Land Res. Manage.* **7**, 103-111.

Nijland, H., Croon, F. W., and Ritzema, H. P. (2005). "Subsurface drainage practices: guidelines for the implementation, operation and maintenance of subsurface pipe drainage systems," ILRI.

Nimmo, J. R. (2004). Porosity and pore size distribution. *Encyclopedia of Soils in the Environment* **3**, 295-303.

Nulsen, R. (1981). Critical depth to saline groundwater in non-irrigated situations. *Soil Res.* **19**, 83-86.

Oster, J. (1994). Irrigation with poor quality water. *Agric. Water Manage.* **25**, 271-297.

Oster, J. D. (1982). Gypsum usage in irrigated agriculture: A review. *Fertilizer Res.* **3**, 73-89.

Ostonen, I., Püttsepp, Ü., Biel, C., Alberton, O., Bakker, M. R., Lõhmus, K., Majdi, H., Metcalfe, D., Olsthoorn, A. F. M., Pronk, A., Vanguelova, E., Weih, M., and Brunner, I. (2007). Specific root length as an indicator of environmental change. *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology* **141**, 426-442.

Pang, H.-C., Li, Y.-Y., Yang, J.-S., and Liang, Y.-S. (2010). Effect of brackish water irrigation and straw mulching on soil salinity and crop yields under monsoonal climatic conditions. *Agric. Water Manage.* **97**, 1971-1977.

Paparella, S., Araújo, S., Rossi, G., Wijayasinghe, M., Carbonera, D., and Balestrazzi, A. (2015). Seed priming: state of the art and new perspectives. *Plant Cell Rep.* **34**, 1281-1293.

Parihar, P., Singh, S., Singh, R., Singh, V. P., and Prasad, S. M. (2015). Effect of salinity stress on plants and its tolerance strategies: a review. *Environ. Sci. Pollut. Res.* **22**, 4056-4075.

PDO-ICZMP (2006). Program development office for integrated Coastal zone management plan. Draft coastal development strategy, water resources planning organization, ministry of water resources Bangladesh.

Pearson, K. E., and Bauder, J. W. (2006). The basics of salinity and sodicity effects on soil physical properties. *MSU Extension Water Quality Program*.

Ponnamperuma, F. N. (1984). Effects of flooding on soils. *In:* Kozlowski, T. T. (ed.) *Flooding and plant growth.* San Diego: Academic Press.

Qadir, M., Noble, A., Schubert, S., Thomas, R. J., and Arslan, A. (2006). Sodicity-induced land degradation and its sustainable management: Problems and prospects. *Land Degrad. Dev.* **17**, 661-676.

Qadir, M., and Oster, J. (2004). Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. *Sci. Total Environ.* **323**, 1-19.

Qadir, M., Schubert, S., Ghafoor, A., and Murtaza, G. (2001). Amelioration strategies for sodic soils: a review. *Land. Degrad. Dev.* **12**, 357-386.

Qureshi, R., and Barrett-Lennard, E. (1998). "Saline agriculture for irrigated land in Pakistan: a handbook," Australian Centre for International Agricultural Research (ACIAR).

Rao, S. N., and Mathew, P. K. (1995). Effects of exchangeable cations on hydraulic conductivity of a marine clay. *Clays Clay Miner.* **43**, 433-437.

Rasheed, H., Al-Anaz, H., and Abid, K. (1989). Evaporation from soil surface in presence of shallow water tables. *IAHS Publication (United Kingdom)*.

Rashid, M. H., Nasrin, S., and Mahalder, D. (2014). Zero tilled dibbled sunflower enables planting earlier and harvests more in the coastal saline area of Bangladesh. *Int. J. Environ. Sci. Dev.* **5**, 260.

Rauf, S. (2008). Breeding sunflower (Helianthus annuus L.) for drought tolerance. *Commun. Biometry Crop. Sci* **3**, 29-44.

Rengasamy, P. (2002). Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. *Aust. J. Exp. Agric.* **42**, 351-361.

Rengasamy, P. (2006). World salinization with emphasis on Australia. *J. Exp. Bot.* **57**, 1017-1023.

Rengasamy, P. (2010). Soil processes affecting crop production in salt-affected soils. *Funct. Plant Biol.* **37**, 613-620.

Rengasamy, P., and Olsson, K. (1991). Sodicity and soil structure. *Soil Res.* **29**, 935-952.

Rhoades, J. D. (1992). "The use of saline waters for crop production. Food and Agriculture Organization irrigation and drainage paper 48, Rome, Italy."

Richards, L. (1954). Diagnosis and improvement of saline and alkali soils. Handbook No. 60. *US Department of Agriculture, Washington, DC*.

Ritzema, H., Satyanarayana, T., Raman, S., and Boonstra, J. (2008). Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. *Agric. Water Manage.* **95**, 179-189.

Rondanini, D., Mantese, A., Savin, R., and Hall, A. J. (2006). Responses of sunflower yield and grain quality to alternating day/night high temperature regimes during grain filling: Effects of timing, duration and intensity of exposure to stress. *Field Crops Res.* **96**, 48-62.

Rowell, D., Payne, D., and Ahmad, N. (1969). The effect of the concentration and movement of solutions on the swelling, dispersion, and movement of clay in saline and alkali soils. *J. Soil Sci.* **20**, 176-188.

Sadras, V., Hall, A., Trapani, N., and Vilella, F. (1989). Dynamics of rooting and root-length: leaf-area relationships as affected by plant population in sunflower crops. *Field Crops Res.* **22**, 45-57.

Salama, K. H., Mansour, M. M., and Hassan, N. S. (2011). Choline priming improves salt tolerance in wheat (Triticum aestivum L.). *Aust J Basic Appl Sci* **5**, 126-132.

Salama, R. B., Otto, C. J., and Fitzpatrick, R. W. (1999). Contributions of groundwater conditions to soil and water salinization. *Hydrogeol. J.* **7**, 46-64.

Saleque, M., Uddin, M., Salam, M., Ismail, A., and Haefele, S. (2010). 11 Soil Characteristics of Saline and Non-saline Deltas of Bangladesh. *Tropical Deltas and Coastal Zones*, 144.

Saqib, M., Akhtar, J., and Qureshi, R. H. (2004). Pot study on wheat growth in saline and waterlogged compacted soil: I. Grain yield and yield components. *Soil Tillage Res.* **77**, 169-177.

Schjønning, P., and Rasmussen, K. J. (2000). Soil strength and soil pore characteristics for direct drilled and ploughed soils. *Soil Tillage Res.* **57**, 69-82.

Seiler, G., and Gulya Jr, T. (2010). Chapter 1, Basic Information. In: Hu, J., Seiler, G., Kole, C., editors. Genetics, Genomics and Breeding of Sunflower. Enfield, NH: Science Publishers. pp. 1-50.

Seiler, G. J. (1994). Primary and lateral root elongation of sunflower seedlings. *Environ. Exp. Bot.* **34**, 409-418.

Setia, R., and Marschner, P. (2013). Impact of total water potential and varying contribution of matric and osmotic potential on carbon mineralization in saline soils. *Eur. J. Soil Biol.* **56**, 95-100.

Setter, T. L., Waters, I., Sharma, S. K., Singh, K. N., Kulshreshtha, N., Yaduvanshi, N. P. S., Ram, P., Singh, B. N., Rane, J., Mcdonald, G., Khabaz-Saberi, H., Biddulph, T. B., Wilson, R., Barclay, I., Mclean, R. and Cakir, M. (2009). Review of wheat improvement for waterlogging tolerance in Australia and India: the importance of anaerobiosis and element toxicities associated with different soils. *Ann. Bot.* **103,** 221-235.

Shainberg, I., Sumner, M., Miller, W., Farina, M., Pavan, M., and Fey, M. (1989). Use of gypsum on soils: A review. *In* "Adv. Soil Sci.", pp. 1-111. Springer.

Shalhevet, J. (1994). Using water of marginal quality for crop production: major issues. *Agric. Water Manage.* **25**, 233-269.

Sharma, B. R., and Minhas, P. S. (2005). Strategies for managing saline/alkali waters for sustainable agricultural production in South Asia. *Agric. Water Manag.* **78**, 136-151.

Sharma, D. P., Singh, K., and Rao, K. V. G. K. (2000). Subsurface Drainage for Rehabilitation of Waterlogged Saline Lands: Example of a Soil in Semiarid Climate. *Arid Soil Research and Rehabilitation* **14**, 373-386.

Sheldon, A. R., Dalal, R. C., Kirchhof, G., Kopittke, P. M., and Menzies, N. W. (2017). The effect of salinity on plant-available water. *Plant Soil* **418**, 477-491.

Singh, A. (2015). Soil salinization and waterlogging: A threat to environment and agricultural sustainability. *Ecol. Indic.* **57**, 128-130.

Singh, A. (2018). Salinization of agricultural lands due to poor drainage: A viewpoint. *Ecol. Indic.* **95**, 127-130.

Singh, A., Singh, A., Tiwari, H., and Dwivedi, P. K. (2011). The effect of salts of the hydraulic conductivity of the saline alkali soil. *Indian J. Scientific Res.*, 117-120.

Slavich, P., and Petterson, G. (1993). Estimating the electrical conductivity of saturated paste extracts from 1: 5 soil, water suspensions and texture. *Soil Res.* **31**, 73-81.

Smaling, E., and Bouma, J. (1992). Bypass flow and leaching of nitrogen in a Kenyan Vertisol at the onset of the growing season. *Soil Use Manage.* **8**, 44-47.

Steppuhn, H., Van Genuchten, M. T., and Grieve, C. (2005). Root-zone salinity. *Crop Sci.* **45**, 209-220.

Stieger, P. A., and Feller, U. (1994). Senescence and protein remobilisation in leaves of maturing wheat plants grown on waterlogged soil. *Plant Soil* **166**, 173-179.

Tabatabaei, S. (2014). The effect of priming on germination indexes and seed reserve utilization of maize seeds under salinity stress. *Seed. Sci. Technol.* **3**, 44-51.

Tapela, M., and Colvin, T. S. (2002). Quantifying seedbed condition using soil physical properties. *Soil Tillage Res.* **64**, 203-210.

Tindall, J. A., Beverly, R., and Radcliffe, D. (1991). Mulch effect on soil properties and tomato growth using micro-irrigation. *Agron. J.* **83**, 1028-1034.

Tiwari, P., and Goel, A. (2017). An overview of impact of subsurface drainage project studies on salinity management in developing countries. *Appl. Water Sci.* **7**, 569-580.

Todd, D. K., and Mays, L. W. (2005). Groundwater hydrology edition. *Welly Inte*.

Triplett, G., and Dick, W. A. (2008). No-tillage crop production: A revolution in agriculture! *Agron. J.* **100**, S-153-S-165.

Tuong, T., Cabangon, R., and Wopereis, M. (1996). Quantifying flow processes during land soaking of cracked rice soils. *Soil Sci. Soc. Am. J.* **60**, 872-879.

Valipour, M. (2014). Drainage, waterlogging, and salinity. *Arch. Agron. Soil Sci.* **60**, 1625-1640.

van der Most, H. (2009). "Towards Sustainable Development of Deltas, Estuaries and Coastal Zones: Description of Eight Selected Deltas; Trends and Responses," Deltares.

van Genuchten, M. T., Hoffman, G. J., Hanks, R. J., Meiri, A., Shalhevet, J., and Kafkafi, U. (1984). Management Aspect for Crop Production. pp. 258-338. Springer Berlin Heidelberg, Berlin, Heidelberg.

Velasco-Muñoz, J. F., Aznar-Sánchez, J. A., Batlles-delaFuente, A., and Fidelibus, M. D. (2019). Rainwater Harvesting for Agricultural Irrigation: An Analysis of Global Research. *Water* **11**, 1320.

Wallender, W. W., and Tanji, K. K. (1990). "Agricultural salinity assessment and management."

Wallender, W. W., and Tanji, K. K. (2011). Agricultural salinity assessment and management. American Society of Civil Engineers.

Wang, H., Wang, C., Zhao, X., and Wang, F. (2015a). Mulching increases water-use efficiency of peach production on the rainfed semiarid Loess Plateau of China. *Agric. Water Manage.* **154**, 20-28.

Wang, W., Lai, D., Wang, C., Pan, T., and Zeng, C. (2015b). Effects of rice straw incorporation on active soil organic carbon pools in a subtropical paddy field. *Soil Tillage Res.* **152**, 8-16.

Warrence, N. J., Bauder, J. W., and Pearson, K. E. (2002). Basics of salinity and sodicity effects on soil physical properties. *Departement of Land Resources and Environmental Sciences, Montana State University-Bozeman, MT*, 1-29.

Xiukang, W., Zhanbin, L., and Yingying, X. (2015). Effects of mulching and nitrogen on soil temperature, water content, nitrate-N content and maize yield in the Loess Plateau of China. *Agric. Water Manage.* **161**, 53-64.

Xue, J.-F., Ren, A.-X., Li, H., Gao, Z.-Q., and Du, T.-Q. (2018). Soil physical properties response to tillage practices during summer fallow of dryland winter wheat field on the Loess Plateau. *Environ. Sci. Pollut. Res.* **25**, 1070-1078.

Yadav, P. V., Kumari, M., and Ahmed, Z. (2011). Seed priming mediated germination improvement and tolerance to subsequent exposure to cold and salt stress in capsicum. *Res. J. Seed Sci.* **4**, 125-136.

Yadav, S., Mondal, M. K., Shew, A., Jagadish, S. K., Khan, Z. H., Sutradhar, A., Bhandari, H., Humphreys, E., Bhattacharya, J., and Parvin, R. (2019). Community water management to intensify agricultural productivity in the polders of the coastal zone of Bangladesh. *Paddy Water Environ.*, 1-13.

Yu, Y., Mainuddin, M., Sarangi, S., Maniruzzaman, M., and Mandal, U. K. (2019). Rainfall and temperature characteristics in the coastal zones of Bangaldesh and West Begal, India. *J. Indian Soc Coastal Agric. Res.* **32**, 12-23.

Zhao, Y., Pang, H., Wang, J., Huo, L., and Li, Y. (2014). Effects of straw mulch and buried straw on soil moisture and salinity in relation to sunflower growth and yield. *Field Crops Res.* **161**, 16-25.

Zhu, J.-K. (2002). Salt and drought stress signal transduction in plants. *Annu. Rev. Plant Biol.* **53**, 247-273.

Chapter 3

Variation in the yield of sunflower (*Helianthus annuus* L.) due to differing tillage systems is associated with variation in solute potential of the soil solution in a salt-affected coastal region of the Ganges Delta

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3 Variation in the yield of sunflower (*Helianthus annuus* L.) due to differing tillage systems is associated with variation in solute potential of the soil solution in a salt-affected coastal region of the Ganges Delta

Priya Lal Chandra Paul [a, *], Richard W Bell [a], Edward G. Barrett-Lennard [a, b, d], Enamul Kabir [c]

[a] *Land Management Group, Agriculture Discipline, College of Science, Health, Engineering and Education, Murdoch University, WA-6150, Australia*

[b] *Department of Primary Industries and Regional Development, South Perth, WA-6151, Australia*

[c] *Agrotechnology Discipline, Khulna University, Khulna 9208, Bangladesh*

[d] *School of Agriculture and Environment, The University of Western Australia, Nedlands, WA 6009, Australia*

[*] *Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur-1701, Bangladesh and*

[*] *Corresponding author: Tel.: +8801716617378, +610470569881; E-mail: plcpauliwm@yahoo.com*

3.1 Abstract

Intensification of crop production in the coastal zones of the mega-deltas of Asia by dry season cropping requires timely crop establishment to mitigate the adverse effects of waterlogging, drought, salinity and poor soil structure. In the salt-affected coastal zone of the Ganges Delta, the best method of mechanized cultivation for the timely establishment of non-rice dry season crops on poorly structured, wet clay soils is unknown. Two field experiments were conducted to evaluate the effects of tillage systems with different levels of soil disturbance on the establishment, growth and yield of sunflower, and on soil physical and chemical properties. In 2016-17, five tillage treatments were tested: zero tillage (ZT), narrow strip tillage (NST), bed planting (BP), single pass shallow tillage (SPST) and double pass shallow tillage (DP); in 2017-18, four tillage types were tested: NST, wide strip tillage (WST), BP and SPST. Intensive soil disturbance (BP, DP and SPST) maintained higher soil water content in the surface soil (0-15 cm depth) than less disturbance (ZT, NST and WST) in both years. Tillage treatments had no effect on soil salinity ($EC_{1:5}$) in 2016-17, but in 2017-18 BP significantly reduced the soil salinity relative to NST throughout the season. Highest yields (19% and 10% improvements in 2016-17 and 2017-18 respectively) were associated with tillage treatments with greatest soil disturbance, the BP and DP treatments in 2016-17, and the SPST treatment in 2017-18. These effects were mostly due to increases in soil water content and solute potential in surface soil layers. We conclude that for a wet-clay soil, heavy soil disturbance, such as with BP has the potential to increase the yield of sunflower by increasing soil water supply, decreasing soil salinity and maintaining a higher solute potential in the upper soil layers.

Keywords: Bulk density, relative water content, soil salinity, soil water content, stomatal conductance.

3.2 Introduction

The south-west Ganges Coastal Zone in Bangladesh is characterized by low-lying land which is influenced by tidal effects since the elevation is around 2-3 metres above mean sea level. In this environment, most farmers grow only late-planted wet season (‘aman’) rice using tall seedlings of long duration and photoperiod sensitive varieties (Mondal et al., 2015a). The late-planted varieties usually mature in December or January but have low yield. Therefore, the establishment of dry season crops (rabi crops) is delayed because the soil is too wet to cultivate until January, and with this delay in establishment, the rabi crops are forced to ripen during a period of acute water deficiency in May and rising soil salinity (Mondal et al., 2015b).

Conventional tillage, especially puddling soil for transplanted rice in the wet season creates adverse physical conditions for dry season crop establishment (Kirby and Ringrose-Voase, 2000). The common practice of sowing rabi crops is through cultivation by 3-4 tillage passes by rotary tillage that is possible only when the surface soil has drained but often occurs in wet soil with water content at or above field capacity. However, if growers wait for drying of the soil surface, valuable soil moisture can be lost, and the soil becomes harder which results in the poor germination and emergence of seeds. Moreover, the late established rabi crops are often damaged or completely fail due to exposure to drought and soil salinity at the end of the growing season, and the risk of inundation or lodging from early monsoon rains prior to the harvest (Mondal et al., 2015b). A possible solution to these constraints is the early sowing of rabi crops in November and December after drainage of excess water, so that crop's avoid soil salinity constraints and pre-monsoon rains.

Reduced tillage technologies could be applied to enable early establishment of rabi crops into the moist soil as soon as possible after rice harvest, and the use of mulch would help to conserve soil moisture and reduce surface salinization due to the capillary rise of soil pore water (Bezborodov et al., 2010; Pang et al., 2010). However, suitable methods are needed to assist early crop establishment, together with appropriate agronomic management in combination with reduced tillage and mulching (Paul et al., 2016). The advantages and disadvantages of minimum tillage, reduced tillage and conventional tillage have been documented in many studies in different environment and soil conditions (Triplett and Dick, 2008). In the Ganges Delta, conventional tillage (2-5 passes) is the most common practice for the establishment of non-rice crops (Bell et al., 2018; Johansen et al., 2008). This practice substantially disturbs soil structure which can be harmful to root penetration (Johansen et al., 2012; Rahmianna et al., 2000). On the other hand, minimum tillage might help to conserve water in the soil profile, optimize seed and fertilizer placement while decreasing fuel and labour requirement and advancing the sowing time for rabi crops (Haque et al., 2017; Hobbs et al., 2007). However, the negative effects of minimum tillage on soil properties and crops yields have been highlighted by some studies. Minimum tillage in some studies decreased soil profile water (Kováč et al., 2011), crop yields (Alvarez and Steinbach, 2009), and increased soil bulk density (Klute, 1982), soil salinity and evaporation (Gholami et al., 2014). By contrast, bed planting can store soil moisture, alleviate waterlogging and decrease exposure to salt caused by capillary rise (Devkota et al., 2015).

In the coastal area of the Ganges delta, early establishment of high-value crops such as sunflower can be achieved by dibbling into the moist soil (Mondal et al., 2015b). However, minimum (zero and strip tillage) and reduced tillage (bed planting and single pass rather than 3-4 passes) have not been tested in this salt-affected coastal zone. The present study was therefore undertaken to evaluate the effects of decreasing levels of soil surface disturbance on a saline-clay soil for sunflower establishment, and subsequent growth and development. The objectives of our study were to determine the effects of different tillage treatments on: (i) plant establishment, (ii) soil water availability, bulk density, salinity and solute potential, and (iii) grain yield of sunflower.

3.3 Materials and methods

3.3.1 Location and experimental setup

Replicated field experiments were established in 2016-17 and 2017-18 with different tillage systems in a farmer's field at Pankhali, Dacope Khulna Bangladesh (22^0 37' 55'' N and 89^0 30' 10'' E at an elevation of 2-3 m above mean sea level). The climate is sub-tropical monsoonal with high summer temperatures (March-June), dry and cool winters (November-February), and a rainy monsoon period (June to October) with an average annual rainfall of 1800 mm (Mondal et al., 2015b) . The experimental site belongs to the Ganges Tidal Floodplain agro-ecological zone (known as AEZ 13) (BARC, 2012). The soil texture ranged from a silty clay at 0-30 cm depth to clay at 30-60 cm (Supplementary Materials, Table 3S1).

3.3.2 Experimental details and crop management

A medium maturity high-yielding aman rice variety was grown in the wet season and harvested in the last week of November. The land was cleaned by removing the rice straw at ground level to allow excess water to evaporate from the soil surface. Sunflower was established at the start of the dry season using a variety of tillage systems. In 2016-17, the tillage treatments were: ZT (zero tillage), NST (narrow strip tillage), BP (bed planting), SPST (single pass shallow tillage) and DP (double pass shallow tillage). In 2017-18, tillage treatments were: NST, WST (wide strip tillage), BP and SPST. In both years, all tillage systems were tested using the Versatile Multi-crop Planter (VMP) powered with a two-wheel tractor (Haque et al., 2017) in the same field. The field was sown to rice under flooded puddled soil conditions between the two rabi cropping seasons. The treatments were re-randomised in each season. The details of tillage treatments and field performance are described in Table 3.1 and photographic evidence of the effects of the different tillage operations are given in the Supplementary Material (Fig. 3S1).

Table 3.1. Tillage types and associated soil physical constraints for sunflower establishment

Tillage types	Tillage techniques	Disturbance width and depth	Observations [A]
Zero tillage (ZT)	A single tine furrow opener only	Width: 2-4 cm Depth: 2-3 cm	Wheel slip, high draft requirement, compaction and smearing on bottom and side walls of the furrow
Narrow strip tillage (NST)	Four rotary blades with furrow opener	Width: 4-5 cm Depth: 3-5 cm	Some wheel slip, compaction and smearing on bottom and side walls of the strip
Wide strip tillage (WST)	Four rotary blades (Modified tine width) with furrow opener	Width: 8-10 cm Depth: 6-8 cm	Some smearing and compaction of the bottom and side walls of the strip
Bed planting (BP)	One pass full rotary tillage (Fixed 32 tines) arranged to form shallow raised bed	Width: 35-40 cm Depth: 12-15 cm	Large clods and poor seed-soil contact
Single pass shallow tillage (SPST)	One pass full rotary tillage (Fixed 28 tines)	Depth: 9-12 cm	Large clods, machine traffic compaction and poor seed-soil contact
Double pass tillage (DP)	Two pass full rotary tillage (Fixed 28 tines)	Depth: 12-15 cm	Large clods, machine traffic compaction and poor seed-soil contact

[A]: See also photographs of the soil conditions Fig. 3S1.

Each experiment was set-up in a randomized complete block design with four replications in plots 7 m long and 3.5 m wide. Sunflower seeds (cv. Hysun-33, hybrid) were sown on 18 December 2016 and 9 January in 2018 with a plant to plant spacing of 40 cm and a row to row spacing of 60 cm. Before sowing, soil samples were collected at 15 cm increments to a depth of 60 cm to measure soil physical and chemical properties following standard procedures. The collected soils were air-dried and crushed to pass a 2-mm sieve. Analysis of soil physicochemical properties (see Supplementary Material Table 3S3) showed that the soil was slightly alkaline, highly sodic and deficient in some mineral nutrients. These deficiencies were overcome by fertiliser application. Fertilizer (urea-triple super phosphate-muriate of potash-gypsum-zinc sulphate-boric acid) was applied at 200-200-170-170-10-12 kg ha^{-1} based on the recommendation of the Bangladesh Agricultural Research Institute (Mondal et al., 2011). Fertilizers including 25% of urea were applied at sowing; the rest of the urea was topdressed in three splits at 22, 36 and 51 days after sowing (DAS) in 2016-17 and 28, 50 and 60 DAS in 2017-18. Glyphosate (2.5 L ha^{-1}) was applied seven days before sowing to control weeds. Preventive spraying with the insecticide Nitro (Cypermethrin Chlorpyriphos) occurred three times to control pests. Light irrigation water was applied by hose pipe from a nearby canal at 22, 36, 51 and 65 DAS in 2016-17 and at 16, 28, 50 and 60 DAS in 2017-18. Irrigation water was measured volumetrically, and the amounts applied in 2016-17 and 2017-18 were 70 mm and 80 mm respectively, split across four times of application. Dates of sunflower emergence, flower bud initiation, first flowering, 80% flowering and physiological maturity were recorded for both seasons. During harvest, yield and yield related parameters such as average plant height, head diameter, number of seeds per head, and thousand seed weight were calculated from 10 randomly selected plants in each plot. Seeds were threshed manually from heads and air-dried for 1-2 days to calculate the final yield (t ha^{-1}) at an adjusted moisture content of 9% (w/w).

3.3.3 Soil water content and bulk density measurement

Soil water content was measured gravimetrically at 0-7, 7-15,15-30, 30-45 and 45-60 cm depths at 15-30 days intervals between sowing and harvest for all tillage treatments. Before sowing, undisturbed soil at these depths was collected to measure soil water content at field capacity and wilting point by using pressure plate apparatus (Eijkelkamp pF set). Soil bulk density was measured at 0-7, 7-15,15-30, 30-45 and 45-60 cm depths before sowing and after the harvesting of the crops. Intact soil cores (5 cm height and 4.8 to 5 cm in diameter) were extracted from the soil. The initial weight of the samples was measured, and then soils were dried in an oven at 105^0 C for about 48 hours. After removing from the oven, soils were weighed again, and bulk density was calculated (Cresswell and Hamilton, 2002).

3.3.4 Soil electrical conductivity ($EC_{1:5}$) and the calculation of soil solute potential

The $EC_{1:5}$ of soil was measured for soil from 0-7, 7-15, 15-30, 30-45 and 45-60 cm depth at different stages of plant growth. Measurements were made in $EC_{1:5}$ (dS m^{-1}) extracts (a 1:5 soil: water suspension) using a portable EC meter. The solute potential of the soil solutions was calculated by the following equation:

$\Psi_s = -22580 \times EC_{1:5}/W$

where, Ψ_s is the solute potential (kPa), $EC_{1:5}$ is the electrical conductivity (dS m^{-1}) of the 1:5 soil: water extract and W is the soil water content (% w/w). This formula is based on that of Rengasamy (2010), with the additional considerations that the mix of salts in the soils of Ganges-Bramaputra Delta is ~2/3 NaCl and ~1/3 $MgSO_4$ (Bandyopadhyay et al., 2003), and that the slopes of the lines between EC and solute potential for these two salts were as reported by Wolf et al., (1986).

3.3.5 Measurement of leaf relative water content

Relative water content (RWC) of the leaves was measured at different stages of the growing season in 2017-18 (4 March, 14 March and 24 March). In each replication, the 3-4 top-most fully expanded leaves were sampled and placed into a plastic pre-weighed sealed jar. The fresh weight (FW) of the leaf was measured immediately, and the sample was then placed in a cool box before 20 mL of water was added to the jar. The samples were placed in a refrigerator to chill overnight before the samples were taken from the jar and the external moisture was removed with a paper towel before measuring the turgid leaf weight (TW). After that, the samples were oven dried at 70^0C for 24 hours before dry weight (DW) of the samples were measured. The RWC (%) was then calculated using the following equation (Pask et al., 2012).

RWC (%) = [(FW-DW)/(TW-DW)] x 100

3.3.6 Stomatal conductance

Stomatal conductance of sunflower leaves was measured with a leaf porometer (SC-1 Leaf Porometer, Decagon Devices) in 2017-18. Weekly measurements were made from maximum vegetative to flowering stage. In each replication, three readings were taken from three fully expanded leaves. The readings were made between noon and 2 pm to avoid morning dew and reduced light in the later afternoon. Measurements were also taken before irrigation and after irrigation to monitor the effect of water stress on plant transpiration.

3.3.7 Statistical analysis

The effects of tillage on grain yield and yield components (Table 3.2) were determined using an one-way analysis of variance (ANOVA) (STAR Version 2.0.1). The significance of effects of tillage on soil water content, $EC_{1:5}$ and solute potential (Figs. 3.1, 3.2 and 3.3) were determined using three-way factorial ANOVA model that also took account of the effects of tillage treatments, soil depth and date after sowing (time) as repeated measures (STAR). The differences between means were tested using the least significance difference (LSD) at the 95% confidence level. Microsoft Office 365 was used to prepare the graphs.

3.4 Results

3.4.1 Weather

In 2016-17, total rainfall throughout the cropping season (December to April) was 173 mm, but two-thirds of this fell in March during the flowering stage. However, in the 2017-18 season, 51 mm of rain in December delayed the sowing, while no rain fell in the following months except 64 mm of rain in the second week of April (Supplementary Materials; Fig. 3S2). Monthly mean pan evaporation in each season was similar from November to April but slightly lower in the early growing season (December to February) than the later part of the growing season (March-April). Daily maximum temperature was similar in both seasons apart from higher values in March and April in 2017-18. The winter spell (December-February) in 2017-18 was warmer than in 2016-17 (Supplementary Materials; Fig. 3S3).

3.4.2 Emergence and growth observations

In 2016-17, most emergence occurred in the ZT and NST treatments after 5-7 days, whereas it was delayed 6-8 days for SPST and DP, and 7-10 days for the BP (Supplemental Materials; Table S2). In 2017-18, emergence was delayed relative to 2016-17 by 3-7 days in NST, WST and SPST and 2-9 days in BP. The reason for the delayed emergence in the BP, SPST, and DP treatments was poor seed-soil contact, because intensive tillage in the wet soil produced large clods. In addition, emergence was later in 2017-18 because the soil water content was slightly lower than in 2016-17 which increased surface dryness and soil shrinkage.

At 25 days after emergence, there were more plants per square metre in the NST and fewer in the BP treatment in both years. Flower bud initiation was earlier in 2017-18 (59-61 DAS) than in 2016-17 (60-63 DAS). The first flowering in both seasons started at 72-74 days while 80% flowering was completed 3-5 days earlier in 2017-18 than in 2016-17. The physiological maturity took 2-3 days longer (112 days) in the ZT and NST than the BP and DP treatments

(109 days) in 2016-17, whereas physiological maturity was longer in the BP (107 days) than the NST treatments (105 days) in 2017-18 (Supplementary Materials; Table 3S2).

3.4.3 Yield and yield attributes under different tillage types

Analysis of variance showed significant effects of tillage treatment on seed yield in both years (Table 3.2). In 2016-17, seed yield was highest with the greatest soil disturbance (BP, SPST and DP), it was lower with the NST treatment (8% less than BP) and lowest with the ZT treatment (19% less than BP). The number of seeds per head was highest with the BP and DP treatment and was lowest (14% lower than BP) with the ZT treatment. Plant height in the BP and SPST treatments was significantly higher than with ZT and NST treatments but not different to DP. However, tillage treatments did not affect thousand seed weight. Head diameter was highest with the BP, DP and SPST treatments and was lowest (8% lower) with the ZT treatment. The higher grain yields were correlated with increased number of seeds per head ($r^2 = 0.49$; $P < 0.001$) and with increased plant height ($r^2 = 0.46$; $P < 0.001$). Differences in plant yields were not correlated with differences in head diameter (where tillage had significant effects, but overall, these were uncorrelated with yield) or thousand grain weight (where there were no significant effects on yield).

In 2017-18, the highest grain yield was also with the greatest soil disturbance(SPST and BP) and lowest with the NST and WST treatments. Bed planting produced significantly more seeds per head than NST and WST, whereas there was no difference between the BP and SPST treatmetns. Thousand seed weight with BP was significantly higher than with the NST and WST treatments. The higher grain yields were correlated with increased numbers of seeds per head ($r^2 = 0.86$; $P < 0.001$) and increased thousand seed weight ($r^2 = 0.81$; $P < 0.001$) but not with plant height or head diameter.

Table 3.2. Yield and growth attributes of sunflower under different tillage treatments in Pankhali, Dacope, Bangladesh in 2016-17 and 2017-18.

Treatments	Seed yield ($t\ ha^{-1}$)	Number of seeds per head	Plant height (cm)	1000 seed weight (g)	Head diameter (cm)
		Year 2016-17			
ZT	2.9	1229	119	84.5	22
NST	3.3	1257	119	85.2	23
BP	3.6	1422	128	90.5	24
SPST	3.5	1349	129	85.3	24
DP	3.6	1373	125	85.5	24
P-value	0.001	0.04	0.04	0.22	0.01
LSD at $P < 0.05$	0.32	132	7.6	NS	0.8
		Year 2017-18			
NST	2.8	1160	135	82	17.8
WST	2.7	1140	133	81	16.8
BP	2.9	1233	138	83	18.8
SPST	3.1	1201	141	83	18.2
P-value	0.02	0.007	0.23	0.01	0.08
LSD at $P < 0.05$	0.21	66.8	NS	1.31	NS

NS indicates not significant. LSD indicates least significant difference. Abbreviations: ZT-zero tillage, NST-narrow strip tillage, WST-Wide strip tillage, BP-bed planting, SPST-single pass shallow tillage, DP-double pass shallow tillage.

3.4.4 Changes in soil water content at different soil depths and over time

In both growing seasons, soil water content (SWC) was significantly affected by tillage treatments ($P < 0.001$), soil depth ($P < 0.001$), date after sowing (Time) ($P < 0.001$), and there were significant interaction between treatments and Time ($P < 0.001$), treatments and soil depth ($P < 0.01$), and Time and soil depth ($P < 0.001$) (for ANOVA see Supplementary Materials Table 3S4; and for effects see Fig. 3.1). In 2016-17, after crop establishment on 18 December, SWC decreased gradually at all depths until 17 March when it increased after heavy rainfall in the second week of March (Fig. 3.1A). The least SWC was at bud formation stage (17 Feb) where SWC decreased by 10.8% (w/w), 9%, 7.2%, 9% and 8.3% under ZT, NST, BP, SPST and DP treatments compared to the sowing time (Fig. 3.1A). During the season, tillage altered SWC mostly in the topsoil (0-15 cm) and the effect of tillage on SWC decreased with increasing soil depth (Fig. 3.1B). Most of the time during the growing season, SWC was higher at 0-7 cm than at 7-15 cm depth, and it was most responsive at 0-7 cm to the five tillage treatments. By contrast, at 45-60 cm depth, there was a higher SWC compared to other depths and the level changed only slightly between sowing and harvest (Fig. 3.1C).

In 2017-18 during crop establishment, the SWC was about 9-15% lower at all depth intervals between 0 and 60 cm depth than in 2016-17 (Fig. 3.1D-F). Compared to the sowing time, there was a substantial decrease in SWC at flowering (25 March) where SWC were lower by 11.9% (w/w), 9.2%, 8.8% and 9.6% under NST, WST, BP and SPST tillage treatments respectively (Fig. 3.1D). Throughout the growing season, SWC was consistently higher with BP than with NST and WST treatment (Fig. 3.1D). The effect of tillage treatments was more pronounced at 0-7 and 7-15 cm and less noticeable at greater depths (Fig. 3.1E). During the season, SWC was significantly lower at 0-15 cm than at 45-60 cm, and SWC at 0-7 cm depth was most altered by tillage treatments.

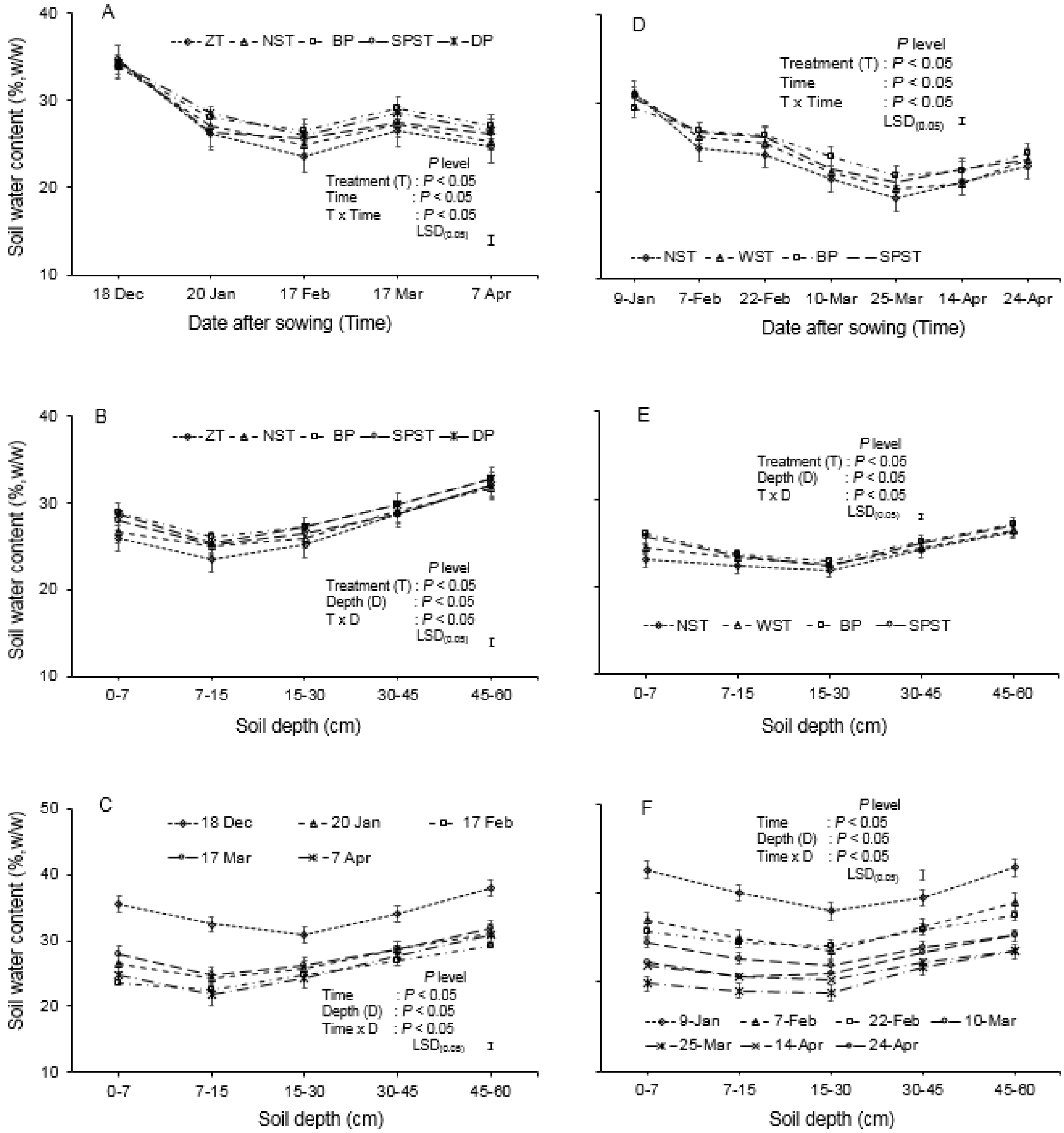

Fig. 3.1. Effects on soil water content in 2016-17 (A, B and C) and in 2017-18 (D, E and F). A and D show effects of tillage treatments and Time, B and E show effects of tillage treatments and soil depth, and C and F show effects of Time and soil depth. Abbreviations: ZT = Zero tillage, NST = Narrow strip tillage, WST = Wide strip tillage, BP = Bed planting, SPST = Single pass shallow tillage and DP = Double pass tillage. Bars represent standard error. LSD is the least significant difference of treatment and Time (A and D), treatment and depth (B and E), and Time and depth (C and F).

3.4.5 *Changes in $EC_{1:5}$ at different soil depths during the growing season*

In both seasons, $EC_{1:5}$ values were significantly affected by soil depth ($P < 0.001$) and Time ($P < 0.001$), but not tillage treatments ($P > 0.05$) in 2016-17 (for ANOVA see Supplementary Materials Table 3S4; and for effects see Fig. 3.2). There was no interaction between treatments and soil depth, and treatments and time on $EC_{1:5}$ in both years. With the progress of the dry season in 2016-17, the $EC_{1:5}$ values increased until 17 March when they decreased sharply after heavy rainfall (Fig. 3.2A). $EC_{1:5}$ values at 0-7 cm and 45-60 cm were significantly higher than 15-30 cm, and the greatest $EC_{1:5}$ variation was at 0-7 cm (Fig. 3.2C). Similar trends were observed in the 2017-18 season, although $EC_{1:5}$ values were generally lower (Fig. 3.2D, E and F). Over the entire season, there were larger changes in $EC_{1:5}$ at 0-7 cm than lower depths up to 60 cm. By the end of the growing season, $EC_{1:5}$ (0.77 dS m^{-1}) at 0-7 cm was 37% higher compared to $EC_{1:5}$ (0.48 dS m^{-1}) at the sowing time (Fig. 3.2F).

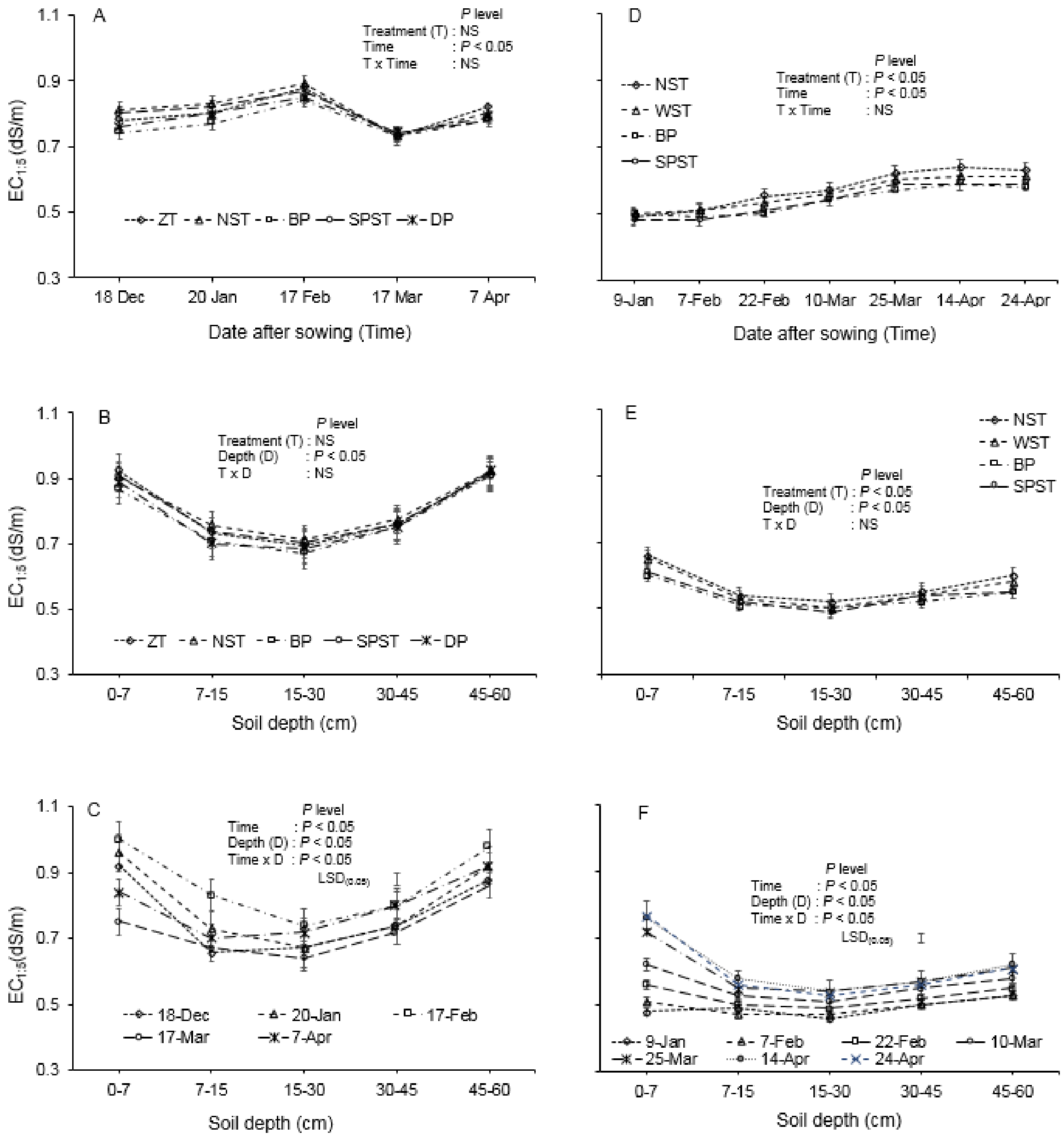

Fig. 3.2. Effects on $EC_{1:5}$ values in 2016-17 (A, B and C) and in 2017-18 (D, E and F). A and D show effects of tillage treatments and Time, B and E show effects of tillage treatments and soil depth, and C and F show effects of Time and soil depth. Abbreviations: ZT = Zero tillage, NST = Narrow strip tillage, WST = Wide strip tillage, BP = Bed planting, SPST = Single pass shallow tillage and DP = Double pass tillage. Bars represent standard error. LSD is the least significant difference of Time and soil depth (C and F).

3.4.6 Changes in solute potential (SP)at different soil depths during the growing season

In both growing seasons, solute potential (SP) were significantly affected by tillage treatments ($P < 0.001$), soil depth ($P < 0.001$), and Time ($P < 0.001$), and there were significant interaction between treatments and Time ($P < 0.001$), treatments and soil depth ($P < 0.01$), and Time and soil depth ($P < 0.001$) (for ANOVA see Supplementary Materials Table 3S4; and for effects see Fig. 3.3). In both years, the SP of the soil solution decreased (i.e., became more negative) with the progress of the dry season due to the combined effects of increasing soil salinity and declining soil moisture (Fig. 3.3A and 3.3D). This was avoided to some degree on 17 March in the 2016-17 cropping season and 24 April in the 2017-18 cropping season because of the hydrating effects of rainfall. In 2016-17, tillage treatments affected the SP at 0-15 cm but not at deeper depths (Fig. 3.3B), while in 2017-18, there was an effect at all depths to 60 cm (Fig. 3.3E). In all cases where there were significant effects of tillage on SP, BP had the highest (least negative) potentials and ZT (2016-17 growing season) or NST (2017-18 growing season) had the lowest (most negative) potentials. Over the period, the differences in the SP due to tillage were greatest at 0-7 cm depth on 17 February for the 2016-17 growing season and on 25 March for the 2017-18 growing season (Fig. 3.3C and 3.3F).

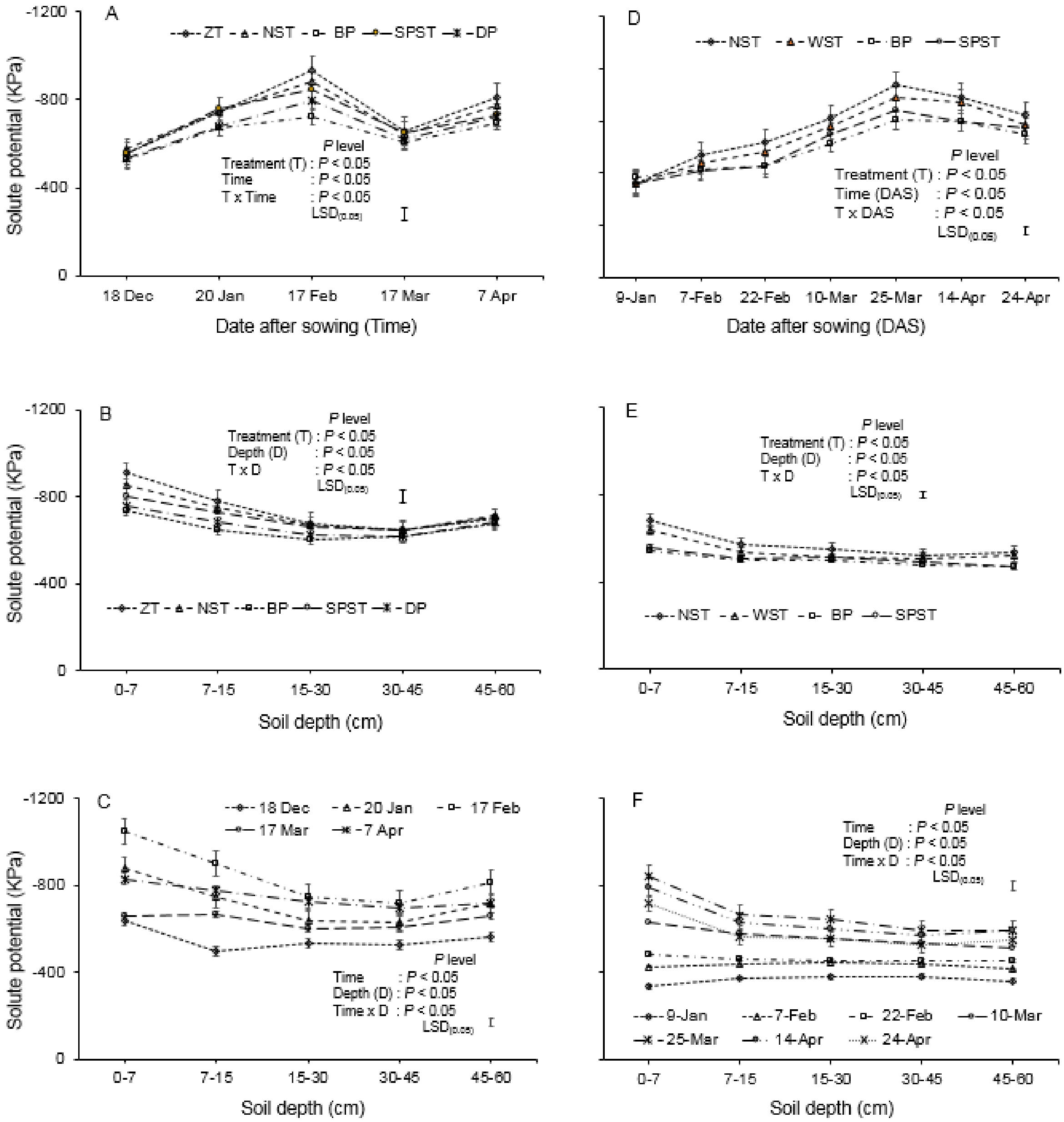

Fig. 3.3. Effects of solute potential in 2016-17 (A, B and C) and in 2017-18 (D, E and F). A and D show effects tillage treatments and Time, B and E show effects of tillage treatments and soil depth, and C and F show effects of Time and soil depth. Abbreviations: ZT = Zero tillage, NST = Narrow strip tillage, WST = Wide strip tillage, BP = Bed planting, SPST = Single pass shallow tillage and DP = Double pass tillage. Bars represent standard error. LSD is the least significant difference of treatment and Time (A and D), treatment and soil depth (B and E), and Time and soil depth (C and F).

3.4.7 Changes in bulk density at different soil depth

Before sowing in 2016-17, the soil bulk density (BD) was lowest (1.4 Mg m^{-3}) at 0-7 cm and 45-60 cm depths compared to 1.6-1.7 Mg m^{-3} at 15-30 cm and 30-45 cm (Fig. 3.4a). Bulk density after harvest was strongly influenced by tillage (Fig. 3.4b). With the BP treatment, the BD was significantly lower than the ZT and NST at depths up to 60 cm. However, there was no difference in BD between the ZT and NST or SPST and DP at 0-7 cm and 7-15 cm depths. Before sowing in 2017-18, the BD at 0-7 cm was ~ 1.4 Mg m^{-3} increasing to 1.6 Mg m^{-3} at greater depth (Fig. 3.4c). After harvest, the BD had increased at 0-7 cm depth, but there was little change at the greater depths (Fig. 3.4d). The bulk density in the BP was significantly lower than that of the NST and WST, but there was no difference between NST and WST, and BP and SPST. The BD density at 0-7 cm significantly lower than bottom depth up to 60 cm. Grain yields were correlated with bulk density in 2016-17 ($P < 0.02$) but were not correlated in 2017-18.

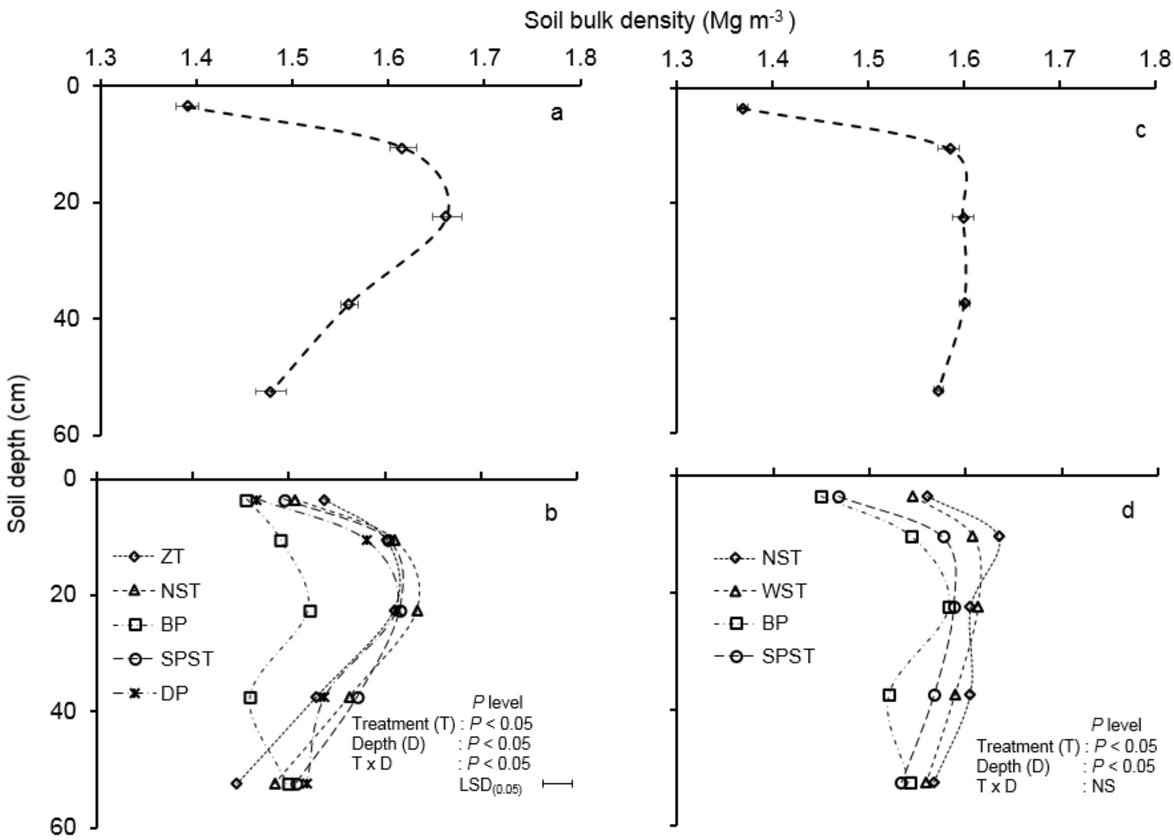

Fig. 3.4. Average bulk density by depth before sowing (a – 2016/17) and (c – 2017/18), and after harvest (b – 2016/17) and (d – 2017/18). Parts (b) and (d) also show the effects of tillage treatment; these were statistically analysed as tillage x depth with depth as a repeated factor. LSD is the least significant difference of treatment by depth.

3.4.8 Effect of tillage treatments on plant water relations

Plant water relations data are only available for the second growing season. The relative water content (RWC) and stomatal conductance (SC) were higher on 4 March than on 14 March and 24 March (Supplementary Materials; Fig. S4). There was no difference of RWC in four tillage treatments on 4 March. The RWC in BP was significantly higher than NST and WST on 24 March but no different to SPST. At 44 DAS, stomatal conductance (SC) in WST and SPST were significantly greater (P < 0.05) than NST but not different to BP (Supplementary

Materials; Fig. 3S5). The SC was increased in all tillage treatments at 50 DAS after applied irrigation. The SC was higher by about 9-6% and 12-9% in BP and SPST over NST and WST, respectively, at 50 DAS. At 61 DAS, SC did not differ among NST, WST and BP but the value was considerably higher in SPST.

3.4.9 Plant response to solute potential (SP) of soil solutions

In general, sunflower yield decreased with decreasing SP (increasingly negative) (Fig. 3.5 for the 2016-17 season and Fig. 3.6 for the 2017-18 season). In 2016-17, the SP at 0-7, 7-15 and 15-30 cm were corelated with yield on eight date × depth combinations with r^2 values between 0.38 and 0.68, and *P* values <0.01 and <0.001 (Fig. 3.5). There was no correlation between yield and SP at 30-45 cm or 45-60 cm depth.

In a similar manner in 2017-18, the SP at 0-7, 7-15 and 15-30 cm depth were correlated with sunflower yield on eight date × depth combinations with r^2 values between 0.22 and 0.57, and *P* values < 0.05, < 0.01 and < 0.001 (Fig. 3.6). In each growing season, the strongest relationship between SP and grain yield (highest r^2 and lowest *P*-values) was in the mid-season (17 February in the 2016-17; 7 Feb in the 2017-18) at either 7-15 cm or 0-7 cm, respectively (Fig. 3.5 and 6). Moreover, in both years, SP had a better fit with yield at 0-7 cm depth than $EC_{1:5}$ (Fig. 3.7).

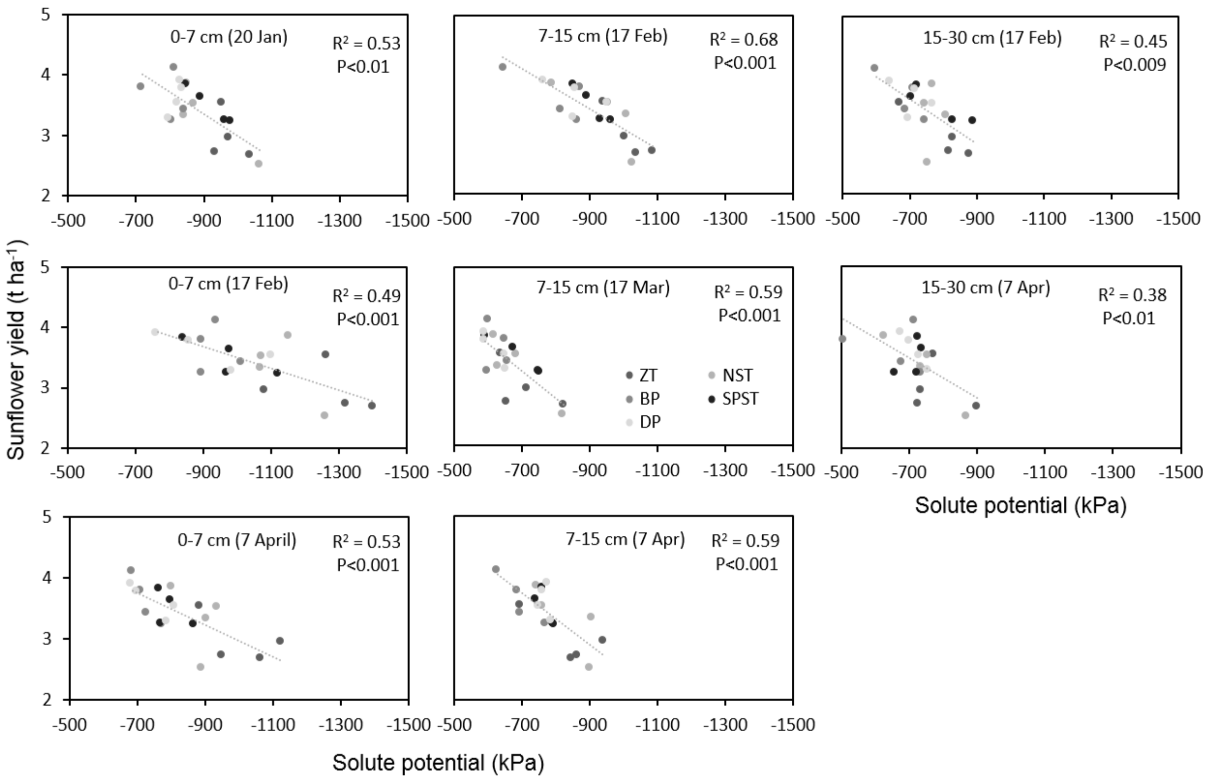

Fig. 3.5. Relationship between sunflower yield and solute potential of soil solutions at different growth stages of sunflower and at different depths of soil in the 2016-17 growing season. Abbreviations: ZT-zero tillage, NST-narrow strip tillage, BP-bed planting, SPST-single pass shallow tillage, DP-Double pass tillage.

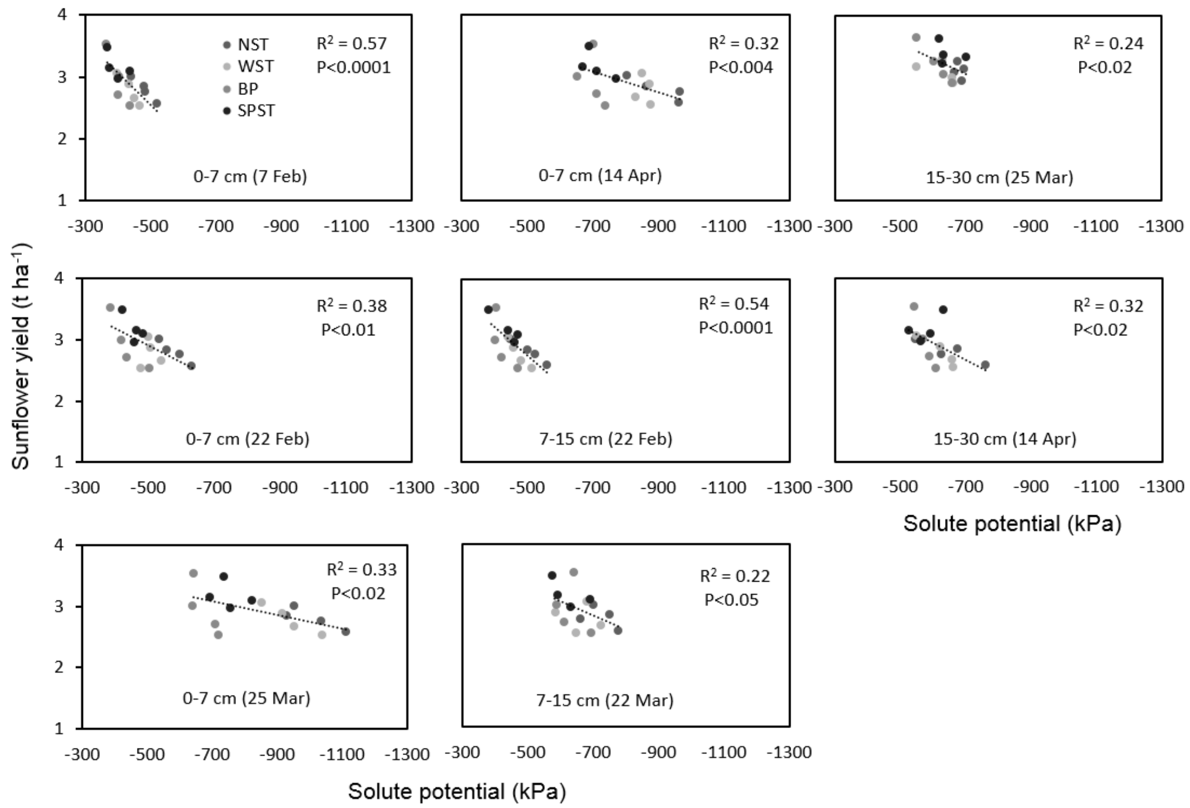

Fig. 3.6. Relationship between sunflower yield and solute potential of soil solutions at different growth stages of sunflower at different depth of soil in the 2017-18 growing season. Abbrebations: Legend: NST-narrow strip tillage, WST-Wide strip tillage, BP-bed planting, SPST-single pass shallow tillage.

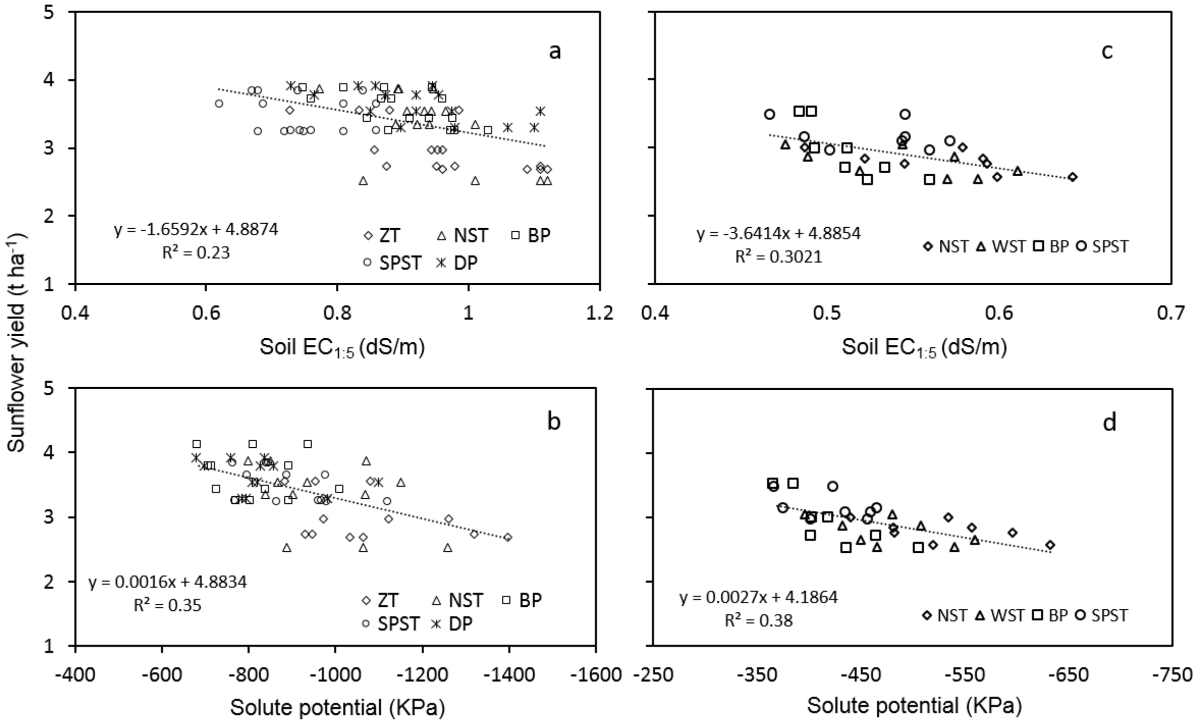

Fig. 3.7. Sunflower yield as a function of: (a) soil $EC_{1:5}$ and (b) solute potential in 2016-17 and (c) soil $EC_{1:5}$ and (d) solute potential of the soil solution in 2017-18 at 0-7 cm depth.

3.5 Discussion

Numerous studies worldwide have pointed to the value to crop production and soil management of zero or minimum tillage. However, the present work presents a contrary case. In our studies, in a heavy textured moderately saline soil, in both years, it was the tillage methods which substantially disturbed the soil (BP, SPST and DP) that increased crop yield; this was attributed to increased soil water content (SWC), decreased soil salinity, and therefore higher solute potential in surface soil layers. These conclusions were contrary to the expectations that we had at the outset of the work. The responses to tillage systems were related to changes in bulk density, increased penetration of root systems and improved plant water status. The following text focuses on the impacts of tillage on crop establishment, growth and yield. We then discuss in more detail the effects of tillage on soil water content, soil salinity and solute potential, and soil bulk density.

3.5.1 Crop emergence, growth and yield

Across all tillage treatments, there were no relationships between crop emergence and later growth and grain yield. In fact, the tillage systems that showed the least crop emergence were not those that had the highest subsequent growth and grain yield. The fastest emergence with more plants per square metre occurred with the tillage treatments that caused least soil disturbance (i.e. ZT, NST and WST), but subsequent crop growth and development was less vigorous than with plants established with greater soil disturbance. In 2016-17, the BP and DP treatments had more seeds per head which led to greater yield (3.6 t ha^{-1}) than the ZT (2.9 t ha^{-1}) and NST (3.3 t ha^{-1}) treatments. In 2018, the SPST had a 10% higher yield than NST and WST, but there was no difference among NST, WST and BP treatments. Similar yields of sunflower (3.5 t ha^{-1}) were found in the coastal zone of Bangladesh, where tillage was performed by rotary tractor (3-4 passes) (Mondal et al., 2015b) and by dibbling in low salinity soils (Bhattacharya et al., 2019). The plausible reasons for the better yield in the BP, DP, and SPST (intensive soil disturbance) were greater soil water content and lower soil salinity which together resulted in higher (less negative) solute potential in soil water. Across all tillage treatments, we found significant linear relationships between sunflower grain yield and SP for eight combinations of time and depth in the soil profile (Figs. 3.5 and 3.6). In each year, the most compelling of these relationships ($P < 0.001$) were at 0-7 cm and 7-15 cm. In this study, sunflower growth was most closely related to the SP in the surface layers (Fig. 3.7) suggesting that the plant availability of this pore water was more important to critical stages of sunflower growth than water deeper in the profile.

3.5.2 Soil water content

Sunflower yield is generally more sensitive to water stress at flowering than seedling and bud initiation stages (Unger, 1983). However, the effects of water stress in the present experiments may have not been most severe at flowering. In both years, from 30 DAS onwards, soil water content with the ZT and ST (strip tillage) treatments was lower than with the BP, SPST, and DP treatments. The lowest gravimetric SWC was at bud formation and flowering stage in the first and second year; this was 20% (w/w) and 25% in ZT and BP in the first year and 19% and 22% in NST and BP in the second year (Fig. 3.1). The gravimetric soil water content at field capacity and wilting point in the heavy clays soil were 35-37% (w/w) and 25-28%, respectively. Therefore, in the minimum tillage treatments, SWC dropped below the wilting point at 0-7 cm, whereas for the more disruptive tillage SWC was close to or above the wilting point. Water stress with minimum tillage mainly appeared at the bud initiation stage but there was higher soil water content at flowering and maturity stages due to rainfall. At the time when SWC was close to or below the wilting point in the surface soil layers, there were higher SWCs at depths up to 60 cm (Fig. 3.1) which suggests that sunflower could have extracted water from 15-60 cm depth to avoid severe water stress. Cox and Jolliff (1986) reported that under dry-land conditions sunflower can extract water from depths to 1.8 m during the reproductive stage. Other studies such as Xue et al. (2018) have also reported that intensive tillage (deep ploughing) increased SWC at 0-50 cm depth compared to no-tillage on the Loess Plateau for dry land winter wheat. Kováč et al. (2011) showed that SWC under conventional tillage (mouldboard ploughing to 30 cm depth) was significantly higher than with no-tillage under maize-spring-barely and maize-peas crop rotations. Studies in Scandinavian countries and the Argentine Pampas have shown that minimum tillage treatments like ZT and ST in wet-clay saline soils increase soil densification (Rasmussen, 1999), decrease soil structural stability (Alvarez and Steinbach, 2009), and promote the formation of large vertical voids deep cracks (Strudley et al., 2008) which accelerate water loss from the soil by evaporation. In addition, surface dryness, plus compaction and smearing on the wall of furrow and strips in zero and strip tillage may inhibit root elongation and growth of sunflower plants

3.5.3 Soil salinity and soil solute potential

In the present study, $EC_{1:5}$ was affected by tillage, soil depth and rainfall. In the first season, the $EC_{1:5}$ was slightly higher with the ZT and NST treatments than with the BP during the period from emergence to bud initiation. Later, the $EC_{1:5}$ decreased at the flowering and grain filling stages because of rainfall in 2017 (Fig. 3.2A). By contrast, in the second growing season, in the absence of rain, the $EC_{1:5}$ increased from emergence to flowering (Fig. 3.2D) and the NST had a significantly higher salinity than the BP treatment. A range of studies have focused on the effects of tillage on soil salinity. In the arid region, Gholami et al. (2014) found higher EC_e in no-tillage than conventional tillage. In addition, raised beds have been regarded an effective option for reducing waterlogging and soil salinity in landscapes with shallow saline groundwater (Bakker et al., 2010; Slavich, 2006). Devkota et al. (2015) reported that soil salinity was significantly lower in the permanent bed planting compared to conventional tillage. The higher level of soil salinity with the ZT and NST treatments could be related to the reduced soil disturbance after puddled soil in wet season rice which leads to greater soil drying and cracking thereby increasing evaporation and salt accumulation at the surface. In addition, the lower soil salinity in the upper soil layers with the BP treatment may be associated with the increased production of coarse soil clods with capillary breaks that slow down evaporation and decrease the upward movement of salt to the surface (So and Ringrose-Voase, 2000).

Water uptake by plants is governed by the total water potential of the root zone soil which is determined by both the soil matric potential and the solute potential (SP) of the soil solutions (Campbell, 1988; Rengasamy, 2006). The SP is proportional to the salt concertation in the soil and inversely related to the soil water content (Chi, 2014; Rengasamy, 2006). Osmotic stress, with its adverse effects on growth, can therefore increase with cultural practices which either elevate salt concentrations or decrease soil water content (Benlloch-González et al., 2005; Chen and Jiang, 2010) or both. In our study, the combination of greater SWC, lower soil salinity and higher SP with BP and SPST treatments maintained the higher RWC and SC at vegetative and flowering stages than with NST treatments.

In the present work, the SP varied with soil depth, tillage and rainfall. The main effects of tillage occurred at 0-7 and 7-15 cm in both seasons. In the first year, the SP became more negative with the ZT (-1264 kPa) and NST (-1137 kPa) treatments and was close to permanent wilting point (-1500 kPa) at 0-7 cm at the bud formation stage; however, there were increases in SP with rainfall at flowering in mid-March (Fig. 3.3A). By contrast, in the second rabi season (a season without rain up to flowering) the lowest SP was with the NST and WST treatments (-1007 kPa and -941 kPa) and occurred at flowering; these were less limiting to plant water uptake than in 2017. In both seasons, the SP with the BP treatment was significantly higher than with the ZT and NST treatments. The lower SP with the ZT and ST treatments appeared to be due to the increased soil salinity and decreased SWC caused by higher evaporation rate because of reduced soil disturbance. On the other hand, the higher SP with the BP and DP treatments demonstrated the effect of increased soil disturbance in decreasing soil salinity and increasing soil water storage in the upper soil layers which we attribute to reduced evaporation caused by increased clods at the soil surface and the breakdown of capillary connectedness.

One of the issues that has come sharply into focus in our study is the best method of reporting salinity in field experiments. There has been a tradition of reporting soil salinities as concentrations of salinity in the soil (of which the $EC_{1:5}$ or EC_e are estimates) (Katerji et al., 2000; Maas and Hoffman, 1977; Steppuhn et al., 2005). In our study, the response of sunflower yield to salt stress was more closely related to SP of soil solutions than to $EC_{1:5}$ (Fig. 3.7a-d). When soil water content varies together with EC, SP would be more beneficial to the interpretation and evaluation of salt effects on plants growth and yield than EC (Ben-Gal et al., 2009).

3.5.4 Soil bulk density

One way in which tillage may impact on crop growth is through effects on soil bulk density, although, the effects of tillage on soil bulk density are not consistent. Bulk density is influenced by soil texture, compaction and organic matter; values greater than 1.47 Mg m^{-3} are said to restrict root growth (Hunt et al., 1992). In some cases, under zero tillage there have been reports of decreased bulk density (Alam et al., 2018; Kahlon et al., 2013; Shaver et al., 2002) and in other cases there have been reports of increased bulk density (Celik, 2011; Grant and Lafond, 1993; Klute, 1982) under ZT. In the present work, in the first growing season, the bulk densities for the BP and DP treatments (1.46 and 1.47 Mg m^{-3} ,respectively) were borderline for root growth while with the ZT treatment the BD was high enough to limit root growth (1.54 Mg m^{-3}). That the BP treatment had lower a BD in the surface soil compared to the others tillage treatments can be attributed to the intensive soil disturbance required to form a bed including the incorporation of loosened soil. By contrast, with the reduced tillage treatments (ZT and ST) in wet clay-soil, the elevation in bulk density was presumably caused by the many sequences of swelling and shrinkage over many prior years of rice-fallow rotation.

3.6 Conclusions

On wet-clay soil in the salt-affected coastal zone of the Ganges delta, tillage techniques that reduced soil disturbance (ZT and ST) enhanced the emergence and density of sunflower, but subsequent shoot growth and development was depressed. The reduced soil disturbance increased soil dryness, soil bulk density and salinity and decreased the solute potential in soil surface layers. Tillage techniques that increased soil disturbance (BP, SPST and DP) decreased soil salinity and increased water storage in the surface layers of soil profile. Bed planting, SPST, and DP improved soil water uptake by the plant due to increased solute potential and produced maximum yield. Therefore, increasing surface disturbance was most effective for achieving maximum yield in the salt-affected area. We attribute this as being largely due to the increased solute potential in the surface soil.

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3.7 References

Alam, M., Bell, R., Salahin, N., Pathan, S., Mondol, A., Alam, M., Rashid, M., Paul, P., Hossain, M., and Shil, N. (2018). Banding of fertilizer improves phosphorus acquisition and yield of zero tillage maize by concentrating phosphorus in surface soil. *Sustainability* **10**, 3234.

Alvarez, R., and Steinbach, H. (2009). A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. *Soil Tillage Res.* **104**, 1-15.

Bakker, D. M., Hamilton, G. J., Hetherington, R., and Spann, C. (2010). Salinity dynamics and the potential for improvement of waterlogged and saline land in a Mediterranean climate using permanent raised beds. *Soil Tillage Res.* **110**, 8-24.

Bandyopadhyay, B., Maji, B., Sen, H., and Tyagi, N. (2003). Coastal soils of West Bengal: their nature, distribution and characteristics. Bulletin No. 1/2003, Central Soil Salinity Research Institute, Regional Station, Canning Town, West Bengal, 62.

BARC (2012). Fertilizer recommendation guide, 2012. Bangladesh Agric. Res. Council (BARC) Dhaka, Bangladesh.

Bell, R., Haque, M., Johansen, C., Vance, W., Kabir, M., Musa, M., Mia, M., Neogi, M., and Islam, M. (2018). Mechanised minimum soil disturbance establishment and yield of diverse crops in paddy fields using a two-wheel tractor-mounted planter suitable for smallholder cropping. *Exp. Agric.* **54**, 755-773.

Ben-Gal, A., Borochov-Neori, H., Yermiyahu, U., and Shani, U. (2009). Is osmotic potential a more appropriate property than electrical conductivity for evaluating whole-plant response to salinity? *Environ. Exp. Bot.* **65**, 232-237.

Benlloch-González, M., Fournier, J. M., Ramos, J., and Benlloch, M. (2005). Strategies underlying salt tolerance in halophytes are present in Cynara cardunculus. *Plant Sci.* **168**, 653-659.

Bezborodov, G., Shadmanov, D., Mirhashimov, R., Yuldashev, T., Qureshi, A. S., Noble, A. D., and Qadir, M. (2010). Mulching and water quality effects on soil salinity and sodicity dynamics and cotton productivity in Central Asia. *Agric. Ecosyst. Environ.* **138**, 95-102.

Bhattacharya, J., Saha, N. K., Mondal, M. K., Bhandari, H., and Humphreys, E. (2019). The feasibility of high yielding aus-aman-rabi cropping systems in the polders of the low salinity coastal zone of Bangladesh. *Field Crops Res.* **234**, 33-46.

Campbell, G. S. (1988). Soil water potential measurement: An overview. *Irrig. Sci.* **9**, 265-273.

Celik, I. (2011). Effects of tillage methods on penetration resistance, bulk density and saturated hydraulic conductivity in a clayey soil conditions. *J. Agric. Sci. (Turkey)*.

Chen, H., and Jiang, J.-G. (2010). Osmotic adjustment and plant adaptation to environmental changes related to drought and salinity. *Environ. Rev.* **18**, 309-319.

Chi, X. L. a. C. (2014). Estimating osmotic potential from electrical conductivity for solutions/extracts in

salt-affected soils using an universal equation. *J. Food Agric. Environ.* **12**, 1033-1035.

Cox, W. J., and Jolliff, G. D. (1986). Growth and yield of sunflower and soybean under soil water deficits. *Agron. J. 78, 226-23.*

Cresswell, H., and Hamilton, G. (2002). Bulk density and pore space relations. In 'Soil physical measurement and interpretation for land evaluation.' (Eds N McKenzie, K Coughlan and H Cresswell) pp. 35-58. (CSIRO publishing; Victoria, Australia).

Devkota, M., Devkota, K. P., Martius, C., Gupta, R. K., McDonald, A. J., and Lamers, J. P. A. (2015). Managing soil salinity with permanent bed planting in irrigated production systems in Central Asia. *Agric. Ecosyst. Environ.* **202**, 90-97.

Gholami, A., Asgari, H., and Saeidifar, Z. (2014). Short-Term Effect of Different Tillage Systems on Soil Salinity, Density and Nutrients in Irrigated Wheat. Case Study: Agricultural Land, City of Chenaran–Khorasan Razavi. *Int. J. Advan. Biol. Biom. Res.* **2**, 1513-1524.

Grant, C., and Lafond, G. (1993). The effects of tillage systems and crop sequences on soil bulk density and penetration resistance on a clay soil in southern Saskatchewan. *Can. J. Soil Sci.* **73**, 223-232.

Haque, M. E., Islam, A. K. M. S., Hossain, M. M., Bell, R. W., and Sayre, K. D. (2017). An innovative versatile multi-crop planter for crop establishment using two-wheel tractors. *AMA, Agricultural Mechanization in Asia, Africa and Latin America* **48**, 33-44.

Hobbs, P. R., Sayre, K., and Gupta, R. (2007). The role of conservation agriculture in sustainable agriculture. *Phil. Trans. R. Soc. Biol. Sci.* **363**, 543-555.

Hunt, N., Gilkes, R. J., and Land Management, S. (1992). "Farm monitoring handbook: a practical down-to-earth manual for farmers and other land users," University of Western Australia, Nedlands, W.A.

Johansen, C., Bakr, M., Islam, M. S., Mondal, N., Afzal, A., MacLeod, W., Pande, S., and Siddique, K. H. (2008). Integrated crop management of chickpea in environments of Bangladesh prone to Botrytis grey mould. *Field crops Res.* **108**, 238-249.

Johansen, C., Haque, M., Bell, R., Thierfelder, C., and Esdaile, R. (2012). Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. *Field Crops Res.* **132**, 18-32.

Kahlon, M. S., Lal, R., and Ann-Varughese, M. (2013). Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. *Soil Tillage Res.* **126**, 151-158.

Katerji, N., Van Hoorn, J., Hamdy, A., and Mastrorilli, M. (2000). Salt tolerance classification of crops according to soil salinity and to water stress day index. *Agric. Water Manage.* **43**, 99-109.

Kirby, J., and Ringrose-Voase, A. (2000). Drying of some Philippine and Indonesian puddled rice soils following surface drainage:: Numerical analysis using a swelling soil flow model. *Soil Tillage Res.* **57**, 13-30.

Klute, A. (1982). Tillage Effects on the Hydraulic Properties of Soil: A Review1. *In* "Predicting Tillage Effects on Soil Physical Properties and Processes" (P. W. Unger and D. M. Van Doren Jr, eds.), pp. 29-43. Am. Soc. Agron. and Soil Sci. Soc. Am., Madison, WI.

Kováč, K., Macák, M., and Švančárková, M. (2011). The effect of soil conservation tillage on soil moisture dynamics under single cropping and crop rotation. *Plant Soil Environ.* **51**, 124-130.

Maas, E. V., and Hoffman, G. J. (1977). Crop salt tolerance–current assessment. *J. Irrig. Drain. Div.* **103**, 115-134.

Mondal et al. (2011). Krishi projukti hatboi (Handbook on agro-technology), 5th edition. *Bangladesh Agricultural Research Institute, Gazipur-1701, Bangladesh*

Mondal, M. K., Paul, P., Humphreys, E., Tuong, T., Ritu, S., Rashid, M., Humphreys, E., Buisson, M., Pukinskis, I., and Phillips, M. (2015b). Opportunities for cropping system intensification in the coastal zone of Bangladesh. In:Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF), 449–476.

Mondal, M. K., Saha, N., Ritu, S., Paul, P., Sharifullah, A., Humphreys, E., Tuong, T., and Rashid, M. (2015a). Optimum sowing window for boro cultivation in the coastal zone of Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF), 342-360.

Pang, H.-C., Li, Y.-Y., Yang, J.-S., and Liang, Y.-S. (2010). Effect of brackish water irrigation and straw mulching on soil salinity and crop yields under monsoonal climatic conditions. *Agric. Water Manage.* **97**, 1971-1977.

Pask, A., Pietragalla, J., Mullan, D., and Reynolds, M. (2012). "Physiological breeding II: A field guide to wheat phenotyping," CIMMYT.

Paul, P., Rashid, M., Alam, M., Ghani, M., and Hossain, M. (2016). Selection of profitable rice based cropping system under prevailing water environment in Satkhira district of Bangladesh. *Acad. J. Agric. Res.* **4**, 581-588.

Rahmianna, A., Adisarwanto, T., Kirchhof, G., and So, H. (2000). Crop establishment of legumes in rainfed lowland rice-based cropping systems. *Soil Tillage Res.* **56**, 67-82.

Rasmussen, K. (1999). Impact of ploughless soil tillage on yield and soil quality: a Scandinavian review. *Soil Tillage Res.* **53**, 3-14.

Rengasamy, P. (2006). World salinization with emphasis on Australia. *J. Exp. Bot.* **57**, 1017-1023.

Rengasamy, P. (2010). Soil processes affecting crop production in salt-affected soils. *Functional Plant Biology* **37**, 613-620.

Shaver, T., Peterson, G., Ahuja, L., Westfall, D., Sherrod, L., and Dunn, G. (2002). Surface soil physical properties after twelve years of dryland no-till management. *Soil Sci. Soc. Am. J.* **66**, 1296-1303.

Slavich, P. (2006). Reducing impacts of salinity on crops growing in tsunami-affected areas in Nanggore Aceh Darussalam Province, Indonesia. *http://www. agric. nsw. gov. au/reader/salinity/reduce-salinity-tsunami-areas. pdf*.

So, H. B., and Ringrose-Voase, A. J. (2000). Management of clay soils for rainfed lowland rice-based cropping systems: an overview. *Soil Tillage Res.* **56**, 3-14.

Steppuhn, H., van Genuchten, M. T., and Grieve, C. M. (2005). Root-Zone Salinity. *Crop Sci.* **45**, 209.

Strudley, M. W., Green, T. R., and Ascough II, J. C. (2008). Tillage effects on soil hydraulic properties in space and time: State of the science. *Soil Tillage Res.* **99**, 4-48.

Triplett, G., and Dick, W. A. (2008). No-tillage crop production: A revolution in agriculture! *Agron. J.* **100**, S-153-S-165.

Unger, P. W. (1983). Irrigation effect on sunflower growth, development, and water use. *Field Crops Res.* **7**, 181-194.

Wolf, A., Brown, M., and Prentiss, P. (1986). Concentrative properties of aqueous solutions: conversion tables. In: Weast RC (ed). CRC Handbook of Chemistry and Physics, 67th edition. CRC press, Inc., Boca Raton FL, D 219–259.

Xue, J.-F., Ren, A.-X., Li, H., Gao, Z.-Q., and Du, T.-Q. (2018). Soil physical properties response to tillage practices during summer fallow of dryland winter wheat field on the Loess Plateau. *Environ. Sci. Pollut. Res.* **25**, 1070-1078.

3.8 Supplementary materials

Supplementary Table

Table 3S1. Average particle size distribution in soil at Pankhali, Dacope, Khulna Bangladesh.

Depth (cm)	Particle size			Textural Class
	Sand (%)	Silt (%)	Clay (%)	
0-15	8	43	49	Silty clay
15-30	8	41	51	Silty clay
30-45	8	37	55	Clay
45-60	10	35	55	Clay

Table 3S2. Phenological development of sunflower at Pankhali, Dacope, Khulna Bangladesh in the 2016-17 and 2017-18 rabi seasons.

Tillage types	Emergence (DAS)*	Plants m^{-2} after emergence	Bud initiation (DAS)*	First flowerin g (DAS)*	80% flowering (DAS)*	Physiologic al maturity (DAS)*
			2016-17			
ZT	5-7	3.39	61	72	82	113
NST	5-7	3.71	63	74	84	113
BP	7-10	3.34	60	73	81	110
SPST	6-8	3.47	62	74	81	110
DP	6-8	3.37	61	73	81	110
P-value		NS**	NS	NS	0.02	NS
			2017-18			
NST	8-14	3.90	59	72	78	105
WST	8-14	3.87	59	72	76	105
BP	9-19	3.21	61	74	79	107
SPST	8-14	3.82	61	72	77	105
P-value		0.002	0.004	NS	NS	NS

* Days after sowing
**NS = Not significant

Table 3S3. Physicochemical properties of the soil in Pankhali, Dacope, Khulna, Bangladesh in 2016-17*

Depth (cm)	pH	Organic C	Total N (g kg^{-1})	Extractable				Exchangeable			
				P	S	B	Zn	Na	K	Ca	Mg
		(g kg^{-1})		(mg kg^{-1})				(cmol kg^{-1})			
0-15	7.0	12	13	3.0	81	1.5	0.85	4.4	0.9	15.9	1.08
15-30	7.5	7	13	2.0	61	1.2	0.85	5.2	1.0	14.5	1.22
30-45	7.6	8	11	2.7	62	1.2	0.85	6.2	1.0	13.0	1.32
45-60	7.5	7	12	2.6	73	1.4	0.83	7.0	1.0	13.0	1.02

* The collected soils were air-dried and crushed to pass a 2-mm sieve. Part of each sampled soil was analysed at the Soil Science laboratory of Bangladesh Rice Research Institute (BRRI) for: (i) soil texture by the hydrometer method (Bouyoucos, 1962), (ii) soil pH by the glass electrode method at a soil-water ratio of 1:2.5 (Peech, 1965), (iii) organic carbon by a wet oxidation method (Walkley, 1935), (iv) total nitrogen by Micro-Kjeldahl method (Bremner and Mulvaney, 1982), (v) extractable phosphorus by the Olsen method (Olsen, 1954), and (vi) extractable sulfur by the Turbidimetric method (Black et al., 1965). The rest of each sampled soil was used to prepare saturated soil extracts to obtain Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} and HCO_3^- concentrations as described by Richards (1954). Sodium ions and K^+ were determined by flame spectrophotometry, and Ca^{2+} and Mg^{2+} were measured by atomic absorption spectrophotometry. The titration method with standard silver nitrate solution was used to estimate Cl^- and the turbidimetric method was followed to determine SO_4^{2-} (Jackson, 1967). The exchangeable cations, Na^+, K^+, Ca^{2+}, Mg^{2+} were extracted with 1 N NH_4OAc to calculate the exchangeable sodium percentage (ESP).

References

Black, C.A., Evans, D.D., Dinauer, R., 1965. Methods of soil analysis. Am. Soc. Agron Madison, WI.

Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size analyses of soils 1. Agron. J. **54**, 464-465.

Bremner, J.M., Mulvaney, C., 1982. Nitrogen—Total 1. Methods of soil analysis. Part 2. Chemical and Microbiological Properties, 595-624.

Jackson, M.L., 1967. Soil chemical analysis. Prentice Hall, New Delhi.

Olsen, S.R., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. United States Department Of Agriculture; Washington.

Peech, M., 1965. Lime requirement. Methods of soil analysis. Part 2. Chemical and Microbiological Properties, 927-932.

Richards, L., 1954. Diagnosis and improvement of saline and alkaline soils. Washington: United States Salinity Laboratory Staff, Agriculture Handbook 60.

Walkley, A., 1935. An Examination of Methods for Determining Organic Carbon and Nitrogen in Soils 1.(With One Text-figure.). The J. Agric. Sci. **25**, 598-609.

Table 3S4. Significance (P-values) of effects of tillage on soil water content, $EC_{1:5}$ and solute potential in 2016-17 and 2017-18. These were determined using three-way factorial ANOVA model that also took account of the effects of tillage treatments, soil depth and date after sowing (time) as repeated measures using Statistical Tool for Agricultural Research (STAR) software (Version 2.0.1).

Year/Factors	df	Soil water content (SWC)	$EC_{1:5}$	Solute potential (SP)
2016-17 growing season		*P*-value		
Tillage treatment (T)	4	<0.001	NS*	<0.001
Soil depth (D)	4	<0.001	<0.001	<0.001
Date after sowing (Time)	4	<0.001	<0.001	<0.001
T: D	16	<0.01	NS	<0.01
T: Time	16	<0.001	NS	<0.001
Time: D	16	<0.001	<0.001	<0.001
T: D: Time	64	NS	NS	NS
2017-18 growing season				
Tillage treatment (T)	3	<0.001	<0.01	<0.001
Soil depth (D)	4	<0.001	<0.001	<0.001
Date after sowing (Time)	6	<0.001	<0.001	<0.001
T: D	12	<0.001	NS	<0.01
T: Time	18	<0.001	NS	<0.001
Time: D	24	<0.001	<0.001	<0.001
T: D: Time	72	NS	NS	NS

*NS = Not significant

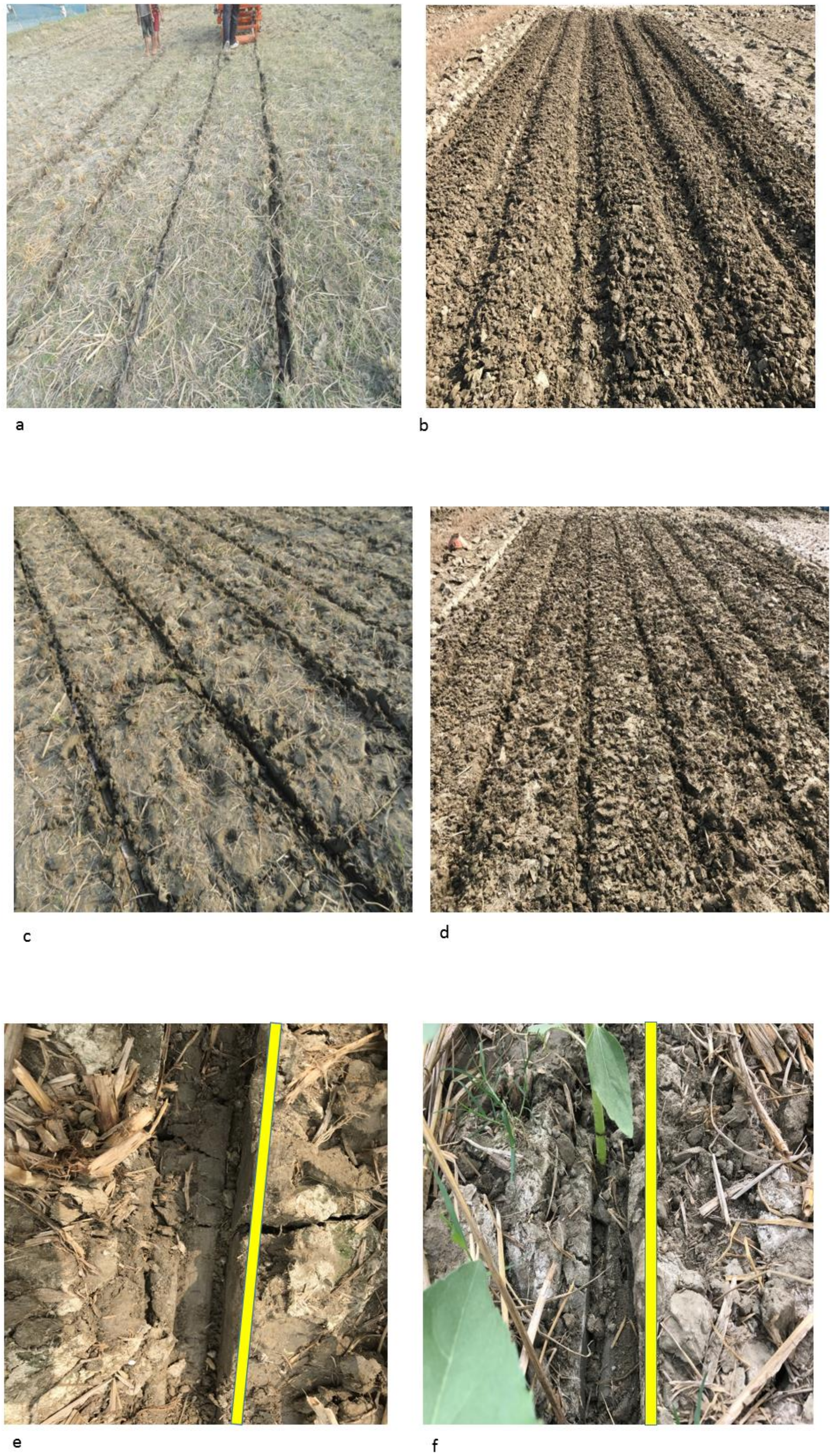

Fig. 3S1. The surface conditions of soil under different tillage systems for sunflower establishment (a) ZT, (b) BP, (c) NST, (d) WST, (e) smeared furrow wall of ZT and (f) smeared furrow wall of NST. Row spacing was 60 cm in all tillage treatments.

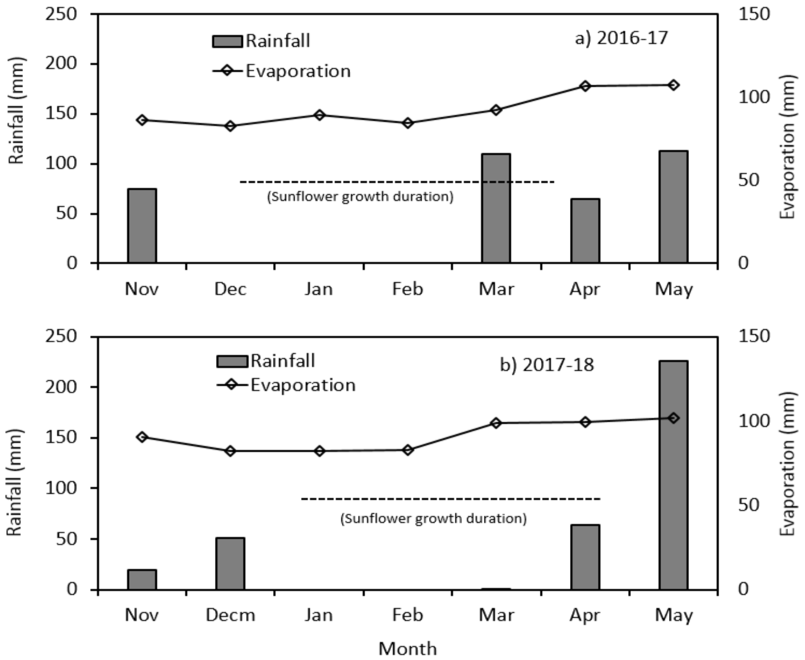

Fig. 3S2. Monthly mean total rainfall and evaporation during (a) 2016-17 and (b) 2017-18 at Pankhali, Dacope, Khulna Bangladesh. The dotted line indicates the duration of crop growth.

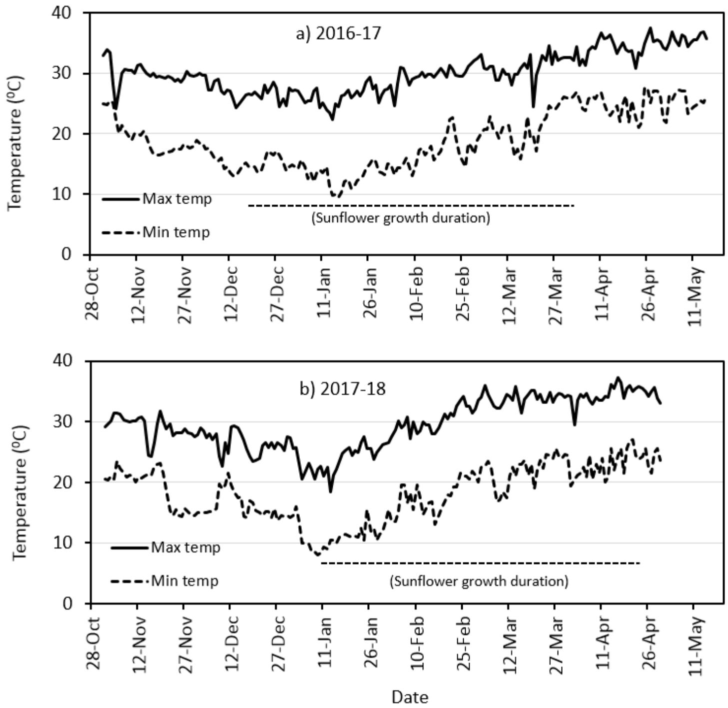

Fig. 3S3. Daily maximum and minimum temperature during (a) 2016-17 and (b) 2017-18 at Pankkali, Dacope, Khulna Bangladesh. The dotted line indicates the duration of crop growth.

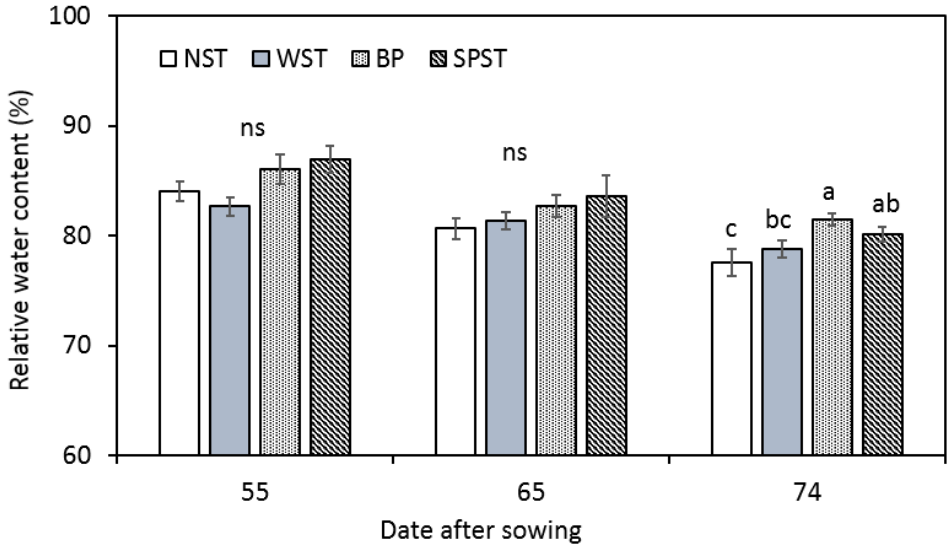

Fig. 3S4. The mean of leaf relative water content (RWC) (%) of the sunflower crop under four tillage treatments in 2017-18. Legend: NST = narrow strip tillage, WST = wide strip tillage, BP = bed planting, and SPST = single pass tillage. Values are means of four replicates. Vertical bars on each data point indicate standard error of the means. Means with identical letters are not significantly different at $P < 0.05$. ns indicates not significant.

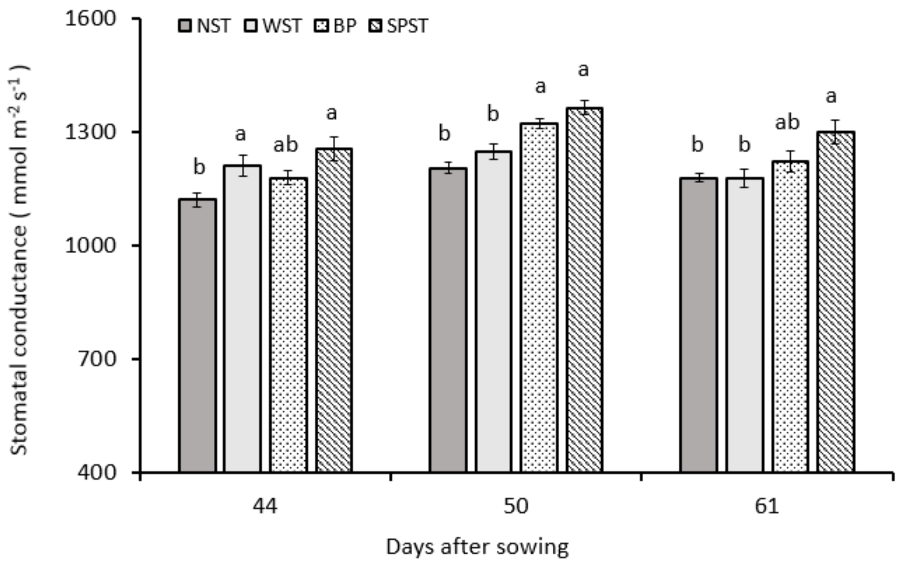

Fig. 3S5. The mean stomatal conductance (mmol $m^{-2}s^{-1}$) in four tillage treatments in 2017-18. Legend: NST = narrow strip tillage, WST = wide strip tillage, BP = bed planting, and SPST = single pass tillage. Values are means of four replicates. Vertical bars on each data point indicate standard error of the means. Same lowercase in each measurement do not differ at $P < 0.05$ in four tillage treatments.

Chapter 4

Straw mulch and irrigation affect solute potential and sunflower yield in a heavy textured soil in the Ganges Delta

This chapter was accepted in ‘Agricultural Water Management’ and is currently in press.

In Chapter 3, we explored the effects of different tillage treatments on sunflower growth and yield in clay-textured saline soil. Tillage techniques that increased soil disturbance (BP, SPST and DP) decreased soil salinity and increased water storage and solute potential in the surface soil, which was related to higher yield. By contrast, minimum soil disturbance (ZT and ST) depressed sunflower yield because of increased soil surface dryness and soil salinity and created soil smearing and compaction.

In the present Chapter, the hypothesis is that applying rice straw mulch on the soil surface would offset the negative effect of strip tillage on sunflower yield by increasing soil water storage, decreasing soil salinity, and increasing soil solute potential.

4 Straw mulch and irrigation affect solute potential and sunflower yield in a heavy textured soil in the Ganges Delta

Priya Lal Chandra Paul [a, e, *], Richard W Bell [a], Edward G. Barrett-Lennard [a, b, d], Enamul Kabir [c]

[a] *Land Management Group, Agriculture Discipline, College of Science, Health, Engineering and Education, Murdoch University, WA-6150, Australia*

[b] *Department of Primary Industries and Regional Development, South Perth, WA-6151, Australia*

[c] *Agrotechnology Discipline, Khulna University, Khulna 9208, Bangladesh*

[d] *School of Agriculture and Environment, The University of Western Australia, Nedlands, WA 6009, Australia*

[e] *Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur-1701, Bangladesh and* [*]*Corresponding author: Tel.: +8801716617378, +610470569881; E-mail: plcpauliwm@yahoo.com*

4.1 Abstract

Since soil water depletion and salinity are major constraints for crop production, rice straw mulch could be beneficial for increasing yield and water productivity due to its role in conserving soil water and decreasing soil salinity. Two field experiments were conducted on a saline, silty clay soil to determine the effects of mulch and irrigation on the dynamics of soil water content and soil salinity, and on the growth and yield of sunflower sown by strip planting. In 2017, the mulching treatments were: no mulch (NM), rice straw mulch (RS) and retaining 15-20 % of the crop residue of the previous rice crop (RR). In 2018 three irrigation treatments: one (I_1), two (I_2) and three irrigation events (I_3), and two mulching treatments (NM and RS) were tested. In both years, the average gravimetric soil water content (SWC) was higher and topsoil salinity ($EC_{1:5}$) was lower under RS treatment at 0-7 and 7-15 cm depth than with the NM treatment. The substantially higher solute potential of the soil solution in the surface soil with the RS treatment at 0-7 and 7-15 cm (-644 and -588 kPa in 2017, and -649 and -558 kPa in 2018) than with NM treatment (-925 and -728 kPa in 2017, and -801 and -641 kPa in 2018) was associated with increased grain yield (2.7 and 2.5 t ha^{-1} in 2017 and 2018, respectively). In the second year, the increasing number of irrigation events also increased yield, but the effects were additive to those of mulch. We conclude that the application of a rice straw mulch to the surface of saline-clay soils under strip planting can increase the solute potential of the soil solution, thereby improving the growth and yield of sunflower.

Keywords: Soil salinity, soil water content, straw mulch, water productivity

4.2 Introduction

Soil water deficit and salinity stresses are the major limits to crop production in many parts of the world (Keesstra et al., 2018) and hamper efforts to achieve United Nations Sustainable Development Goals, particularly those related to global food security (Keesstra et al., 2016). The Ganges coastal zone consists of low-lying lands in a tidal floodplain and river delta (Paul et al., 2020). In this area, the growth of dry season (rabi) crops is hampered by the depletion of residual soil water and increases in soil salinity, both exacerbated by the late harvesting of the preceding traditional wet season rice. In addition, in the dry season, river water is generally unsuitable for irrigation because of its high salinity (EC_w values of 4-20 dS m^{-1}). However, there are some canals and homestead ponds that contain non-saline water, which can be used as sources for irrigation (Mondal et al., 2015b; Paul et al., 2016).

Recently, sunflower in the south-west coastal region of Bangladesh has been identified as a promising oilseed crop (Rashid et al., 2014). It has moderate drought tolerance because of its deep branched root system (Rauf, 2008). However, delays in the sowing time and a lack of proper management of residual soil moisture and salinity has hampered sunflower production in this region. Appropriate agronomic management technology is, therefore, needed to overcome these problems and improve yields.

One of the strategies to overcome the above-mentioned soil problems is to increase soil cover through mulching. Mulching has been used as an agronomic practice in many parts of the world to conserve soil moisture, increase water use efficiency, mitigate soil salinity and boost crop yields (Ji and Unger, 2001; Zhao et al., 2014). However, the type of mulching materials used vary due to availability, land suitability and the economic cost (Cerdà et al., 2017). Rice straw mulch is an organic biodegradable material that is suitable for use as a mulch in many climatic areas and benefits from its use have been reported (Kader et al., 2017). In India, rice straw mulch on clay loam soils reduced soil evaporation by 35 and 40 mm in high and low rainfall areas, respectively, and increased soil water storage in the 0-40 cm soil layer (Balwinder et al., 2011). In terms of soil health, rice straw mulch was more effective than plastic mulch as it was more easily decomposed (Reddy and Yang, 2006). Straw mulch has been reported to improve soil aeration on compacted soils in the dry season, increase soil organic matter, increase infiltration, improve soil structure (Atreya et al., 2008; Jordán et al., 2010), decrease soil salinity (Kitou and Yoshida, 1994) and improve soil hydrological properties and crop yields (Ning and Hu, 1990; Yang et al., 2006).

While the use of rice straw mulch for improving crop production has been reported elsewhere, there are over 1 million hectares of clay-textured, saline soil in the Ganges coastal zone where the effects of rice straw mulch for rabi season crop production have not been determined. In previous experiments examining the effects of different tillage methods on sunflower yield, Paul et al. (2020) found that solute potential was a better estimate of abiotic stress than either soil water content or soil salinity ($EC_{1:5}$ values) alone. It was shown that minimum tillage (zero tillage and strip planting) increased soil surface dryness and soil salinity, thereby decreasing the solute potential of the soil solution and decreasing sunflower growth and yield. In this paper, we hypothesized that the application of a rice straw mulch (~ 5 t ha^{-1}) on the soil surface after strip planting would also maintain soil moisture and decrease soil salinity, thereby increasing the solute potential of the soil solution and improving the growth and yield of sunflower.

4.3 Materials and methods

4.3.1 Description of the study site

Field experiments were undertaken in 2017 and 2018 on a farmer's field in Pankhali, Dacope, Khulna district of Bangladesh (22^0 37' 55'' N and 89^0 30' 10'' E, ~ 2-3 m above sea level). At this site, a hot and humid summer occurs between March and June, and a cooler dry winter occurs between November and February. In this sub-tropical monsoonal climate, about 1,800 mm of rain falls annually (Mondal et al., 2015a), mostly between July and October. During the study, the lowest daily temperatures occurred in January (ranging between 8-10 ^{0}C and 28-29 ^{0}C), and the highest daily temperatures occurred in April (ranging between 19-21 ^{0}C and 37-38 ^{0}C). Total rainfall during the growing season was 173 and 66 mm in the first and second years, respectively (Fig. 4.1). Mean pan evaporation during the season (Nov-Apr) varied from 82-107 mm per month (Paul et al., 2020). The soil texture of the site was silty clay (0-30 cm) overlying clay (30-60 cm). The initial soil physicochemical properties at 0-15 cm are presented in Table 4.1.

Table 4.1. Soil physicochemical properties (0-15 cm) at the experimental site

Bulk density ($Mg\ m^{-3}$)	pH	$EC_{1:5}$ ($dS\ m^{-1}$)	Organic carbon ($g\ kg^{-1}$)	total nitrogen ($g\ kg^{-1}$)	Extract-able P ($mg\ kg^{-1}$)	Extract-able K ($mg\ kg^{-1}$)	Soil texture		
							Sand (%)	Silt (%)	Clay (%)
1.56	7.5	0.45	12	1.3	3	338	8	43	49

4.3.2 Experimental design

In 2017, the experiment consisted of strip-planted plots with three mulching treatments: no-mulch (NM), rice straw mulch at ~ 5 t ha^{-1} (RS), and retaining 15-20 % of the residue from the previous rice crop which was less than 1 t ha^{-1} (RR). The same amount of irrigation water was applied at each time in all treatments (Fig. 4.1). In 2018, the experiment had two mulching treatments (NM and RS) and three irrigation treatments: one irrigation (I_1) at 28 days after sowing (DAS), two irrigations (I_2) at 28 and 50 DAS, and three irrigations (I_3) at 28, 50 and 67 DAS. The total cumulative water supplied as rain and irrigation over each of the two growing seasons is presented in Fig. 4.1. In 2017, the experiment had a randomized complete block design with three replications and each plot was 11 x 4 m in size. In 2018, the experiment had a split-plot design with irrigation treatments in the main plots and mulch treatments in the sub-plots; there were three replications and each plot was 6 x 3 m in size. Sunflower seeds (cv. Hysun-33, hybrid) were sown on 8 January in both years with a plant to plant spacing of 40 cm and a row to row spacing of 60 cm. The fertilizers applied were urea (200 kg ha^{-1}), triple superphosphate (200 kg ha^{-1}), muriate of potash (170 kg ha^{-1}), gypsum (170 kg ha^{-1}), zinc sulphate (10 kg ha^{-1}) and boric acid (12 kg ha^{-1}). In both seasons, all fertilizers except 75 % of the urea were applied at sowing; the rest of the urea was top-dressed in three splits with irrigation at 32, 44 and 60 DAS in 2016-17 and at 28, 50 and 67 DAS in 2017-18. Rice straw mulch was applied at 5 t ha^{-1} at 4 DAS in 2017 and at 16 DAS in 2018. To control pests, the insecticide Nitro (Cypermethrin chlorpyriphos) was sprayed three times throughout the season.

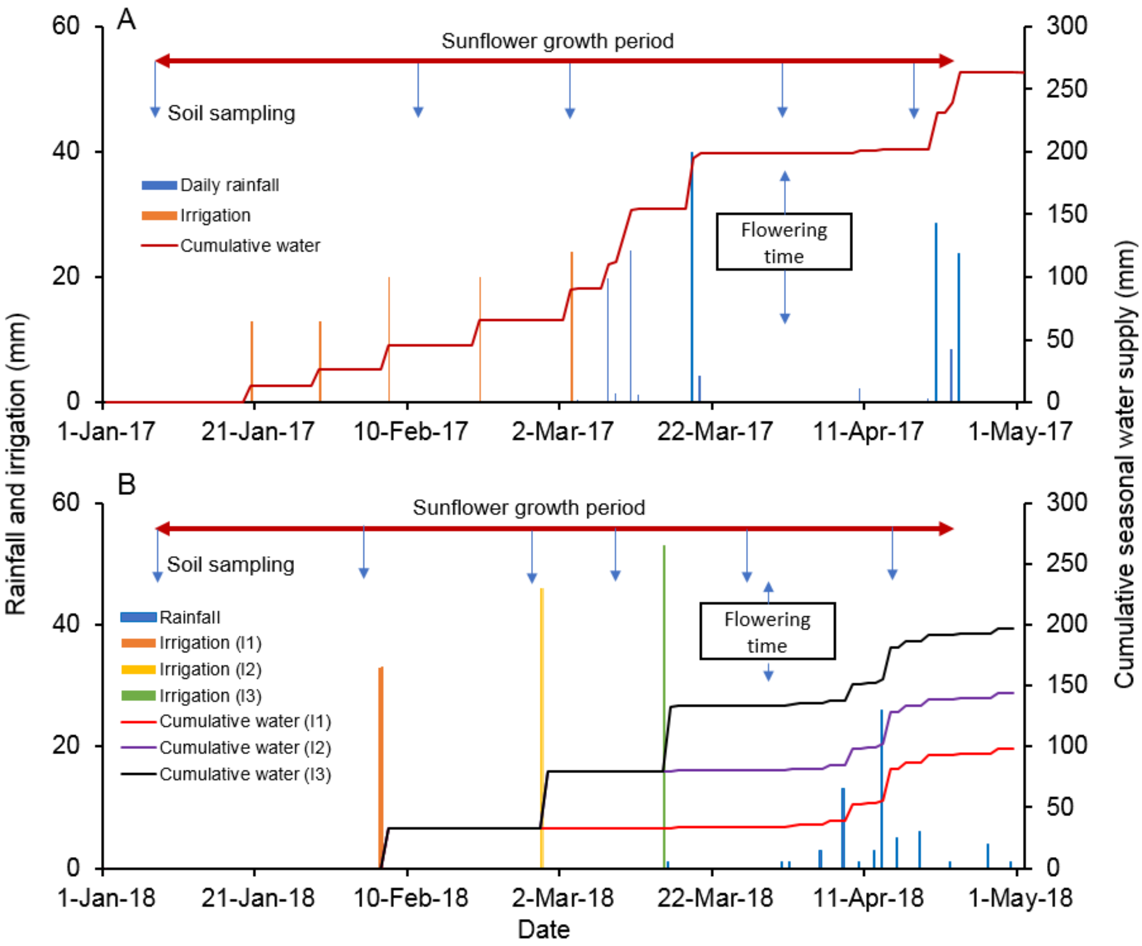

Fig. 4.1. Effects of daily rainfall, and irrigations on cumulative seasonal water supply in the 2017 (A) and 2018 (B) growing seasons. The horizontal arrows indicate the sunflower growth period; the vertical arrows indicate the periods of soil sampling.

4.3.3 Sampling and measurements

4.3.3.1 Measurement of soil water content, $EC_{1:5}$ and solute potential

Gravimetric soil water content (SWC) was measured at 0-7, 7-15, 15-30, 30-45 and 45-60 cm depth at 15-30 day intervals between sowing and harvest in both seasons (dates indicated in Fig. 4.1). A hand-held auger was used to collect soil samples from each depth, and these were kept in sealed polyethylene bags. The wet weight of the samples was measured immediately, and they were then oven-dried to constant weight. Gravimetric SWC was calculated from the difference between soil wet and dry weight. The volumetric soil water content was calculated by multiplying the gravimetric SWC by the bulk density for each respective soil layer. Typical

SWC at field capacity (- 0.03 MPa) and permanent wilting point (-1.5 MPa) was determined using the pressure plate apparatus. The gravimetric SWC over the upper 60 cm of the soil profile ranged between 25-28 % (at wilting point) and 35-37 % (at field capacity).

The electrical conductivities of 1:5 soil: water extracts ($EC_{1:5}$) were measured in the same soil samples. The $EC_{1:5}$ was measured in 1:5 soil: water suspension using a portable EC meter. The solute potential (SP) of the soil solutions was calculated, according to Paul et al. (2020) from the equation:

$$\Psi s = -22580 \frac{EC\ (1:5)}{W} \tag{1}$$

where Ψ_s is the solute potential (kPa), $EC_{1:5}$ is the electrical conductivity (dS m^{-1}) of the 1:5 soil: water extract and W is the gravimetric SWC (%).

4.3.3.2 Total water use and crop water productivity

The irrigation schedule for sunflower followed Bangladesh Agricultural Research Institute guidelines (Mondal et al., 2011). Irrigation water (EC_w between 1.8 and 2.5 dS m^{-1}) was applied through a plastic hose pipe from a nearby canal at initial, maximum vegetative and flowering stages. A USA class "A" pan evaporimeter was set-up near the experimental plots. The irrigation water requirement was calculated based on the following equation.

$$ET_{crop} = E_p \times K_p \times K_c \tag{2}$$

Where ET_{crop} is the crop water requirement (mm), Ep is the cumulative pan evaporation (mm), Kp is the pan coefficient considered to be 0.7 (Michael, 1978), and; Kc is the average crop factor for sunflower, considered to be 0.6 (Allen et al., 1998).

Total water use (TWU) was measured by the following equation:

$$TWU = I + P + \Delta W - R - D \tag{3}$$

where I is the irrigation, P is the rainfall, ΔW is the change in soil moisture between sowing and harvest, R is the runoff and D is the drainage (runoff was zero since plots were enclosed by an earthen bud and drainage were considered to be negligible as there was no evidence of increases in SWC at 45- 60 cm depth following irrigation events).

The water productivity (WP) was calculated as the grain yield divided by the total water used for the entire period and expressed as crop production per unit volume of water applied (kg ha^{-1} mm^{-1}).

4.3.3.3 Sunflower growth

Records were taken of sunflower seedling emergence, and the times of flower bud initiation, flowering, and physiological maturity. Yield related parameters such as plant height, head diameter, the number of seeds per head, and thousand seed weight were measured at harvest. Threshed seeds of sunflower were air-dried, and grain yield was calculated at 9 % moisture content (w/w).

4.4 Statistical analysis

Statistical analyses were conducted using STAR software version 2.0.1. The effects of mulch and irrigation on grain yield and yield components were determined using one-way and two-way analysis of variance (ANOVA) for 2017 and 2018, respectively. The significance of effects of mulch and irrigation on SWC, $EC_{1:5}$ and SP were determined using three-way and four-way factorial ANOVA models that in addition to the effects of mulch in 2017 and of mulch and irrigation in 2018 also took account of soil depth and date after sowing (time) or soil depth and date after sowing (time) as repeated measures. The comparison of means was tested using the least significant difference (LSD) at the 95 % confidence level.

4.5 Results

4.5.1 Sunflower growth and yield

Mulch had significant effects on grain yield in both years (Table 4.2). In 2017, the RS treatment had a 0.5-0.7 t ha^{-1} higher yield (P = 0.01) than the NM and RR treatments (Table 4.2A). Also, the 1000-seed weight and number of seeds per head were significantly higher in the RS treatment (both P = 0.04) than the RR and NM treatments (Table 4.2A). In 2018 (Table 4.2B), the RS treatment increased grain yield by 16 %, increased thousand seed weight by 6 % and increased the number of seeds per head by 11 % (Table 4.2B). In 2018, there was also a strong effect of irrigation on grain yield. Averaged across mulch treatments, the I_3 treatment increased grain yields (relative to the I_1 treatment) by 28 %, increased thousand seed weight by 16 % and increased the number of seeds per head by 27 % (Table 4.2B).

Table 4.2 Yield and yield attributes of sunflower under mulch and irrigation treatments in Pankhali, Dacope, Khulna Bangladesh in 2017 and 2018*.

A. 2017.

Treatments	Grain yield ($t\ ha^{-1}$)	Thousand seed weight (g)	Number of seeds per head
RS	2.7	73	1243
RR	2.2	67	1152
NM	2.0	65	1128
P value	0.01	0.04	0.04
$LSD_{0.05}$	0.37	5.2	87

B. 2018

Treatment	Grain yield ($t\ ha^{-1}$)		Thousand seed Weight (g)		Number of seeds per head	
Irrigation	NM	RS	NM	RS	NM	RS
I_3	2.1	2.5	61	68	1067	1156
I_2	2.0	2.2	57	60	978	1114
I_1	1.7	1.9	55	56	839	918
P-values						
Mulch	0.001		0.002		0.012	
Irrigation	0.04		0.006		0.013	
Irrigation × Mulch	NS		0.005		NS	
$LSD_{0.05}$						
Mulch	0.11		1.89		70	
Irrigation	0.37		3.6		121	
Irrigation × Mulch	-		1.8		-	

* NS indicates not significant. LSD indicates the least significant difference at $P < 0.05$. NM = no-mulch, RS = rice straw and RR = rice residue; I_1 = One irrigation, I_2 = two irrigations and I_3 = three irrigations.

4.5.2 *Impacts of SWC, $EC_{1:5}$ and SP on yield at different times during the growing season*

The SWC, $EC_{1:5}$ and SP were measured at five depths and 5-6 times during each growing season. Table 4.3 summarizes the significance of these measures (as single factors) in simple correlations with grain yield. This table shows that SP (the variable that integrated the effects of SWC and $EC_{1:5}$) had more significant effects on yield than SWC or $EC_{1:5}$ alone. There were no significant effects of SWC, $EC_{1:5}$ and SP on yield in the early growing season in either year, but the significance of these impacts increased with time and was greater in the shallow than the deeper soil (Table 4.3A and 4.3B). In 2017, the most significant impacts of SWC, $EC_{1:5}$ and SP on yield were at 99 DAS at 0-30 cm depth (Table 4.3A). In 2018, the most significant impacts were at 75 DAS (at bud formation and flowering) and the effects (especially on SWC and SP) were evident at a greater range of depths (Table 4.3B). Fig. 4.2 shows x:y plots of the most significant relationships, those between SP and yield at 99 and 75 DAS for 2017 and 2018, respectively. The best linear regression between sunflower yield and SP accounted for 97 % and 82 % of the variation in 2017 and 2018, respectively (Fig. 4.2A and 4.2C). By contrast, the best relationship between SWC or $EC_{1:5}$ and grain yield only accounted for 87-91 % in 2017 and 65-89 % of the variation in 2018 (Table 4.3A and 4.3B).

Table 4.3. Significance of effects of soil water content (SWC), electrical conductivity ($EC_{1:5}$) and solute potential (SP) on grain yield at different times during the growing season at depths to 60 cm in (A) 2017 and (B) 2018.

A. 2017

Factor/depth	Time-1 (0 DAS)	Time-2 (34 DAS)	Time-3 (56 DAS)	Time-4 (83 DAS)	Time-5 (99 DAS)
SWC (%)	*Significance level with R^2 values in brackets*				
0-7	-	*(0.52)	**(0.66)	**(0.68)	***(0.87)
7-15	-	-	*(0.58)	**(0.62)	***(0.87)
15-30	-	-	-	-	**(0.62)
30-45	-	-	-	-	*(0.52)
45-60	-	-	-	*(0.52)	*(0.49)
$EC_{1:5}$ (dS m^{-1})					
0-7	-	**(0.74)	**(0.59)	***(0.68)	***(0.91)
7-15	-	*(0.49)			**(0.73)
15-30	-	-	-	-	**(0.69)
30-45	-	-	-	-	-
45-60	-	-	-	-	-
SP (kPa)					
0-7	-	***(0.83)	***(0.81)	***(0.85)	***(0.97)
7-15	-	**(0.72)	**(0.61)	*(0.43)	***(0.92)
15-30	-	-	-	-	**(0.85)
30-45	-	-	-	-	**(0.65)
45-60	-	-	-	-	-

B. 2018

Factor/Depth	Time-1 (0 DAS)	Time-2 (30 DAS)	Time-3 (45 DAS)	Time-4 (60 DAS)	Time-5 (75 DAS	Time-6 (95 DAS)
SWC (%)						
0-7	-	-	* (0.27)	** (0.39)	**(0.44)	-
7-15	-	-	*(0.26)	**(0.43)	***(0.63)	-
15-30	-	-	-	**(0.30)	***(0.60)	-
30-45	-	-	-	**(0.38)	***(0.65)	-
45-60	-	-	-	**(0.32)	***(0.50)	-
$EC_{1:5}$ (dS m^{-1})						
0-7	-	-	** (0.34)	***(0.89)	***(0.68)	*(0.22)
7-15	-	-	-	**(0.44)	***(0.64)	*(0.25)
15-30	-	-	-	-	-	-
30-45	-	-	*(0.27)	-	-	-
45-60	-	-	*(0.24)	-	-	-
SP (kPa)						
0-7	-	-	***(0.57)	***(0.63)	***(0.73)	-
7-15	-	-	*(0.25)	***(0.64)	***(0.82)	**(0.40)
15-30	-	-	-	-	***(0.54)	-
30-45	-	-	**(0.37)	**(0.34)	**(0.52)	-
45-60	-	-	*(0.29)	*(0.29)	**(0.45)	-

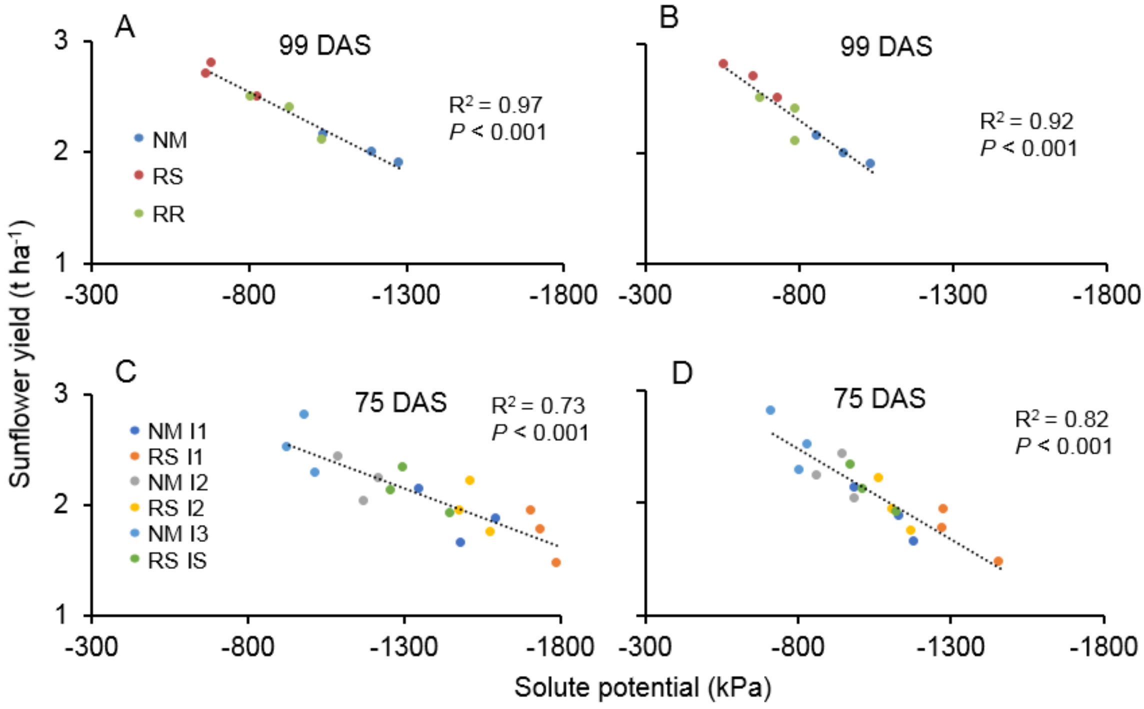

Fig. 4.2. Relationship between sunflower yield and solute potential of the soil solutions at 99 DAS in 2017 at (A) 0-7 and (B) 7-15 cm depth and 75 DAS in 2018 at (C) 0-7 and (D) 7-15 cm. Values plotted are means of the mulch (NM, RS, and RR) and irrigation (I1, I2, and I3) treatments.

4.5.3 Variation in solute potential

Changes in SP with time and soil depth are summarized in Fig. 4.3. In 2017, SP was significantly affected by the interaction between mulch and time (Fig. 4.3A) and mulch and depth (Fig. 4.3B). Compared to the sowing time, SP was more negative at flowering under the NM (-600 to -830 kPa) than the RR (-581 to -692 kPa), and RS (-590 to -777 kPa) treatments. From sowing to harvest, the SP became more negative at 0-7 and 7-15 cm than at lower depths to 60 cm (Fig. 4.3B). In 2018, SP was significantly affected by the interaction between mulch and time (Fig. 4.3C), mulch and depth (Fig. 4.3D), irrigation and time (Fig. 4.3E) and irrigation and depth (Fig. 4.3F). During the growing season, the RS treatment had a higher SP than the NM treatment (Fig. 4.3C), and the difference was highest at flowering (25 March) when SP was -914 kPa and -1118 kPa for RS and NM treatments. While mulch altered the SP at all depths until 60 cm (Fig. 4.3D). Until 50 DAS, irrigation treatments had little effect on SP (Fig. 4.3E). At flowering (25 Mar), the SP was lower with less irrigation (I_1 and I_2 treatments: -1167 and -990 kPa) than with the I_3 treatments (-896 kPa) (Fig. 4.3E). With all irrigation treatments, the SP was lower at 0-7 cm depth than at greater depths (Fig. 4.3F), but increasing irrigation water (I_3) increased the SP at 0-7 cm depth relative to supplying less irrigation (I_1 and I_2).

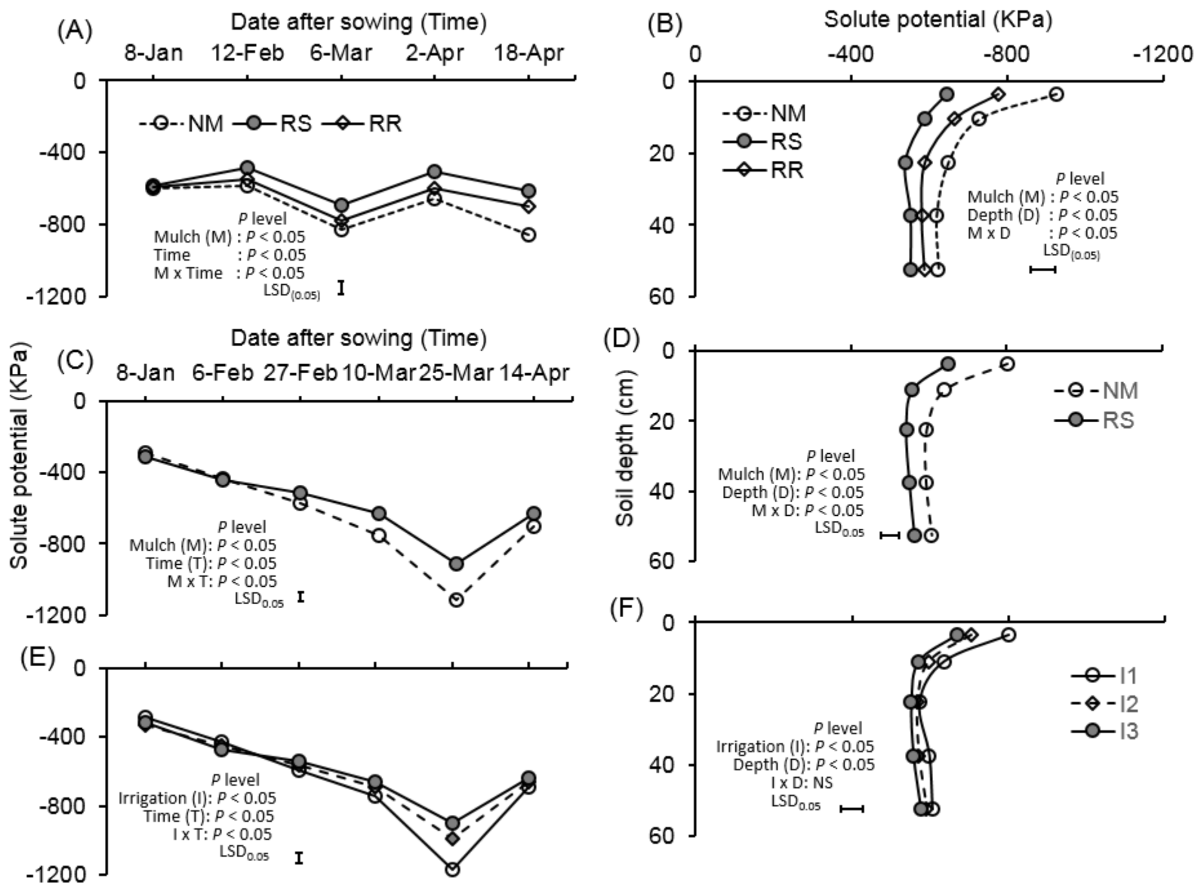

Fig. 4.3. Effects on solute potential of mulch (A and B) in 2017 and (C and D) in 2018, and irrigation (E and F) in 2018, with time (A, C and E) and with soil depth (B, D and F). NM = no-mulch, RS = rice straw, RR = rice residue; I_1= One irrigation, I_2 = two irrigation, I_3 = three irrigation. $LSD_{0.05}$ is the least significant difference of the interaction between mulch and time (A), mulch and depth (B) in 2017, and mulch and time (C), mulch and depth (D) in 2018, and irrigation and time (E) and irrigation and depth (F) in 2018.

4.5.4 Variation in soil water content

The effects of mulch and irrigation on SWC and their interaction with time and soil depth are presented in Fig. 4.4. In 2017, during the early growing season (35 days after sowing), there was little variation in SWC between mulch treatments as light irrigation water was applied on 21 January, 29 January and 7 February. The SWC, thereafter significantly decreased until harvest except on 2 April (at flowering), when there was an increase in SWC because of the 109 mm of rain that fell in March (Fig. 4.4A). From early vegetative growth (12 Feb) to maturity (14 Apr), the RS treatment had significantly ($P < 0.05$) higher SWC than the NM and RR treatments (Fig. 4.4A). Among the mulch treatments, the greatest difference in SWC was at 0-15 cm where the RS treatment had a 3-4 % and 2-3 % (w/w) higher SWC than the NM and RR treatments at 0-7 and 7-15 cm depth, respectively (Fig. 4.4B). In 2018, throughout the growing season, SWC decreased gradually at all depths down to 60 cm, but the surface soil at 0-7 cm and 7-15 cm dried faster than the soil at the lowest depth (45-60 cm) (Fig. 4.4C and D). The average SWC was about 4 % (w/w) and 2.5 % higher with RS treatment at 0-7 and 7-15 cm, respectively than with the NM treatment. Among the irrigation treatments, the difference of SWC was more pronounced after second and third irrigations at 50 and 67 DAS, respectively (Fig. 4.4E) when SWC was significantly higher with the I_3 (three irrigations) treatment compared to the I_1 and I_2 treatments. In all irrigation treatments, the upper soil at 0-7 and 7-15 cm depth had a lower SWC than at 45-60 cm (Fig. 4.4F).

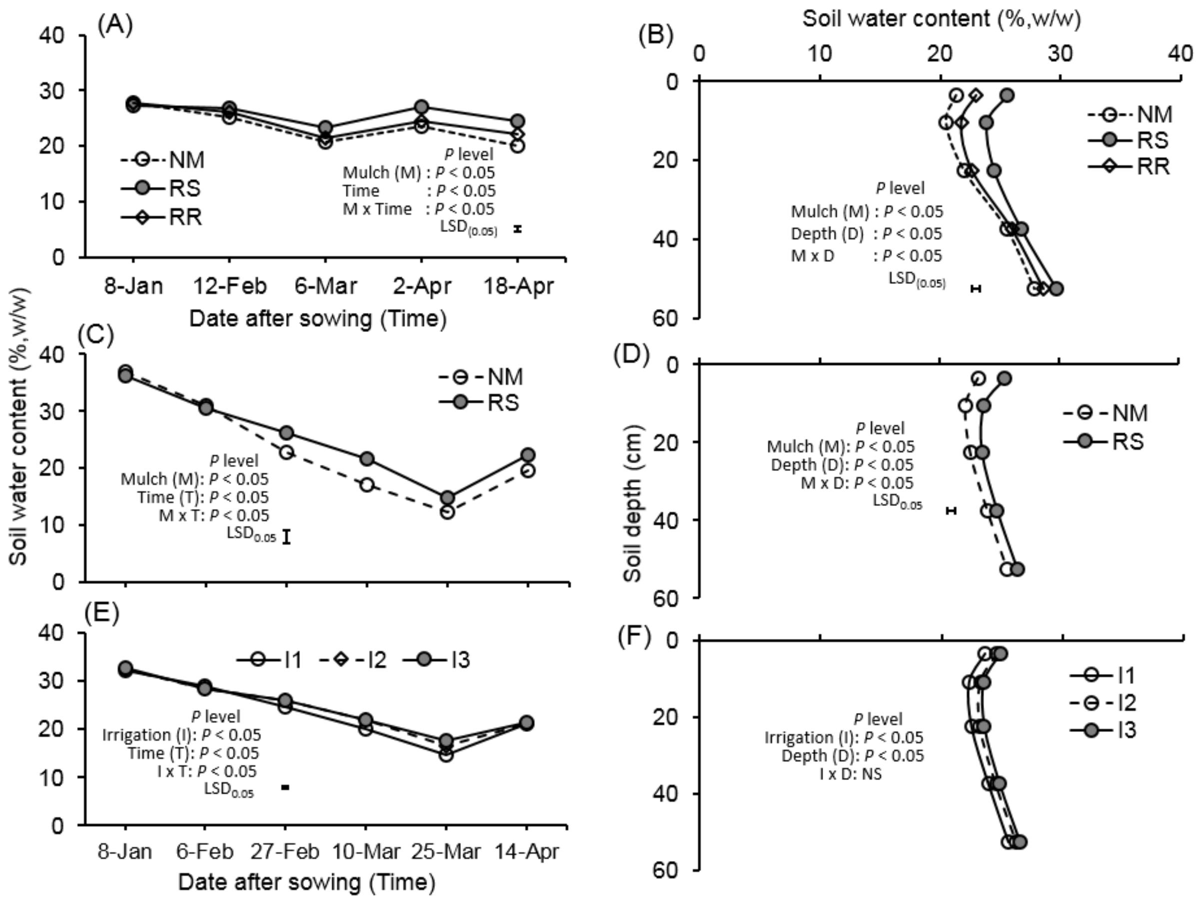

Fig. 4.4. Effects on soil water content of mulch (A and B) in 2017 and (C and D) in 2018, and irrigation (E and F) in 2018, with time (A, C and E) and with soil depth (B, D and F). NM = no-mulch, RS = rice straw, RR = rice residue; I_1= One irrigation, I_2 = two irrigations, I_3 = three irrigations. $LSD_{0.05}$ is the least significant difference of the interaction between mulch and time (A), or mulch and depth (B) in 2017, and mulch and time (C) or mulch and depth (D) in 2018, and irrigation and time (E) and irrigation and depth (F) in 2018. NS indicates no significant interaction between irrigation and depth (F).

4.5.5 *Variation in soil salinity*

The effects of mulch (2017) and mulch and irrigations (2018) on salinity and their interaction with time and soil depth are presented in Fig. 4.5. In 2017, between sowing and 35 days later (12 Feb), the $EC_{1:5}$ decreased from 0.86 to 0.72, 0.89 to 0.55 and 0.83 to 0.65 dS m^{-1} under the NM, RS and RR treatments, respectively, as light irrigation water was applied on 21 January, 29 January and 7 February (Fig. 4.5A). The $EC_{1:5}$ increased slightly from mid-February to the first week of March and declined afterwards because of the heavy rainfall in the second week of March (Fig. 4.5A). During that time, $EC_{1:5}$ was consistently lower with the RS treatment than with the NM and RR treatments. Throughout the season, the most substantial changes in soil salinity were at 0-7 cm depth, which was significantly higher than at depths to 60 cm (Fig. 4.5B). Throughout the entire period in 2018, there was a significant reduction of soil salinity with the RS treatment (Fig. 4.5C). Compared to values at sowing time, $EC_{1:5}$ at flowering increased from 0.41 to 0.74 and 0.42 to 0.68 dS m^{-1} under NM and RS treatments. After sowing, the $EC_{1:5}$ also gradually increased in all irrigation treatments with the progress of the dry season except at maturity when $EC_{1:5}$ was slightly lower than at flowering. At flowering (25 Mar), the I_3 treatment had an $EC_{1:5}$ (0.68 dS m^{-1}) that was slightly lower than with the I_2 (0.71 dS m^{-1}) and I_1 (0.74 dS m^{-1}) treatments (Fig. 4.5E). The average values of $EC_{1:5}$ between sowing and harvest were consistently higher at 0-7 cm and at 45-60 cm than at 7-15 and 15-30 cm (Fig. 4.5D and F).

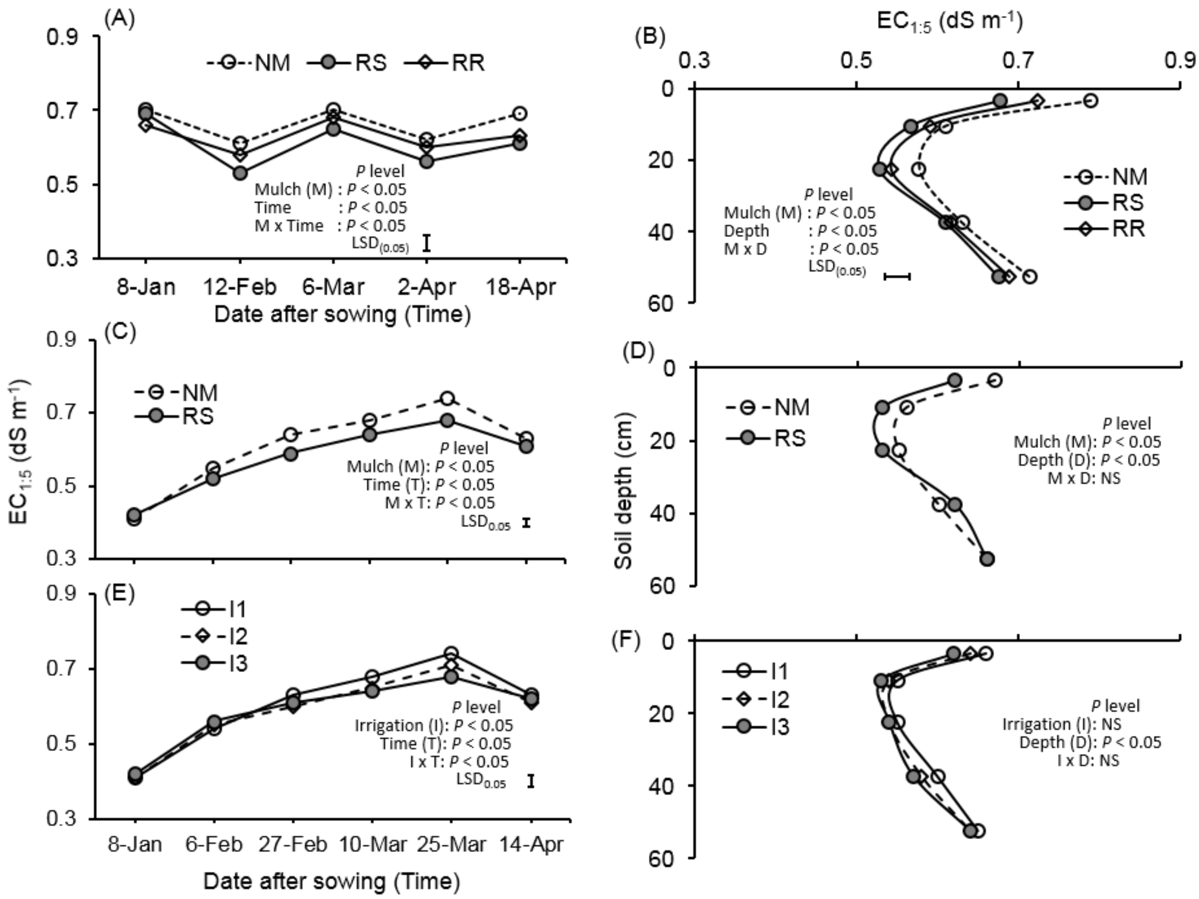

Fig. 4.5. Effects on $EC_{1:5}$ of mulch (A and B) in 2017 and (C and D) in 2018, and irrigation (E and F) in 2018, with time (A, C and E) and with soil depth (B, D and F). NM = no-mulch, RS = rice straw, RR = rice residue; I_1= One irrigation, I_2 = two irrigations, I_3 = three irrigations. $LSD_{0.05}$ is the least significant difference of the interaction between mulch and time (A), or mulch and depth (B) in 2017, and mulch and time (C) and irrigation and time (E) in 2018. NS indicates not a significant interaction between mulch and depth (D) and irrigation and depth (F).

4.5.6 Total water use and crop water productivity

In 2017, the same amount of irrigation water and rain was applied to all mulch treatments, and mulch treatments had no substantial difference in soil water between sowing and harvest down the soil profile to 60 cm (Table 4.4A). In 2018, the soil water depletion between sowing and harvest ranged from 51 to 61 mm at 0-60 cm depth (Table 4.4B). There was no difference in soil water depletion among irrigation treatments. However, soil water depletion was significantly higher with the NM treatment than with the RS treatment. Although soil water depletion was lower in the RS treatment, the total water use was higher in the NM than in the RS treatments. Both irrigation and mulching significantly affected the total water use during the season. The total water use in the I_2 and I_3 treatments was significantly greater than the I_1 treatment. In 2017, mulch treatments had significant effects on the water productivity of grain and biomass (Fig. 4.6A and B). The RS treatment had 26-32 % higher grain and biomass productivity than the NM treatment. In 2018, the RS treatment significantly increased grain and biomass productivity by about 16 % relative to the NM treatment (Fig. 4.6C and D). The lowest irrigation treatment (I_1) had the highest water productivity for grain and biomass (Fig. 4.6E and F) but had a lower yield.

Table 4.4. Irrigation water and total water used by irrigation treatments and mulching in (A) 2017 and (B) 2018

4A

Treatments 2017	Irrigation water (mm)	Rainfall (mm)	*ΔW (mm)	Total water use (mm)
NM	90	173	64	327
RS	90	173	35	298
RR	90	173	44	307
$LSD_{0.05}$			NS	NS

4B

Irrigation treatments	Irrigation water (mm)		Rainfall (mm)		*ΔW (mm)		Total water use (mm)	
2018	NM	RS	NM	RS	NM	RS	NM	RS
I_1	33	33	64	64	56.6	51.7	153.6	148.7
I_2	79	79	64	64	60	51	203	199
I_3	132	132	64	64	61	52	257	248
$LSD_{0.05}$								
Irrigation (I)	-	-	-	-	NS		19	
Mulch (M)					4.4		4.3	
I x M					NS		NS	

*ΔW is the change in soil water content between sowing and harvest at 0-60 cm depth. Legend: NM: no-mulch, RS = rice straw and RR = rice residue; I_1: One irrigation, I_2 = two irrigation and I_3 = three irrigation.

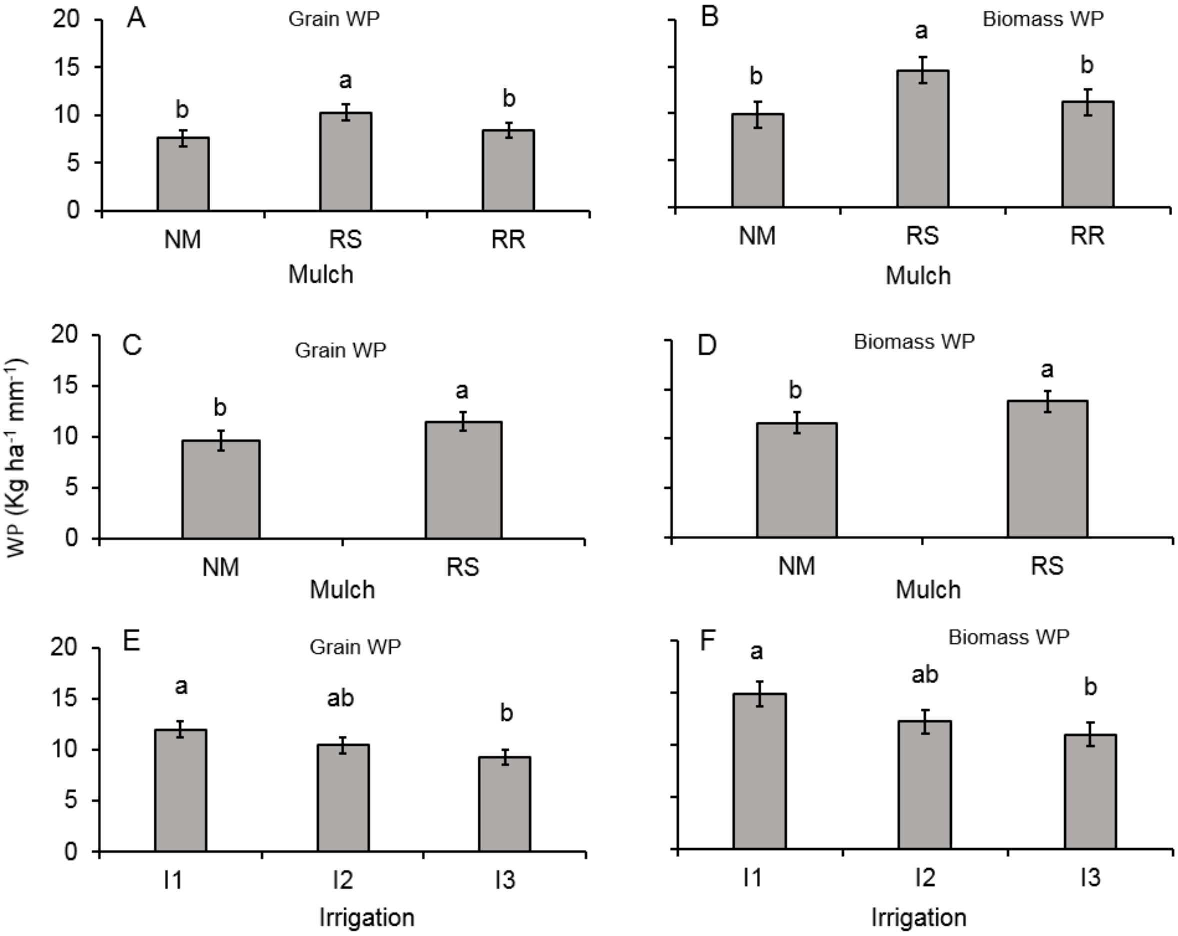

Fig. 4.6. Water productivity (WP) for (A) grain yield and (B) biomass yield in three mulching treatments in 2017, for (C) grain yield and (D) biomass yield in two mulching treatments, and (E) grain yield and (F) biomass yield in three irrigation treatments in 2018. Abbreviations: NM-no-mulch, RS-rice straw mulch and RR-rice residue; I_1: One irrigation, I_2 = two irrigation and I_3 = three irrigation. Means with identical letters are not significantly different.

4.6 Discussion

The calculation of SP from soil $EC_{1:5}$ and water content data is a relatively simple means of integrating the variation in salinity and soil moisture in moderately salinised landscapes. In a previous study(Paul et al., 2020), planting with minimum soil disturbance on wet, clay-textured soil produced lower sunflower yield than planting with full tillage. This result was attributed to lower SP in the upper root zone of soils after minimum soil disturbance. In this study, we hypothesised (correctly) that in clay-textured saline soil under strip planting, the application of rice straw mulch at ~ 5 t ha^{-1} would decrease soil surface dryness and salinity, increase SP, and hence improve sunflower growth and yield. The improvement of sunflower growth and yield was more strongly related to higher SP than to either SWC or soil $EC_{1:5}$ alone. This discussion focuses on the impacts of mulch and irrigation as factors affecting crop yield, SP, SWC and crop water use and productivity.

4.6.1 Mulch and Irrigation effects on growth and yield

In both years, the benefits of RS were more seeds per head, greater seed weight and higher grain yield (2.7 and 2.5 t ha^{-1} in 2017 and 2018) than with NM treatment (2.0 and 2.1 t ha^{-1} in 2017 and 2018). In the second year, an increasing number of irrigations to three events (I_3) also caused an increase in sunflower yield by 22 % relative to less irrigation (I_1), but the effects were additive to mulching. The higher yield in the RS and I_3 treatments were related to higher SP from bud formation to maturity stages, which positively influenced the number of seeds and seed size. Many studies have shown the benefits of different mulching materials on crop yield in saline environments (summarized in Table 4.5). With the rice straw mulch, the average yield of sunflower in the present study was 6-12 % higher than the benefit reported by Bhattacharya et al. (2019) and Gajri et al. (1997b). In most of the studies, higher grain yield under mulch was attributed to either increased soil moisture or reduced soil salinity. However, unlike in the present study, none of these previous studies examined the effects of mulch on SP, which is a function of both soil water and soil salinity. In the present study, sunflower yield was more strongly related to SP than to either soil water or EC.

Table 4.5. Summary of literature reports of the effects of mulching materials on crop yields and the attribution of benefits to the crops.

Crop	Location	Mulch type	Grain yield		% increase	Attribution of benefit			Reference
			No-mulch ($t\ ha^{-1}$)	Mulch ($t\ ha^{-1}$)		Salinity control	Water deficit control	Solute potential control	
Sunflower	Bangladesh	Rice straw	2.0	2.7	26 %	√	√	√	Present study 2017
Sunflower	Bangladesh	Rice straw	2.1	2.5	16 %	√	√	√	Present study 2018
Sunflower	Bangladesh	Rice straw	3.0	3.3	9 %	-	-	-	Bhattacharya et al. (2019)
Sunflower	India	Rice straw	1.8	2.1	14 %	-	√	-	Gajri et al. (1997a)
Maize	Bangladesh	Plastic	3.4	4.7	28 %	√	-	-	Haque et al. (2018)
Cotton	Uzbekistan	Wheat straw	2.0	2.2	9 %	√	-	-	Bezborodov et al. (2010)
Wheat	China	Plastic	4.0	4.3	7 %	√	√	-	Zhang et al. (2018)
Cotton	China	Plastic	0.9	1.07	16 %	√	√	-	Dong et al. (2009)

4.6.2 Mulch and irrigation effects on solute potential

The SP of the soil solution decreases the availability of water for uptake by plants (Munns, 2002; Rengasamy, 2006). The SP is directly proportional to the salt concentration in the soil solution and inversely related to the soil water content (Liu and Chi, 2014). In our study, lower soil salinity and higher SWC under I_3 and RS treatments increased SP of soil solution relative to that with NM and less irrigation (I_1 and I_2). In 2017, the effects of SP were more prominent at vegetative and maturity stages at 0-15 cm depth (R^2 = 0.83 and 0.72, and 0.97 and 0.92 at vegetative and maturity, respectively) (Table 4.3A). In 2018, the low SP was more influential at flowering at depth 0-7 and 7-15 cm (R^2 = 0.73 and 0.82) (Table 4.3B). The higher SP with RS treatment in surface soil layers can be attributed to the action of rice straw mulch as a barrier for evaporative loss of water and upward movement of salts (Abd El-Mageed et al., 2016; Wang et al., 2019).

The SP of surface soils in an irrigated environment with intermittent rainfall can be expected to be highly variable as salt and water contents in the soil respond to evaporation and leaching events. In the present work, in the absence of rainfall for about 90 days before sowing in 2017, there was a higher $EC_{1:5}$ at 0-15 cm than at 15-60 cm depth, but after the establishment of the crop, topsoil salinity dropped below that lower in the soil profile from vegetative growth to maturity as a result of frequent irrigation at the beginning of the season and rainfall before flowering. The impacts of rain and irrigation indicate that soluble salts were leached out of the upper soil layer. By contrast, during sowing in 2018, soil salinity at 0-15 cm was lower than in soil at 15-60 cm depth, and salinity then gradually increased in the surface soil layer more than in deeper soil during the growing period. The plausible reasons for this variation of the salt movement were the 59 mm rainfall that occurred before sowing, and the effects of mulching and irrigation. On average, RS treatment reduced soil salinity ~ 16 % in the first year and 8 % in the second year; this confirms an earlier result for a sub-temperate climate where straw mulch had a 16 % lower salinity than under no-mulch at 0-20 cm soil depth (Abd El-Mageed et al., 2016). This lower salinity under rice straw mulch may be attributed to reduced soil water loss by evaporation from the upper layer of soil. These findings are supported by others who indicated that mulching together with irrigation may achieve more efficient leaching of salt by improving infiltration, increasing soil water availability, and reducing salt accumulation in the surface soil (Bezborodov et al., 2010; Pang et al., 2010; Plaut et al., 2013).

4.6.3 Effect of mulch and irrigation on SWC

Sunflower yield is considered more sensitive to water stress at flowering than during seedling, vegetative growth and bud formation (Unger and Jones, 1998). In our study, the RS treatment increased the average SWC by 3-17 % at 0-60 cm soil depth throughout the crop duration. The previous study has also shown that under dryland conditions, straw mulch enhanced the SWC by around 13-22 % in the 0-20 cm soil layer compared with a no-mulch control (Peng et al., 2015). In 2017, the increase in SWC was more prominent from bud formation to maturity at 0-7 cm depth when the SWC with RS treatment (23-26 %, w/w) was associated with wilting (25-28 %, w/w), but the SWC with the NM and RR treatments (17-20 %) was lower than the wilting point. In 2018, the SWC at flowering was lower than the wilting point at 0-15 cm in NM (12-13 %) and RS (14-16 %) treatments. Among the mulch treatments, the higher soil water with RS treatment can be attributed to greater soil water storage after irrigation as straw mulch reduced soil water evaporation (Balwinder et al., 2011).

The survival of plants in which the surface soil had a SWC below wilting point requires an explanation. Although SWC of the surface soil was much lower than the wilting point for all treatments, there were higher SWCs at depths between 15 and 60 cm which indicates that sunflower could have extracted water from 15-60 cm depth to avoid severe water stress because of its deep rooting systems. In another study (PLC Paul, unpublished data), we excavated sunflower roots to 80 cm depth on the same soil at flowering, supporting the notion that sunflower growth late in the season accessed available soil water below 15 cm depth. Cox and Jolliff (1986) have also noted that sunflower has deep rooting systems which extracted soil water to 1.8 m depth, which allowed the crops to avoid prolonged water stress during the reproductive stage.

4.6.4 Mulch implications for crop yield and water use

In the salt-affected Ganges delta, fresh irrigation water for dry season crops is very limited; efficient water use is, therefore, critical to achieving satisfactory yield. In our study, RS mulch minimized the total water use and increased the WP which was attributed to reducing soil evaporation as well as the increase in crop yield (c.f. (Abd El-Mageed et al., 2016; Zhang et al., 1999). In 2018, the maximum yield in no-mulch clay soil was 2.1 t ha^{-1} after three irrigation events (total 132 mm), but with mulch added two irrigations (79 mm) produced the same yield (2.2 t ha^{-1}), while saving 53 mm of irrigation water. This result shows that in the water scarce coastal Ganges delta, the application of mulch can decrease irrigation water requirements while still producing a profitable yield of sunflower.

4.7 Conclusions

In clay-textured soil in the saline coastal zone of the Ganges delta, rice straw mulch at 5 t ha^{-1} significantly improved plant growth and yield. The effect of rice straw mulch was due to an increased SP of soil solutions in the upper root zone caused by the combined effect of increased soil water content and reduced soil salinity at 0-15 cm depth. Seed yield was more strongly correlated with SP than either $EC_{1:5}$ or SWC, reflecting the fact that SP captures variation in both these other parameters. Yield gains from three irrigation events compared to one irrigation event can also be attributed to higher SP. The combined results over two-years on clay-textured soils suggest that soil management treatments are effective when they increase SP in the upper root zone; this can be achieved with the application of rice straw mulch and two or three irrigation events.

Acknowledgements

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4.8 References

Abd El-Mageed, T. A., Semida, W. M., and Abd El-Wahed, M. H. (2016). Effect of mulching on plant water status, soil salinity and yield of squash under summer-fall deficit irrigation in salt affected soil. *Agric. Water Manag.* **173**, 1-12.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome* **300**, D05109.

Atreya, K., Sharma, S., Bajracharya, R. M., and Rajbhandari, N. P. (2008). Developing a sustainable agro-system for central Nepal using reduced tillage and straw mulching. *J. Environ. Manag.* **88**, 547-555.

Balwinder, S., Eberbach, P. L., Humphreys, E., and Kukal, S. S. (2011). The effect of rice straw mulch on evapotranspiration, transpiration and soil evaporation of irrigated wheat in Punjab, India. *Agric. Water Manag.* **98**, 1847-1855.

Bezborodov, G. A., Shadmanov, D. K., Mirhashimov, R. T., Yuldashev, T., Qureshi, A. S., Noble, A. D., and Qadir, M. (2010). Mulching and water quality effects on soil salinity and sodicity dynamics and cotton productivity in Central Asia. *Agric. Ecosyst. Environ.* **138**, 95-102.

Bhattacharya, J., Saha, N. K., Mondal, M. K., Bhandari, H., and Humphreys, E. (2019). The feasibility of high yielding aus-aman-rabi cropping systems in the polders of the low salinity coastal zone of Bangladesh. *Field Crops Res.* **234**, 33-46.

Cerdà, A., Rodrigo-Comino, J., Giménez-Morera, A., and Keesstra, S. D. (2017). An economic, perception and biophysical approach to the use of oat straw as mulch in Mediterranean rainfed agriculture land. *Ecol. Eng.* **108**, 162-171.

Cox, W. J., and Jolliff, G. D. (1986). Growth and yield of sunflower and soybean under soil water deficits. *Agron. J. 78, 226-23.*

Dong, H., Li, W., Tang, W., and Zhang, D. (2009). Early plastic mulching increases stand establishment and lint yield of cotton in saline fields. *Field Crops Res.* **111**, 269-275.

Gajri, P. R., Gill, K. S., Chaudhary, M. R., and Singh, R. (1997a). Irrigation of sunflower (Helianthus annuus) in relation to tillage and mulching. *Agric. Water Manage.* **34**, 149-160.

Gajri, P. R., Gill, K. S., Chaudhary, M. R., and Singh, R. (1997b). Irrigation of sunflower (Helianthus annuus) in relation to tillage and mulching. *Agric. Water Manag.* **34**, 149-160.

Haque, M. A., Jahiruddin, M., and Clarke, D. (2018). Effect of plastic mulch on crop yield and land degradation in south coastal saline soils of Bangladesh. *Int. Soil Water Conserv. Res.* **6**, 317-324.

Ji, S., and Unger, P. W. (2001). Soil Water Accumulation under Different Precipitation, Potential Evaporation, and Straw Mulch Conditions. *Soil Sci. Soc. Am. J.* **65**, 442.

Jordán, A., Zavala, L. M., and Gil, J. (2010). Effects of mulching on soil physical properties and runoff under semi-arid conditions in southern Spain. *Catena* **81**, 77-85.

Kader, M. A., Senge, M., Mojid, M. A., and Ito, K. (2017). Recent advances in mulching materials and methods for modifying soil environment. *Soil Tillage Res.* **168**, 155-166.

Keesstra, S., Mol, G., De Leeuw, J., Okx, J., Molenaar, C., De Cleen, M., and Visser, S. (2018). Soil-Related Sustainable Development Goals: Four Concepts to Make Land Degradation Neutrality and Restoration Work. *Land* **7**, 133.

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J. N., Pachepsky, Y., and Van Der Putten, W. H. (2016). The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *Soil*.

Kitou, M., and Yoshida, S. (1994). Mulching effect of plant residues on soybean growth and soil chemical properties. . *Soil Sci. Plant Nutr.* **40**, 211-220.

Liu, X., and Chi, C. (2014). Estimating osmotic potential from electrical conductivity for solutions/extracts in salt-affected soils using an universal equation. *J. Food Agric. Environ.* **12**, 1033-1035.

Michael, A. M. (1978). "Irrigation: theory and practice," Vikas publishing house, New Delhi.

Mondal et al. (2011). Krishi projukti hatboi (Handbook on agro-technology), 5th edition. *Bangladesh Agricultural Research Institute, Gazipur-1701, Bangladesh*

Mondal, M., Paul, P., Humphreys, E., Tuong, T., Ritu, S., Rashid, M., Humphreys, E., Buisson, M., Pukinskis, I., and Phillips, M. (2015a). Opportunities for cropping system intensification in the coastal zone of Bangladesh. In:Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF), 449–476.

Mondal, M., Saha, N., Ritu, S., Paul, P., Sharifullah, A., Humphreys, E., Tuong, T., and Rashid, M. (2015b). Optimum sowing window for boro cultivation in the coastal zone of Bangladesh. In:Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF), 449–476

Munns, R. (2002). Comparative physiology of salt and water stress. *Plant Cell Environ.* **25**, 239-250.

Ning, C., and Hu, T. (1990). The role of straw-covering in crop production and soil management. *Better Crops International* **6**, 6-7.

Pang, H.-C., Li, Y.-Y., Yang, J.-S., and Liang, Y.-S. (2010). Effect of brackish water irrigation and straw mulching on soil salinity and crop yields under monsoonal climatic conditions. *Agric. Water Manag.* **97**, 1971-1977.

Paul, P., Rashid, M., Alam, M., Ghani, M., and Hossain, M. (2016). Selection of profitable rice based cropping system under prevailing water environment in Satkhira district of Bangladesh. *Acad. J. Agric. Res.* **4**, 581-588.

Paul, P. L. C., Bell, R. W., Barrett-Lennard, E. G., and Kabir, E. (2020). Variation in the yield of sunflower (Helianthus annuus L.) due to differing tillage systems is associated with variation in solute potential of the soil solution in a salt-affected coastal region of the Ganges Delta. *Soil Tillage Res.* **197**, 104489.

Peng, Z., Ting, W., Haixia, W., Min, W., Xiangping, M., Siwei, M., Rui, Z., Zhikuan, J., and Qingfang, H. (2015). Effects of straw mulch on soil water and winter wheat production in dryland farming. *Sci. Rep.* **5**, 10725.

Plaut, Z., Edelstein, M., and Ben-Hur, M. (2013). Overcoming Salinity Barriers to Crop Production Using Traditional Methods. *Crit. Rev. Plant Sci.* **32**, 250-291.

Rashid, M. H., Nasrin, S., and Mahalder, D. (2014). Zero tilled dibbled sunflower enables planting earlier and harvests more in the coastal saline area of Bangladesh. *Int. J. Environ. Sci. Dev.* **5**, 260.

Rauf, S. (2008). Breeding sunflower (Helianthus annuus L.) for drought tolerance. *Commun. Biometry Crop Sci.* **3**, 29-44.

Reddy, N., and Yang, Y. (2006). Properties of high-quality long natural cellulose fibers from rice straw. *J. Agric. Food Chem.* **54**, 8077-8081.

Rengasamy, P. (2006). World salinization with emphasis on Australia. *J. Exp. Bot.* **57**, 1017-1023.

Unger, P. W., and Jones, O. R. (1998). Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum. *Soil Tillage Res.* **45**, 39-57.

Wang, J., Liu, H., Wang, S., Liu, Y., Cheng, Z., Fu, G., Mo, F., and Xiong, Y. (2019). Surface mulching and a sandy soil interlayer suppress upward enrichment of salt ions in salt-contaminated field. *J. Soils Sediments* **19**, 116-127.

Yang, Y.-m., Liu, X.-j., Li, W.-q., and Li, C.-z. (2006). Effect of different mulch materials on winter wheat production in desalinized soil in Heilonggang region of North China. *J. Zhejiang Univ. Sci. B* **7**, 858-867.

Zhang, H., Wang, X., You, M., and Liu, C. (1999). Water-yield relations and water-use efficiency of winter wheat in the North China Plain. *Irrig. Sci.* **19**, 37-45.

Zhang, M., Dong, B., Qiao, Y., Yang, H., Wang, Y., and Liu, M. (2018). Effects of sub-soil plastic film mulch on soil water and salt content and water utilization by winter wheat under different soil salinities. *Field Crops Res.* **225**, 130-140.

Zhao, Y., Pang, H., Wang, J., Huo, L., and Li, Y. (2014). Effects of straw mulch and buried straw on soil moisture and salinity in relation to sunflower growth and yield. *Field Crops Res.* **161**, 16-25.

Chapter 5

Opportunity and risk with early sowing of sunflower on wet-clay soils after wet season rice in a salt-affected coastal region of the Ganges Delta

(This chapter was submitted to Journal of Agronomy and Crop Science and is currently under review)

Most studies have shown the benefits of mulch either on increasing soil water content or decreasing soil salinity. In Chapter 4, we showed the effectiveness of straw mulch on increasing soil water solute potential, which is a function of both soil water and soil salinity. The yield of sunflower was more highly correlated with the solute potential of soil solution than to either soil water or soil salinity.

In the present chapter, we examined the effect of time of sowing of sunflower (by zero tilled dibbling) on wet soil to determine whether early sowing increased the utilization of stored soil moisture and enabled sunflower avoidance of the salinity hazard later in the growing season. We further investigated which physical factors (soil water, soil salinity, solute potential, and temperature) determined the yield variation in the early to late sowing on wet, clay-saline soil in the Ganges delta.

5 Opportunity and risk with early sowing of sunflower on wet-clay soils after wet season rice in a salt-affected coastal region of the Ganges Delta

Priya Lal Chandra Paul [a, f, *], Richard W Bell [a], Edward G. Barrett-Lennard [a, b, d], Enamul Kabir [c], Donald S Gaydon [e]

[a] *Land Management Group, Agriculture Discipline, College of Science, Health, Engineering and Education, Murdoch University, WA-6150, Australia*

[b] *Department of Primary Industries and Regional Development, South Perth, WA-6151, Australia*

[c] *Agrotechnology Discipline, Khulna University, Khulna 9208, Bangladesh*

[d] *School of Agriculture and Environment, The University of Western Australia, Nedlands, WA 6009, Australia*

[e] *CSIRO Agriculture and Food, Brisbane, Australia*

[f] *Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur-1701, Bangladesh and*

[*] *Corresponding author: Tel.: +8801716617378, +610470569881; E-mail: plcpauliwm@yahoo.com*

5.1 Abstract

Early sowing of dry season (rabi) crops in the salt-affected coastal zone of the Ganges delta is hypothesised to increase yield potential because the current delayed sowing exposes the crop to soil dryness and salinity later in its growth. However, early sowing is challenging due to excess soil water after rice harvest which constrains soil preparation. Field experiments were conducted over two years with contrasting rainfall patterns to identify the opportunities and challenges of early sowing between mid-November and January to maximise sunflower yield on clay-textured soils in Southern Bangladesh. Sunflower was dibbled into untilled wet soil on: 23 November, 30 November, 10 December, 20 December and 30 December in 2016-17, and 25 November, 14 December, 25 December, 10 January and 25 January (dibbled in tilled soil) in 2017-18, with two mulching treatments; rice straw applied ~ 5 t ha^{-1} (RS) and 15-20 % rice residue retained from the previous crop (RR). Sowing before 15 December was associated with larger heads, more seeds per head, greater seed weight and higher grain yield (3.5-4 t ha^{-1}) in the first year, but early sowing was also risky since, in the second year, sowing on 25 November was hampered by heavy rainfall at 14 days after sowing (causing waterlogging) which depressed yield compared to sowing on 14 December. The higher yield of early sowing before 15 December was associated with higher average soil water, lower average soil salinity and higher average solute potential compared to sowing after 15 December. Lower yield in the late sowing was also associated with increased temperature. In both seasons, a 3-factor multivariate regression model (temperature, soil water content and $EC_{1:5}$) suggested that the main driver of yield was soil $EC_{1:5}$ followed by air temperature. The RS mulch significantly increased soil water availability, reduced soil salinity and increased solute potential and also increased yield in the second year. We conclude that sunflower sown before 15 December, which are earlier than present practice, has the highest yield potential, but the earliest sowings do have an elevated risk of yield loss due to waterlogging.

Keywords: Dibbling, soil water content, soil salinity, solute potential, temperature, mulch

5.2 Introduction

In the coastal zone of the Ganges delta, the dilemma is that early rabi crop establishment may be delayed by excess soil moisture after harvest of the previous wet season rice (kharif), which constraints timely soil preparation (Paul et al., 2020a), while delays in sowing expose the crop to soil dryness, salinity and possibly heat stress later in its growth. Currently, farmers prepare the soil to grow rabi crops such as sunflower and maize with 4-5 passes of rotary tillage beginning when the topsoil has dried below field capacity (Mondal et al., 2015a). Rotary tillage accelerates the drying of the tilled surface soil but delays the sowing time, which can lead to low yield.

Due to its low elevation (< 3 m above sea level), much of the coastal zone of the Ganges delta is protected by peripheral earthen embankments (polders) to prevent tidal inundation and seawater intrusion (Mondal et al., 2015b). However, due to a shallow water table, which is temporally dynamic in both depth and salinity, soil and water salinity in the dry season can be unfavourable for crop cultivation (Paul et al., 2016).

The low-land rice environment with intensive soil puddling is problematic for non-rice crop establishment in the dry season because of adverse soil physical constraints (Mitchell et al., 2013; So and Ringrose-Voase, 2000). Firstly, when soil is too wet immediately after harvesting wet season rice, poor drainage and aeration can negatively affect the emergence of seedlings (Kokubun, 2013; Rahmianna et al., 2000). Also, late monsoon rain may expose early sown crops to waterlogging (Yu et al., 2019). On the other hand, if the sowing time is delayed, crop growth and development can be affected by late-season soil dryness and compaction (Cook et al., 1995). In addition to this, late sowings may be damaged by high soil and water salinity and waterlogging from pre-monsoon rains prior to harvest (Mondal et al., 2015a; Zeng et al., 2015). Rather than wait until the soil is dry enough for rotary tillage, the optimum time of sowing (to maximise grain yield) may involve early planting at high soil water content through zero-tilled dibbling.

Sunflower is considered to be a drought-tolerant crop because of its efficient use of soil water (Rauf, 2008). It develops a deeper root system (up to 2 m) compared with other crops such as sorghum, soybean and maize, which aids in the water uptake by the plant during water stress (Sadras et al., 1989; Seiler, 1994). Sunflower is also classed as a moderately salt-tolerant crop (Francois, 1996; Katerji et al., 2003). In addition, low temperatures (< 25 ^{0}C) may delay and reduce germination and emergence (Gay et al., 1991), while high temperatures (> 30 ^{0}C) during bud formation and flowering can depress seed number, grain size and yield (Chimenti et al., 2001a; Rondanini et al., 2006).

In different climates, delayed sowing after the optimum time significantly reduced sunflower yield and yield components because of adverse temperature at particular growth stages (De La Vega and Hall, 2002; Dp and Ja, 1994; Unger, 1980). There is already some information on the effects of the sowing date on sunflower yields in Bangladesh. In the coastal saline area, Rahman et al. (2015) reported that sunflower sown on 10 December had around 1 t ha^{-1} higher yield than a crop sowing on 4 February. Rashid et al. (2014) mentioned that sunflower sown in the first week of January produced larger heads and greater yields than those sown on 22 February. Mondal et al. (2015a) showed that early establishment of rabi crops such as sunflower after wet season rice improved cropping system productivity. While these earlier studies emphasised the importance of early sowing, they did not identify the main yield-limiting factors with early or late sowing of the climatic risks. Nor did they consider the opportunity presented to establish crops early if sown without tillage by dibbling. The present study: (i) evaluated the effect of sowing dates on sunflower yield and yield components over two contrasting seasons, (ii) examined the effects of mulch on sunflower established by dibbling, and (iii) examined the relative impacts on yield from variations in the prevailing soil and weather drivers: soil water content, $EC_{1:5}$, the solute potential of soil solutions and average seasonal temperature during crop growth.

5.3 Materials and Methods

5.3.1 Description of the study site

Two field experiments were conducted in a farmer's field at Pankhali, Dacope Khulna, Bangladesh (22^0 37' 55" N and 89^0 30' 10" E) where the land is low-lying, and wet season rice (Aman) are generally grown from July to January. The area belongs to the Ganges Tidal Floodplain agro-ecological zone, AEZ13 (Paul et al., 2020a). The climate is subtropical with an average annual rainfall of 1,800 mm, a cool dry winter from November to February, and a hot and humid summer from March to June. Initial soil samples were collected at 15 cm increments to a depth of 60 cm (before crop establishment) to measure soil physical and chemical properties (Paul et al., 2020a). The soil texture was silty clay (0-30 cm) overlying clay (30-60 cm). The soil texture was silty clay (0-30 cm) overlying clay (30-60 cm). The soil (0-15 cm) had a bulk density of 1.4 Mg m^{-3}, a pH of 7.5, an $EC_{1:5}$ of 0.45 dS m^{-1}, an organic carbon content of 12 g kg^{-1}, a total nitrogen content of 13 g kg^{-1}, an extractable P concentration of 3 mg kg^{-1}, and an extractable K concentration of 338 mg kg^{-1}. To use the land for sunflower establishment in November, a medium duration high-yielding Aman rice was transplanted in the first week of August and drained of standing water (open ditches: 15-20 cm deep and 20-25 cm wide) before being harvested in the third week of November.

5.3.2 Experimental design and crop management

The experiment was laid out in a randomized complete block design with three replications in plots 10 x 4 m in 2016-17 and 9 x 5 m in 2017-18. Experimental treatments comprised five sowing dates in 2016-17 (23 November, 30 November, 10 December, 20 December and 30 December) and a further five dates in 2017-18 (25 November, 14 December, 25 December, 10 January and 25 January). In each year, there were two mulching treatments (RS = applied rice straw after crop emergence at 5 t ha^{-1} and RR = retained 15-20 % of rice residue, which is approximately 1 t ha^{-1}). Sunflower seeds (cv. Hysun-33) were sown into wet soil (soil water content varied from 43 % to 50 %, w w^{-1} in 2016-17, and from 31% to 51 %, w w^{-1} in 2017-18) by dibbling with a round stick to a depth of 2-3 cm with two seeds per hole except for the fifth sowing in 2017-18, where rotary tillage was done (five passes to achieve a suitable soil tilth) by two-wheel tractor before dibbling. The row to row distance was 70 cm, and plant to plant distance was 40 cm. Plants were thinned to one per hill at the 4-6 leaf stage (20 days after emergence). Fertilizer (urea-triple superphosphate-muriate of potash-gypsum-zinc sulphate-boric acid) was applied at 200-200-170-170-10-12 kg ha^{-1} based on the recommendation of the

Bangladesh Agricultural Research Institute (Mondal et al., 2011). All fertilizers except 75 % of the urea were applied immediately after crop emergence by placing in holes (5-7 cm deep) on both sides of the plant (~ 5 cm distance) along the rows, and the rest of the urea was broadcast between the rows in three splits at seedling stage (30-40 DAS), maximum vegetative period (50-55 DAS) and before flowering (60-65 DAS) in both seasons. Light irrigation was applied by spraying the soil immediately after urea top dressing to wash the urea into the soil. Insecticide Nitro (Cypermethrin Chlorpyriphos) was applied 2-3 times to control hairy caterpillar. In each plot, 7 m^2 was selected to monitor the emergence rate, crop growth, and development, bud initiation, first flowering, and physiological maturity. Ten plants were randomly selected to measure plant height, stem diameter, head diameter, head weight, number of seeds per head, and 1000 seed weight at maturity. Seeds were threshed manually from heads and sun-dried for 2-3 days to calculate the seed yield (t ha^{-1}) at an adjusted moisture content of 9 % (w w^{-1}).

5.3.3 Soil water content measurement (SWC)

Soil samples were collected to measure gravimetric SWC at 0-7, 7-15, and 15-30 cm depth every 10-15 days between sowing and harvest in both seasons. A hand-held auger was used to collect soil samples from each depth. The initial weight of the samples was measured immediately, and samples were then oven-dried to constant weight. The gravimetric SWC was then calculated (Cresswell and Hamilton 2002). The SWC at field capacity (-33 kPa) and wilting point (-1500 kPa) was also measured using a pressure plate apparatus (Eijkelkamp pF set) on undisturbed soil cores collected before sowing at each of the depths.

5.3.4 *Soil electrical conductivity ($EC_{1:5}$) measurements and the calculation of soil solute potential*

The $EC_{1:5}$ of the soil was measured at 0-7, 7-15, 15-30 cm depths at 15-20 days intervals during the growing season. Measurements of electrical conductivity were made in a 1:5 soil: water suspension using a portable EC meter. The solute potential of the soil solutions was calculated (Paul et al., 2020a) from the equation:

$$\Psi_s = -22580 \times EC_{1:5}/W$$

where, Ψ_s is the solute potential (kPa), $EC_{1:5}$ is the electrical conductivity (dS m^{-1}) of the 1:5 soil: water extract and W is the gravimetric SWC (%, w w^{-1}).

5.3.5 *Statistical analysis*

Statistical analyses were done using STAR version 2.0.1 (STAR, 2014). The effects of sowing dates and mulch on grain yield and yield components were determined using a two-way analysis of variance (ANOVA). The significance of effects of sowing dates and mulch on SWC, $EC_{1:5}$ and solute potential were determined using a three-way factorial ANOVA model that also took account of the effects of sowing dates and mulch with soil depth or days after sowing (DAS) as repeated measures. The differences between means were tested using the least significant difference (LSD) at the 95 % confidence level. The relationship between yield and air temperature was tested by a single factor regression model. The relative contribution (weighting) of the prevalent physical drivers for crop performance was examined by performing multiple linear regressions of the observed data, using several different factors. Models selected based on their explanation of yield variation were: (i) a 2-factor model (average seasonal temperature, average seasonal soil solute potential in root zone), and (ii) a 3-factor model (average seasonal temperature, soil water content and soil $EC_{1:5}$). We considered that the magnitude of the coefficient assigned to each of the driving variables represented the relative influence that variable had in determining grain yield.

5.4 Results

5.4.1 Seasonal rainfall and temperature during the growing season

In 2016-17, total rainfall throughout the cropping season (November to 15 April) was 173 mm but two-thirds fell in March during the flowering stage (Fig.5.1A). By contrast, in 2017-18, 51 mm rain fell during 8-10 December, inundating plots previously sown on 25 November and causing waterlogging stress (Fig. 5.1F). This heavy rain also delayed the second sowing until 14 December. There was no rain in the following months until 96 mm fell in April (Fig. 5.1F). In both years, air temperature declined in December/January and increased again from February (Fig. 5.1B and 5.1G). The average winter temperature (December-February) in 2017-18 was warmer than in 2016-17. The lowest minimum temperature was 8 ^{0}C in January 2018 and 9.5 ^{0}C in January 2017. The monthly maximum temperature was similar in both seasons apart from higher values in March and April in 2017-18. The maximum temperature in December and January was less than 30 ^{0}C in both seasons. Temperatures began to increase from February, and the maximum temperature was 36 ^{0}C and 37 ^{0}C in March and April in 2018, respectively.

5.4.2 Soil water content at establishment and crop phenology

There were slight effects of date of sowing in the two seasons on sunflower emergence, plant population, and dates of physiological maturity. These mostly had no substantial effect on grain yield, so the details can be found in the Supplementary Materials (Section S1 and Fig. 5S1). From the point of view of factors affecting yield, the following points are important: Firstly, differences in plant population for the first and fourth sowing dates in the second year between mulch and no-mulch affected the grain yield. Secondly, the late sowings on 30 December in the first year and 25 January in the second year significantly shortened the growth duration by 10 and 21 days, respectively.

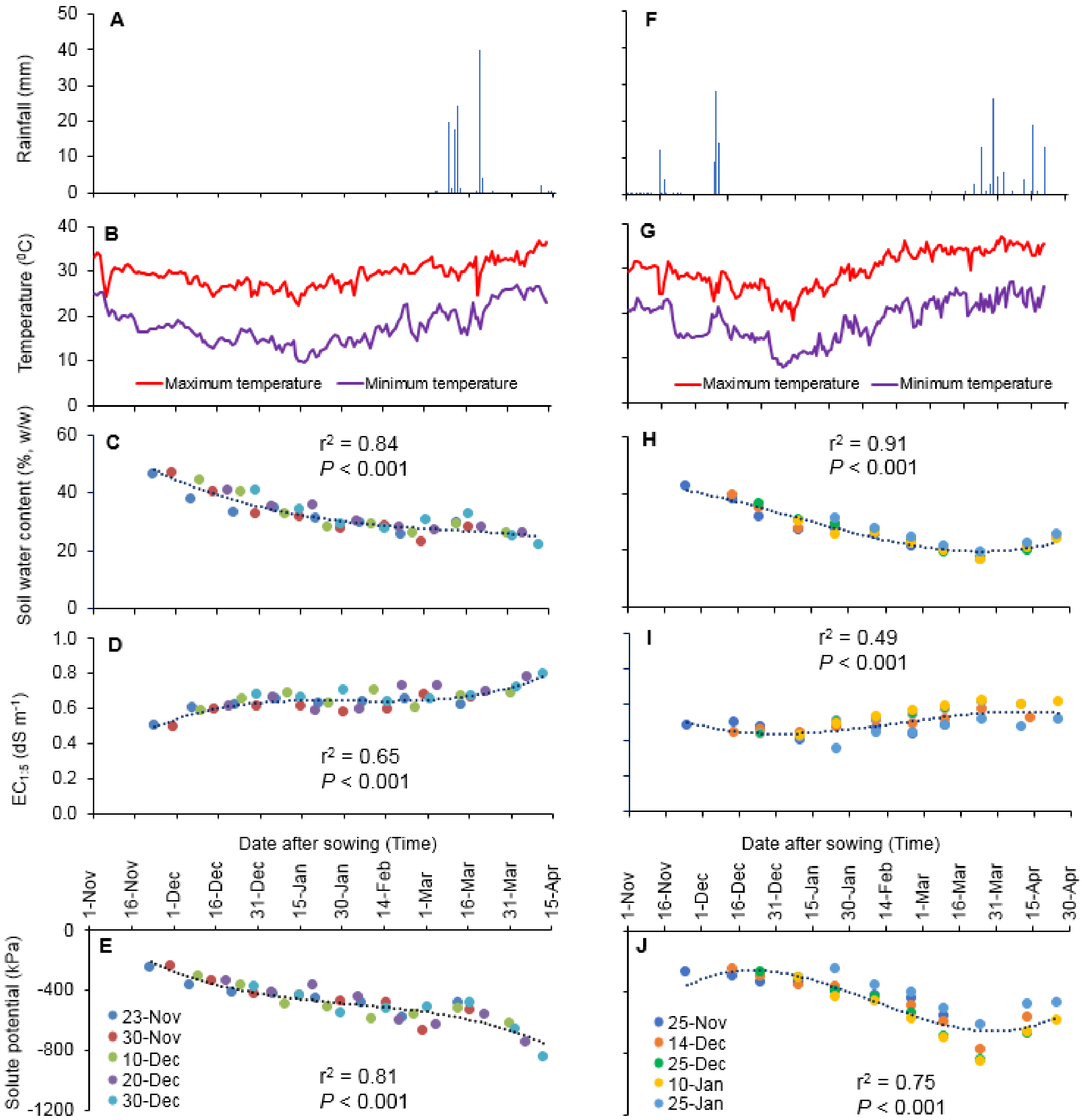

Fig. 5.1. Variation of seasonal weather and average soil data at 0-30 cm depth: (A, F) daily rainfall, (B, G) daily temperature, (C, H) soil water content, (D, I) $EC_{1:5}$ and (E, J) solute potential. Parts A-E are for 2016-17, and parts F-J are for 2017-18.

5.4.3 Yield and yield components of sunflower

In 2016-17, early sowing on 23 and 30 November produced the highest yield (~ 4 t ha^{-1}), later sowings had lower yields, and the last sowing on 30 December had the lowest yield (2.9 t ha^{-1}) (Table 5.1A). By contrast, in the 2017-18 season, the crop sown on 25 November had a lower yield than crops sown on 14 and 25 December as the former sowing was affected by waterlogging (Table 5.1B). The highest yield (2.9 t ha^{-1}) was from crop sown on 14 December and the lowest yield was from crop sown on 25 January (1.3 t ha^{-1}) (Table 5.1B). Overall, there were lower yields in the second season compared to the first season. In the first season, mulch had no effect on yield, but in the second season, the RS treatment had a significantly higher yield than the RR treatment (Table 5.1A and 5.1B).

Early sowing in both seasons was associated with a larger head diameter. The head diameter showed a decreasing trend with delayed sowing. In both seasons, the RS treatment increased the head diameter by 3-4 % relative to RR treatment (Table 5.1A and 5.1B). The number of seeds per head decreased with delayed sowing in both years. In 2017-18, there was a higher number of seeds per head with the sowing on 14 December, and after that a lesser number of seeds per head until the sowing on 25 January (Table 5.1B). Mulch did not affect the number of seeds in the first season, but there was a significant effect on the number of seeds in the second season. In 2016-17, early sowing (23 November, 30 November and 10 December) had significantly greater seed weight (90-97 g) than later sowing on 20 and 30 December (71-85 g). In 2017-18, sowing on 14 December produced the highest seed weight compared to the other sowing dates. For the last sowing on 25 January, seed weight (44 g) was only half of that with early sowing on 25 November and 14 January (80-85 g). There were significant interactions between sowing dates and mulch on seed weight in the second season (Table 5.1B).

Table 5.1 Yield and yield components of sunflower at Pankhali, Dacope, Khulna Bangladesh in (A) 2016-17 and (B) 2017-18.

1A. 2016-17

Sowing treatments	Mulch treatments	Grain yield ($t\ ha^{-1}$)	Head diameter (cm)	Seeds per head (number)	1000 seed weight (g)
23 Nov	RS	3.8	23	1400	97
	RR	3.9	21	1382	96
30 Nov	RS	3.9	22	1333	93
	RR	4.0	23	1380	94
10 Dec	RS	3.6	22	1263	91
	RR	3.4	22	1228	89
20 Dec	RS	3.3	21	1301	87
	RR	3.1	20	1230	82
30 Dec	RS	3.0	20	1232	74
	RR	2.8	19	1137	69
P-values					
Sowing		0.0001	0.001	0.003	0.001
Mulch		NS	0.02	NS	NS
sowing: Mulch		NS	NS	NS	NS
LSD values					
Sowing		0.27	0.78	88	8.6
Mulch		-	0.35	-	-
Sowing: Mulch		-	-	-	-

1B. 2017-18

Sowing treatments	Mulching treatments	Grain yield ($t\ ha^{-1}$)	Head diameter (cm)	Seeds per head (number)	1000 seed weight (g)
25-Nov	RS	2.3	21	1041	82
	RR	1.7	19	945	78
14-Dec	RS	3.1	21	1305	87
	RR	2.6	21	1202	84
25-Dec	RS	2.9	21	1274	84
	RR	2.6	20	1182	78
10-Jan	RS	2.3	19	1205	81
	RR	2.0	19	1147	76
25-Jan	RS	1.7	15	911	50
	RR	0.9	14	780	37

P-values				
Sowing	0.005	0.001	0.001	0.001
Mulch	0.0005	0.007	0.001	0.001
Sowing: Mulch	NS	NS	NS	0.02
LSD values				
Sowing	0.68	1.49	104	3.9
Mulch	0.22	0.56	48	3.9
Sowing: Mulch	-	-	-	3.9

NS indicates no significant difference
LSD indicates the least significant difference at $P < 0.05$. Abbreviations: RS-rice straw and RR-rice residue.

5.4.4 Relative influence (weighting) of temperature, $EC_{1:5}$, SWC, and SP in determining grain yield

In both years, grain yield was negatively correlated (single factor relationship) with increasing minimum and maximum temperature averaged over the season (Fig. 5.2). In the first year, minimum and maximum temperature, respectively, accounted for 79 and 78 % of the variation in crop yield, whereas in the second year, these accounted for 69 and 68 % of the variation, respectively. The mean percentage reduction in yield for increased average minimum and maximum temperature from 15 and 28 ^{0}C at sowing to 18 and 30 ^{0}C at harvesting was 27 % in the first year. In the second year, the percentage yield decrease was 54 % for increased temperature from 17 and 29 ^{0}C at sowing to 22 and 33 ^{0}C at harvesting (Fig. 5.2). We also explored the relative weighting of other driving factors affecting the variation of yield in both seasons by testing multiple linear regression models considering 3-factor (average temperature, SWC, $EC_{1:5}$) and 2-factor (average temperature and SP) (Fig. 5.3 and 5.4). In the first season, the 2-factor model adding the SP factor had minimal effect on explaining yield variation (Fig. 5.3C and 5.3D). By contrast, the 3-factor model (average temperature, SWC and $EC_{1:5}$) explained 91 % of the yield variation with the major contribution from $EC_{1:5}$ and to a lesser extent from temperature (Fig. 5.3A and 5.3B). Moreover, seed yield was mostly determined by $EC_{1:5}$ during the later half of the growing season. In the second season, the 3-factor model (average temperature, SWC and $EC_{1:5}$) explained 72 % of observed yield (Fig. 5.4A): the 2-

factor model (average temperature and SP) explained only 53 % of yield variation, and as in the previous year average temperature had the dominant effect (Fig. 5.4C and 5.4D). While the driving factor for determining the yield in the second season was $EC_{1:5}$ and to a lesser extent to temperature as in the first year, these factors had the most influence on sunflower yield in the first half of the season. The 3-factor model explained more of the variance in yield (higher r^2 values) than the 2- factor model in both seasons.

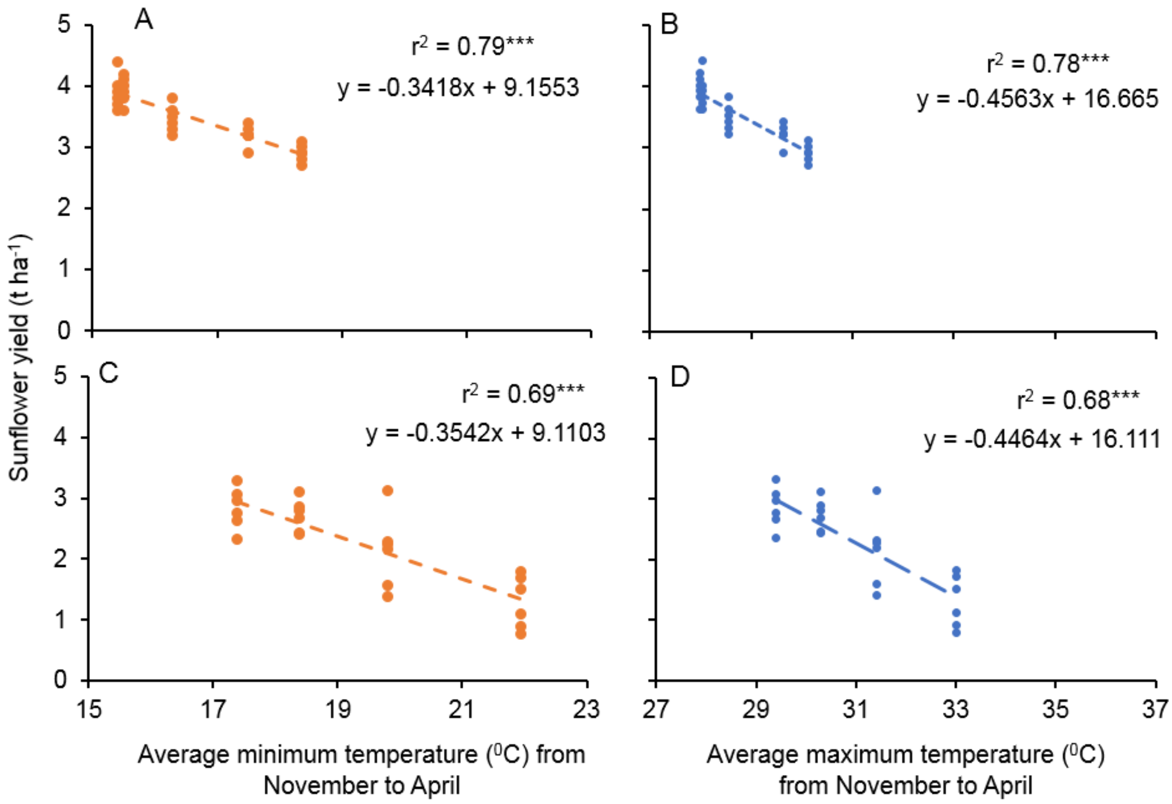

Fig. 5.2. Relationship between sunflower yield and temperature during the growing season (A) average minimum temperature and (B) average maximum temperature in 2016-17, and (C) average minimum temperature and (D) average maximum temperature 2017-18.

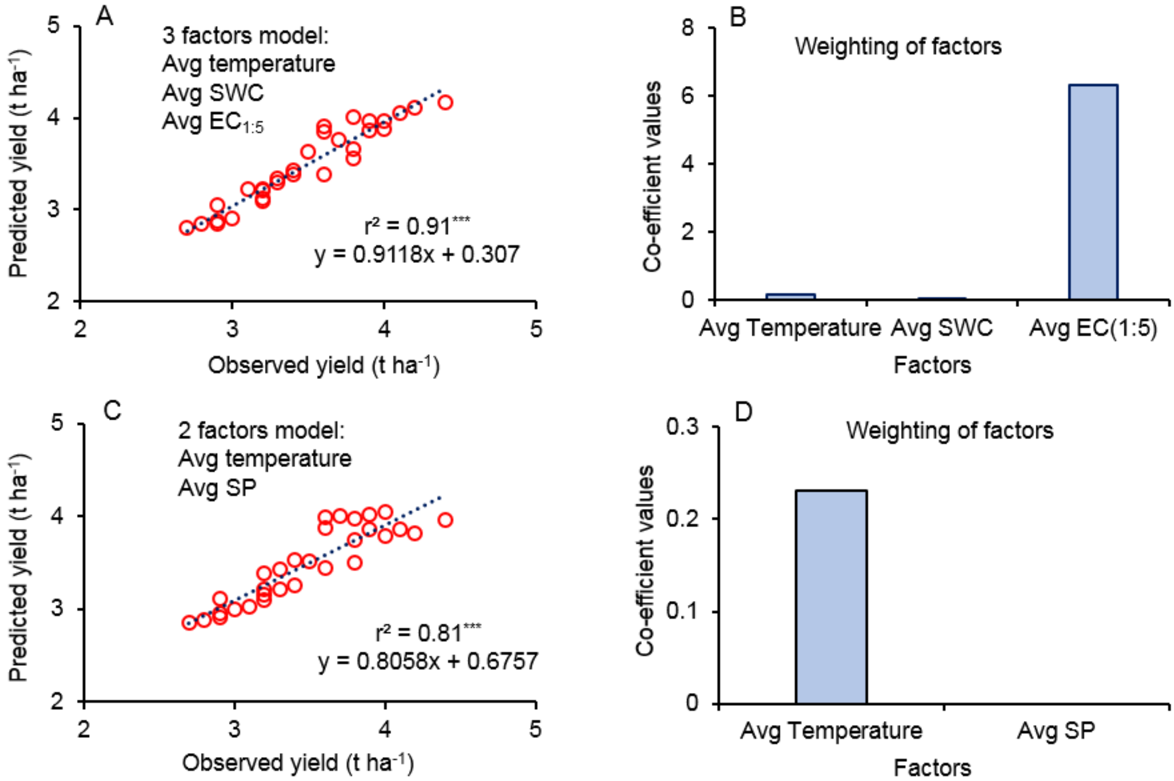

Fig. 5.3. Relationship between observed and predicted yield and weighting of factors (A-B) for 3- factor and (C-D) for 2- factor models from flowering to maturity (75-110 DAS) in 2016-17 season.

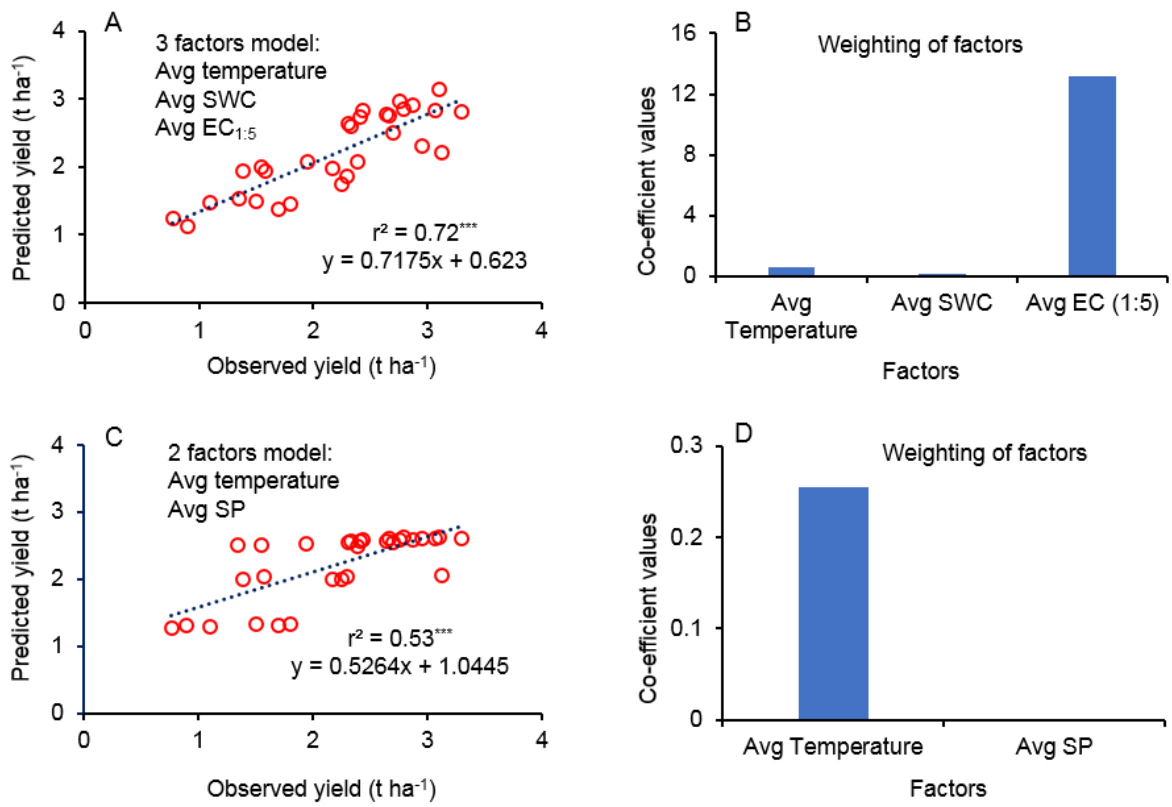

Fig. 5.4. Relationship between observed and predicted yield and weighting of factors (A-B) for 3- factor and (C-D) for 2- factor models from sowing to anthesis (0-60 DAS) in 2017-18 season.

5.4.5 Seasonal dynamics of SWC, $EC_{1:5}$ and SP

For both seasons, the effects on SWC, $EC_{1:5}$ and SP of five sowing dates have been illustrated in the Supplementary Materials (Section S2 and Fig. 5S3, 5S4 and 5S5). All these soil variables changed as the dry season progressed and were affected by seasonal rainfall. In both seasons, the observed data for SWC, $EC_{1:5}$ and SP over the 0-30 cm soil depth for all dates of sowing were best fitted with a polynomial cubic relationship (Fig. 5.1C, D, E, H, I and J). For all dates of sowing, the relationship accounted for 84 and 91 % ($P < 0.001$) of the decrease in SWC with time in the first and second season, respectively (Fig. 5.1C and 5.1H). Irrespective of sowing treatments, the SWC was around 42-46 % (w/w) at the beginning of the season (last week of

November) and declined to 17-22 % by the end of the season. In the second season, the SWC at the last sowing (25 January) was slightly higher because the land was cultivated before dibbling by a rotary cultivator.

The $EC_{1:5}$ increased with time for all dates of sowing at 0-30 cm soil depth (Fig. 5.1D and 5.1I). About 65 and 49 % of increased values of $EC_{1:5}$ can be explained by time in the first and second season (Fig. 5.1D and 5.1I) using the polynomial cubic relationship. The $EC_{1:5}$ was around 0.5 dS m^{-1} at the start of the season, and it increased to 0.8 and 0.6 dS m^{-1} at the end of the season in the first and second years, respectively. In the second year, overall $EC_{1:5}$ was lower due to rainfall in the beginning and later part of the season.

The SP decreased (i.e., became more negative) with the progress of the dry season due to increased soil salinity and reduced soil water content. The variation of the SP with time in all times of sowing can be well explained by the polynomial cubic relationship ($r^2 = 0.81$ and $P < 0.001$ in the first season and $r^2 = 0.75$ and $P < 0.001$ in the second season) (Fig. 5.1E and 5.1J). In both seasons, the SP dropped from around -250 kPa at the beginning of season to -860 kPa at the end of season. In the second year, the last sowing on 25 January increased the SP because of substantial soil disturbance and rainfall.

5.4.6 Effect of mulch on SWC, $EC_{1:5}$ and SP

In both seasons, the RS treatment significantly increased the soil water in all times of sowing, and there was a significant interaction between sowing, mulch and time (DAS) on SWC (Supplementary Materials Fig. 5S6A-J). On average, throughout the season, the RS treatment significantly increased SWC by 3-5 % and 2-3 % (w/w) over RR treatment in the first and second years, respectively. At the beginning of the season, SWC at 0-7 cm layer was higher than at 7-15 cm in both mulching treatments. However surface soil at 0-7 cm dried faster than 7-15 and 15-30 cm at the end of the season, mainly in the RR treatment.

In the first season, there was no difference in $EC_{1:5}$ for early sowing on 23 and 30 November between the two mulching treatments (Supplementary Materials Fig. 5S7A and5S7 B), but the $EC_{1:5}$ was significantly lower under the RS treatment compared to the RR treatment after on sowing 10, 20 and 30 December (Supplementary Materials Fig. 5S7C, D and E). In the second season, rainfall in December lowered the $EC_{1:5}$ during planting time on 14 December onward. There was a significant interaction between mulch and time, but no interaction between sowing and mulch or sowing, mulch and time at $P > 0.05$ (Supplementary Materials Fig. 5S7F-J).

In both seasons, SP increased with the progress of the season in two mulching treatments (Fig. 5.5A and 5.5B). The SP under the RS treatment was significantly greater than with the RR treatment in both seasons. In 2016-17, the range of SP was between -243 kPa and -890 kPa, and -260 kPa and -1316 kPa in RS and RR treatments from the establishment to maturity. In 2017-18, the range of SP was between -213 kPa and -876 kPa, and -221 kPa and -1408 kPa in RS and RR treatments, respectively from the establishment to flowering.

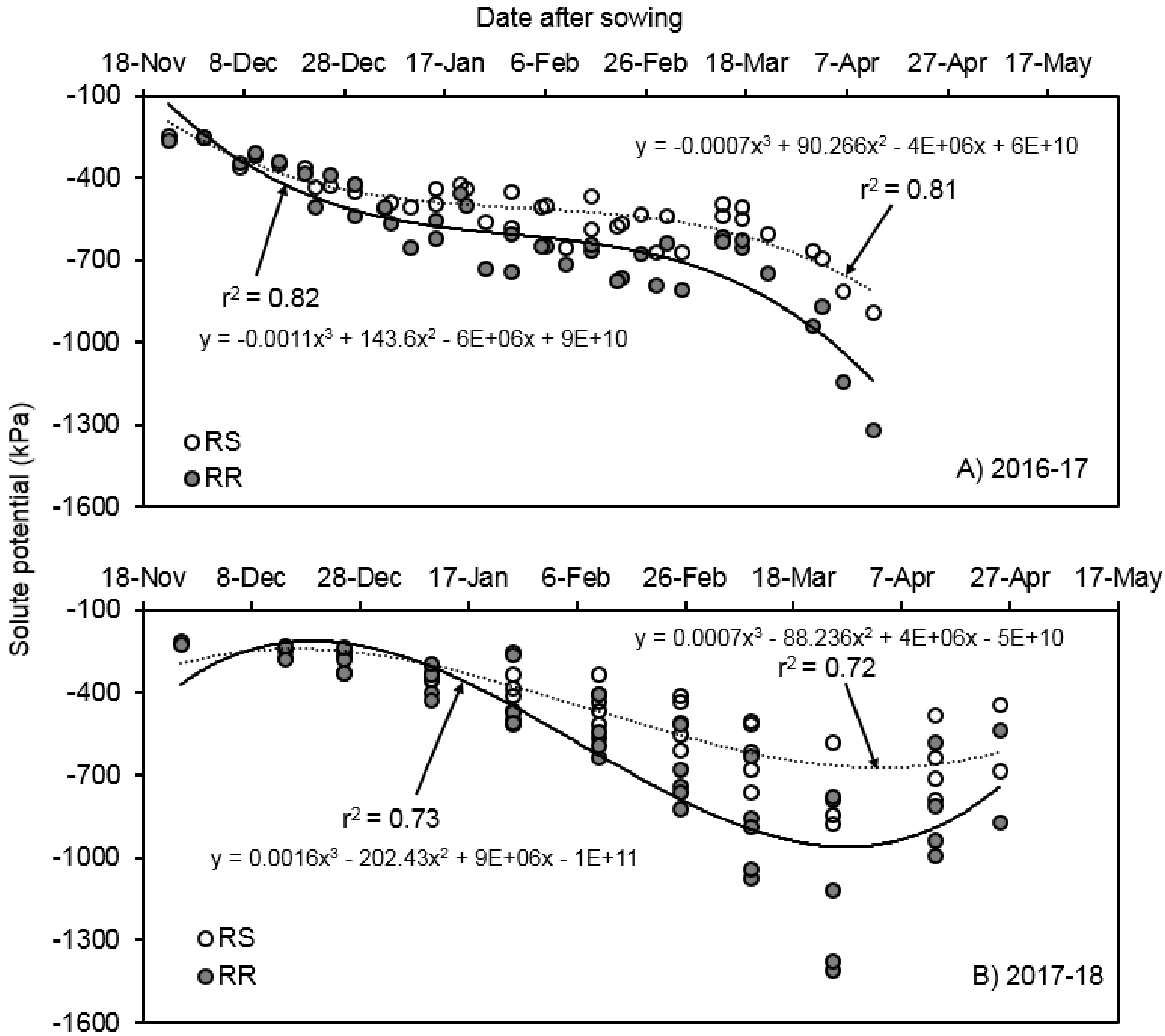

Fig. 5.5. Mulch effects on the solute potential of soil solutions in five dates of sowing in (A) 2016-17 and (B) 2017-18 under the RS (blank circle) and RR (filled circle) treatments.

5.5 Discussion

This discussion focuses firstly on the effect of early sowing time on sunflower yield in the coastal Ganges delta environment. We then discuss the effects of sowing times on average seasonal temperature, SWC, $EC_{1:5}$ and SP to which crop was exposed, and the degree to which each of these drivers influenced sunflower growth and yield.

5.5.1 *Effect of early sowing time on sunflower yield*

Time of sowing had a marked effect on sunflower yield, but the responses differed between years (summarised in Fig. 5.6). In the first year, sunflower yields were highest (~ 4 t ha^{-1}) with the earliest sowing (23 and 30 November) and were lowest (~ 2.9 t ha^{-1}) with the last sowing on 30 December. By contrast, early in the second year, waterlogging stress of the plants sown on 25 November decreased sunflower yields by 30 % compared with the second sowing (14 December) that occurred after the plots had been drained. Hence, in the one trial shown here, when there was no heavy post-monsoon rainfall, early sowing enhances sunflower yield, but it is risky, especially in the absence of rapid and adequate drainage. According to Yu et al. (2019), in this coastal zone in Khulna, there is a chance of heavy rainfall > 40 mm day^{-1} from December to February, which can cause waterlogging. Surface drainage (open ditches: 15-20 cm deep and 20-25 cm wide) installed the day after the heavy rainfall event on 10 December was found to be useful as a means of averting the failure of early sown crops from waterlogging. A more comprehensive assessment of the frequency of yield-damaging waterlogging events could be obtained from well-calibrated crop simulation models such as APSIM (Gaydon et al., 2017). Indeed, the optimum time for early sowing in this environment could be determined from APSIM modelling to determine when the risk of waterlogging becomes acceptably low.

Even though sunflower yield was higher in the first year compared to the second year, the optimum sowing window for sunflower, from the perspective of potential yield (3-4 t ha^{-1}) in both years was between 20 November and 15 December (Fig. 5.6). In the salt-affected Ganges delta, the differences in the final yield of sunflower may be attributed to the establishment time and method, average seasonal air temperature, in-season rainfall and conditions faced later in the growing season such as low soil water rising soil salinity, and increasing crop water demand. The early sowing may be affected by waterlogging, whereas the later sowing can be negatively impacted by higher temperature, salinity and soil water depletion (Fig. 5.6). Rashid et al. (2014) showed that sunflower dibbling on 14 January resulted in a higher yield (3 t ha^{-1}) than sowing on 22 Feb (2.6 t ha^{-1}) in this coastal area, but as illustrated in our study both these times of sowing were later than optimum. Other researchers have reported that delayed planting after normal sowing time caused the reduction of sunflower yield in both temperate and subtropical regions (Barros et al., 2004; De La Vega and Hall, 2002; Unger, 1980), which was mainly attributed to the warmer temperature at reproduction and grain filling stages. Studies showed that the temperature for optimum growth and development of sunflower was between 26-29 ^{0}C (Awais et al., 2017; Rondanini et al., 2006). In the present study, early sown crops (between 20 November and 15 December) in both years were exposed to temperature < 30 ^{0}C during flowering, but later sowing after 15 December exposed the crop to > 30 ^{0}C during flowering and grain filling stages. Thus, the effect of high temperature in later sowings shortened the reproductive period and induced physiological maturity 5-9 days earlier in the first year and 15-20 days earlier in the second year, respectively, which may be related to lower yield under late sowing. Some studies also reported that in subtropical conditions, late-sown crops encounter heat stress during the reproductive stage, which decreases seed numbers, grain unit weight and grain quality (Chimenti et al., 2001b; Rondanini et al., 2003). Fig. 5.2 illustrates the significant negative relationship between temperature and grain yield, where yield decreased with increasing temperature. Considering the range of factors that influenced yield, the high temperature was most influential later in the growing season (Fig. 5.3D and 5.4D).

5.5.2 *Effects of sowing method and time on SWC*

Early sowing of sunflower was achieved by dibbling even though SWC exceeded field capacity (40-50 %, w/w). However, the higher SWC was apparently not limiting for emergence as there was no inhibition of emergence percentage (emergence: 95- 98 %) relative to the second and third sowing with lower SWC. Emergence after dibbling was drastically reduced in the fourth sowing because of decreased SWC (33 %), but emergence was satisfactory in the last sowing even though SWC was 31 %, as the land was cultivated with five passes in the second season. The reason for lower emergence in fourth no-till dibbled sowing may be the detrimental effects of surface drying, soil hardening, surface crusting and high soil strength in the soil. The hardened soils may have reduced the availability of soil water surrounding the seed zone (Mitchell et al., 2013). In the first season, SWC during the early planting treatments (between 23 November and 15 December) was apparently higher than the wilting point (26 %, w/w) from sowing to harvest, but SWC in the last two sowings (20 and 30 December) dropped to 3 % and 5 % below wilting point in the grain filling stage. In 2017-18, SWC was much lower than the wilting point in the later sowings (between 25 December and 25 January) from maximum vegetative to maturity (4-10 % < wilting point). The higher soil water availability during the early sowing treatments may contribute to better plant growth and development and higher yield compared to the late sowings. Although sunflower is considered to be a moderately drought-tolerant crop, water stress in early flowering to grain filling can cause up to 50 % yield loss (Aboudrare et al., 2006; Alahdadi et al., 2011; Hussain et al., 2018). However, in this study, in the 3-factor (temperature, SWC and EC) multivariate regression model, SWC did not have a significant impact on the yield variation (Fig. 5.3B and 5.4B). This may be attributed to the availability of soil water deeper in the profile where sunflower roots are active from flowering onwards (Paul et al., 2020b). In addition, soil water potential and soil salinity may have a greater influence on sunflower yield than SWC (Paul et al., 2020a)

5.5.3 Effects of sowing time on $EC_{1:5}$ SP

In this present study, the time of sowing and seasonal rainfall altered the average and maximum soil $EC_{1:5}$ in the soil profile within and between the two seasons. During establishment time, the $EC_{1:5}$ ranged from 0.5 to 0.68 dS m^{-1} and from 0.4 to 0.48 dS m^{-1} in the first and second year, respectively, but these values had no obvious effects on emergence and germination. Some studies showed that sunflower germination was less sensitive to salinity than the early seedling stage (Delgado and Sánchez-Raya, 2007; van Hoorn, 1991). Increased salt concentration at the early stage of sunflower can cause lower leaf area and dry matter and reduction of leaf water potential and stomatal conductance (Katerji et al., 1994; Zeng et al., 2015). At flowering and grain filling stages, high salt concentration can reduce seed numbers, seed size, and yield (Caterina et al., 2007; Katerji et al., 1996). Across the season, early sowing before 15 December had lower $EC_{1:5}$ (0.4-0.68 dS m) than later planting until 10 January (0.6-0.78 dS m^{-1}), which suggests that there was higher salt stress for sunflower growth after the late sowing. For early sowing, lower average salinity from seedling stage to grain filling may have maintained better plant water status and increased grain yield. By contrast, higher soil salinity from the vegetative period to maturity after late sowing was related to the decreasing number of seeds per head and seed weight, and thus to reduced grain yield.

In previous studies with sunflower in this environment, SP of the soil solutions was an effective integrator of water and salt stress on plant growth and development (Paul et al., 2020a, 2020b). When SWC decreased and soil salinity increased, SP decreased (became more negative), which inhibits water and nutrient uptake by plants, resulting in poor plant growth and development (Bartels and Sunkar, 2005; Munns and Tester, 2008). In the present study, there was a substantial variation of SP among the different sowing date treatments. In both seasons, early sowing had comparatively higher SP (varied from -240 to - 620 kPa) at surface soil 0-7 cm depth from seedling to flowering, which was far above wilting point (-1500 kPa) suggesting that water uptake would not be limiting. By contrast, in the later sowing treatments, plants experienced lower average SP mainly from flowering to maturity (varied from - 980 to -1145 kPa), which was close to wilting point. The higher SP for early sowing can be attributed to adequate soil water and limited salt accumulation in soils and plants. By contrast, the low SP value that approached wilting point at flowering and grain filling stages, especially in the later sowing treatments, may have led to plant water stress and excess Na accumulation, which could explain the reduced number of seeds per head, small grain size and lower yield. In the dryland saline area, one of the strategies to avoid salinity stress (low solute potential) and to maximize yield is the earliness of crop flowering (Worland et al., 1994). For example, Setter et al. (2016) reported that in rainfed saline condition, the average SP was less than -1500 kPa ($EC_{1:5}$ = ~0.55 dS m^{-1} and soil water = 9.5 %, w/w; calculated from their data) during grain filling stage in most plots which severely depressed barley and wheat yield. However, at these salinities, the earlier flowering barley crops had 35 % higher yield than the later flowering wheat crops.

In previous studies with sunflower in the Ganges delta, SP better-explained effects of tillage and mulch on grain yield (Paul et al., 2020a, 2020b); however, in the present study, EC explained the highest yield variation (r^2 = 0.91 and 0.72) in both years in a multivariate regression model that also included temperature and SWC (Fig. 5.3A and 5.4A). Moreover, in a 2-factor model using temperature and SP, temperature was the main driver of yield and SP had minimal effect. The apparent lack of influence of SP on yield relative to other factors across the multiple times of sowing may be because both SWC and $EC_{1:5}$ had contrasting impacts on yield. Higher SWC may have a positive effect on yield under drying conditions later in the growing season, while more water can negatively affect yield due to waterlogging in the early part of the season. Both of these effects were evident in the two years of the experiments. Therefore, combining SWC and $EC_{1:5}$ into a single variable of SP did not improve the predictability of the model which involved multiple times of sowing. Based on the best fit of the line in the 3-factor model (high r^2 values), $EC_{1:5}$ was the strongest driver of grain yield followed by temperature. While the two years of experimentation with sunflower were quite different, longer-term assessment of the optimum sowing window for sunflower and of the major drivers of yield is needed. Calibrated crop simulation models such as APSIM would provide a clearer insight into the long-term variability of sunflower yield in the Ganges delta.

5.5.4 *Mulch effect on soil water and salinity and plant growth*

Mulching with rice straw significantly improved the availability of soil water and reduced the soil salinity, which in turn enhanced SP of soil solutions compared to the RR treatment. These benefits which strengthen the findings of Paul et al., (2020b) were more pronounced in the later part of the growing season. In addition, due to the higher SWC under the mulch, lower soil strength and cracks may favour root growth and crop development compared to the drier surface soil of the rice residue treatment (Abd El-Mageed et al., 2016; Sharma and Minhas, 2005; Zhang et al., 2018). Clay soils puddled for rice cultivation are prone to becoming dense and hard following the formation of large cracks during the dry season which is associated with reduced infiltration within blocks of soil and higher mechanical resistance that restricts the emergence, root growth, and crop growth and development (Bell and Seng, 2003; Kirchhof et al., 2000; Mitchell et al., 2013). Further investigation is needed on whether the positive effects of mulch on sunflower yield can be explained by the alleviation of soil physical limitations to root growth (see chapter 6).

One reason for the absence of mulch effect on yield in the first year may be related to the completion of sowing before the end of December so that anthesis and reproductive stages avoided water deficit and salt stress in both mulching treatments. Another reason may be associated with 109 mm seasonal rainfall in the first week of March, which provided adequate water supply in both mulching treatments. Rice straw mulch on the soil surface was more useful, especially for the later sowings (established on 8 January) for increasing yield, seeds per head and seed weight (Paul et al., 2020b).

5.6 Conclusions

On a wet, clay-textured soil, early sown sunflower established by dibbling had higher grain yield relative to later sowing. Sowing before 15 December was most productive because the higher yield was associated with higher SWC, lower $EC_{1:5}$ and greater SP. The decreasing yield with the late sowing was associated with the lower number of seeds per head and grain weight, and shorter growth duration due to warmer temperature later in the growing season and decreased SP of the soil solutions. Rice straw mulch was effective for increasing yield, especially in the late sowing, by reducing water loss by evaporation and salt accumulation in the root zone and hence by increasing SP. Yield prediction across all times of sowing by a 3-factor (temperature, SWC and $EC_{1:5}$) multiple regression model suggested that $EC_{1:5}$ was the main driver of yield, followed by average seasonal temperature. Considering the two seasons results, early sowing before 15 December had the highest yield potential for sunflower by enhancing utilization of residual, non-saline soil water early in the season, by ensuring that flowering is completed before high temperatures inhibit seed set, and by avoidance of high soil salinity and low SP in the upper root zone in the later part of the growing season (Fig. 5.6). However, the risk of heavy rainfall events is higher in early sown crops, which can reduce yield if effective drainage is absent.

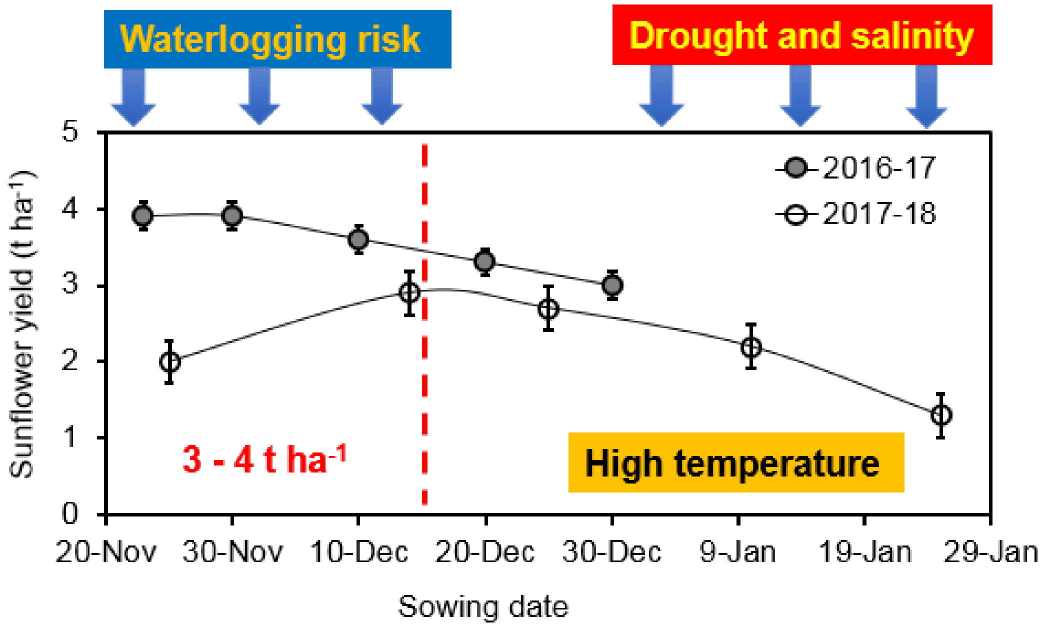

Fig. 5.6. The mean grain yield in five dates of sowing over two seasons (2016-17 and 2017-18), also showing the major constraints to grain yield with time. Error bars indicate standard error of the mean. The vertical dotted line indicates sowing before 15 December has an average yield 3 – 4 t ha^{-1}.

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5.7 References

Abd El-Mageed, T. A., Semida, W. M., and Abd El-Wahed, M. H. (2016). Effect of mulching on plant water status, soil salinity and yield of squash under summer-fall deficit irrigation in salt affected soil. *Agric. Water Manage.* **173**, 1-12.

Aboudrare, A., Debaeke, P., Bouaziz, A., and Chekli, H. (2006). Effects of soil tillage and fallow management on soil water storage and sunflower production in a semi-arid Mediterranean climate. *Agric. Water Manage.* **83**, 183-196.

Alahdadi, I., Oraki, H., and Khajani, F. P. (2011). Effect of water stress on yield and yield components of sunflower hybrids. *Afr. J. Biotechnol.* **10**, 6504-6509.

Awais, M., Wajid, A., Bashir, M. U., Habib-ur-Rahman, M., Raza, M. A. S., Ahmad, A., Saleem, M. F., Hammad, H. M., Mubeen, M., Saeed, U., Arshad, M. N., Fahad, S., and Nasim, W. (2017). Nitrogen and plant population change radiation capture and utilization capacity of sunflower in semi-arid environment. *Environ. Sci. Pollut. Res.* **24**, 17511-17525.

Barros, J. F. C., de Carvalho, M., and Basch, G. (2004). Response of sunflower (Helianthus annuus L.) to sowing date and plant density under Mediterranean conditions. *Eur. J. Agron.* **21**, 347-356.

Bartels, D., and Sunkar, R. (2005). Drought and Salt Tolerance in Plants. *Crit. Rev. Plant Sci.* **24**, 23-58.

Bell, R., and Seng, V. (2003). Rainfed lowland rice-growing soils of Cambodia, Laos, and North-east Thailand. In: CARDI International Conference on Research on Water in Agricultural Production in Asia for the 21st Century, 25 – 28 November, Phnom Penh, Cambodia.

Caterina, D., Giuliani, Rotunno, Caro, D., and Flagella (2007). Influence of salt stress on seed yield and oil quality of two sunflower hybrids. *Ann. Appl. Biol.* **151**, 145-154.

Chimenti, C. A., Hall, A. J., and Sol López, M. (2001a). Embryo-growth rate and duration in sunflower as affected by temperature. *Field Crops Res.* **69**, 81-88.

Chimenti, C. A., Hall, A. J., and Sol López, M. (2001b). Embryo-growth rate and duration in sunflower as affected by temperature. *Field Crops Res.* **69**, 81-88.

Cresswell, H., and Hamilton, G. (2002). Bulk density and pore space relations. In 'Soil physical measurement and interpretation for land evaluation.' (Eds N McKenzie, K Coughlan and H Cresswell) pp. 35-58. (CSIRO publishing: Victoria, Australia).

Cook, S. M. F., Gupta, S. C., Woodhead, T., and Larson, W. E. (1995). Soil physical constraints to establishment of mungbeans (Vigna radiata L. Wilczek) in paddy rice (Oryza sativa L.) soils. *Soil Tillage Res.* **33**, 47-64.

De La Vega, A. J., and Hall, A. J. (2002). Effects of planting date, genotype, and their interactions on sunflower yield: I. Determinants of oil-corrected grain yield. *Crop Sci.* **42**, 1191-1201.

Delgado, I. C., and Sánchez-Raya, A. J. (2007). Effects of Sodium Chloride and Mineral Nutrients on Initial Stages of Development of Sunflower Life. *Commun. Soil. Sci. Plant. Anal.* **38**, 2013-2027.

Dp, H., and Ja, T. (1994). Effect of sowing time on growth, yield, and oil characteristics of irrigated sunflower in southern New South Wales. *Aust. J. Exp. Agr.* **34**, 255.

Francois, L. E. (1996). Salinity effects on four sunflower hybrids. *Agron. J.* **88**, 215-219.

Gay, C., Corbineau, F., and Côme, D. (1991). Effects of temperature and oxygen on seed germination and seedling growth in sunflower (Helianthus annuus L.). *Environ. Exp. Bot.* **31**, 193-200.

Gaydon, D., Wang, E., Poulton, P., Ahmad, B., Ahmed, F., Akhter, S., Ali, I., Amarasingha, R., Chaki, A., and Chen, C. (2017). Evaluation of the APSIM model in cropping systems of Asia. *Field Crops Res.* **204**, 52-75.

Hussain, M., Farooq, M., Farooq, S., Hasan, W., Ul-Allah, S., Tanveer, M., and Nawaz, A. (2018). Drought stress in sunflower: Physiological effects and its management through breeding and agronomic alternatives. *Agric. Water Manage.* **201**, 152-166.

Katerji, N., Van Hoorn, J., Hamdy, A., Karam, F., and Mastrorilli, M. (1994). Effect of salinity on emergence and on water stress and early seedling growth of sunflower and maize. *Agric. Water Manage.* **26**, 81-91.

Katerji, N., van Hoorn, J. W., Hamdy, A., Karam, F., and Mastrorilli, M. (1996). Effect of salinity on water stress, growth, and yield of maize and sunflower. *Agric. Water Manage.* **30**, 237-249.

Katerji, N., van Hoorn, J. W., Hamdy, A., and Mastrorilli, M. (2003). Salinity effect on crop development and yield, analysis of salt tolerance according to several classification methods. *Agric. Water Manage.* **62**, 37-66.

Kirchhof, G., Priyono, S., Utomo, W. H., Adisarwanto, T., Dacanay, E. V., and So, H. B. (2000). The effect of soil puddling on the soil physical properties and the growth of rice and post-rice crops. *Soil Tillage Res.* **56**, 37-50.

Kokubun, M. (2013). Genetic and cultural improvement of soybean for waterlogged conditions in Asia. *Field Crops Res.* **152**, 3-7.

Mitchell, J., Cheth, K., Seng, V., Lor, B., Ouk, M., and Fukai, S. (2013). Wet cultivation in lowland rice causing excess water problems for the subsequent non-rice crops in the Mekong region. *Field Crops Res.* **152**, 57-64.

Mondal *et al*. (2011). Krishi projukti hatboi (Handbook on agro-technology), 5th edition. *Bangladesh Agricultural Research Institute, Gazipur-1701, Bangladesh.*

Mondal, M. K., Paul, P., Humphreys, E., Tuong, T., Ritu, S., Rashid, M., Humphreys, E., Buisson, M., Pukinskis, I., and Phillips, M. (2015a). Opportunities for cropping system intensification in the coastal zone of Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo. SriLanka: CGIAR Challenge Program on Water and Food (CPWF). pp. 449–476.

Mondal, M. K., Saha, N., Ritu, S., Paul, P., Sharifullah, A., Humphreys, E., Tuong, T., and Rashid, M. (2015b). Optimum sowing window for boro cultivation in the coastal zone of Bangladesh.In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF), pp. 342-360..

Munns, R., and Tester, M. (2008). Mechanisms of salinity tolerance. *Annu. Rev. Plant Biol.* **59**, 651-681.

Paul, P., Rashid, M., Alam, M., Ghani, M., and Hossain, M. (2016). Selection of profitable rice based cropping system under prevailing water environment in Satkhira district of Bangladesh. *Acad. J. Agric. Res.* **4**, 581-588.

Paul, P. L. C., Bell, R. W., Barrett-Lennard, E. G., and Kabir, E. (2020a). Variation in the yield of sunflower (Helianthus annuus L.) due to differing tillage systems is associated with variation in solute potential of the soil solution in a salt-affected coastal region of the Ganges Delta. *Soil Tillage Res.* **197**, 104489.

Paul, P. L. C., Bell, R. W., Barrett-Lennard, E. G., and Kabir, E. (2020b). Straw mulch and irrigation affect solute potential and sunflower yield in a heavy textured soil in the Ganges Delta *Agric. Water. Manage.* **239**, 106211.

Rahman, M., Amin, M., Mondal, M., and Humphreys, E. (2015). Rabi crop establishment methods for increasing land productivity in the coastal zone of Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M.

(Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF). p-504.

Rahmianna, A. A., Adisarwanto, T., Kirchhof, G., and So, H. B. (2000). Crop establishment of legumes in rainfed lowland rice-based cropping systems. *Soil Tillage Res.* **56**, 67-82.

Rashid, M. H., Nasrin, S., and Mahalder, D. (2014). Zero tilled dibbled sunflower enables planting earlier and harvests more in the coastal saline area of Bangladesh. *Int. J. Environ. Sci. Technol* **5**, 260.

Rauf, S. (2008). Breeding sunflower (Helianthus annuus L.) for drought tolerance. *Commun. Biometry Crop. Sci* **3**, 29-44.

Rondanini, D., Mantese, A., Savin, R., and Hall, A. J. (2006). Responses of sunflower yield and grain quality to alternating day/night high temperature regimes during grain filling: Effects of timing, duration and intensity of exposure to stress. *Field Crops Res.* **96**, 48-62.

Rondanini, D., Savin, R., and Hall, A. J. (2003). Dynamics of fruit growth and oil quality of sunflower (Helianthus annuus L.) exposed to brief intervals of high temperature during grain filling. *Field Crops Res.* **83**, 79-90.

Sadras, V., Hall, A., Trapani, N., and Vilella, F. (1989). Dynamics of rooting and root-length: leaf-area relationships as affected by plant population in sunflower crops. *Field Crops Res.* **22**, 45-57.

Seiler, G. J. (1994). Primary and lateral root elongation of sunflower seedlings. *Environ. Exp. Bot.* **34**, 409-418.

Setter, T. L., Waters, I., Stefanova, K., Munns, R., and Barrett-Lennard, E. G. (2016). Salt tolerance, date of flowering and rain affect the productivity of wheat and barley on rainfed saline land. *Field Crops Res.* **194**, 31-42.

Sharma, B. R., and Minhas, P. S. (2005). Strategies for managing saline/alkali waters for sustainable agricultural production in South Asia. *Agric. Water Manage.* **78**, 136-151.

So, H. B., and Ringrose-Voase, A. J. (2000). Management of clay soils for rainfed lowland rice-based cropping systems: an overview. *Soil Tillage Res.* **56**, 3-14.

STAR (2014). Biometrics and Breeding Informatics, PBGB Division. *International Rice Research Institute, Los Baños, Laguna. Available at. http://bbi.irri.org/.*

Unger, P. W. (1980). Planting Date Effects on Growth, Yield, and Oil of Irrigated Sunflower1. *Agronomy Journal* **72**, 914-916.

van Hoorn, J. W. (1991). Development of soil salinity during germination and early seedling growth and its effect on several crops. *Agric. Water Manage.* **20**, 17-28.

Wallender, W. W. and Tanji, K. K. (2011). Agricultural salinity assessment and management. American Society of Civil Engineers.

Worland, A., Appendino, M., and Sayers, E. (1994). The distribution, in European winter wheats, of genes that influence ecoclimatic adaptability whilst determining photoperiodic insensitivity and plant height. *Euphytica* **80**, 219-228.

Yu, Y., Mainuddin, M., Sarangi, S., Maniruzzaman, M., and Mandal, U. K. (2019). Rainfall and temperature characteristics in the coastal zones of Bangaldesh and West Begal, India. *J. Indian Soc Coastal Agric. Res.* **32**, 12-23.

Zeng, W., Xu, C., Huang, J., Wu, J., and Ma, T. (2015). Emergence Rate, Yield, and Nitrogen-Use Efficiency of Sunflowers (Helianthus annuus) Vary with Soil Salinity and Amount of Nitrogen Applied. *Commun. in Soil Sci. Plant Anal.* **46**, 1006-1023.

Zhang, M., Dong, B., Qiao, Y., Yang, H., Wang, Y., and Liu, M. (2018). Effects of sub-soil plastic film mulch on soil water and salt content and water utilization by winter wheat under different soil salinities. *Field Crops Res.* **225**, 130-140.

5.8 Supplementary Materials

Section S1. Initial soil water content and crop phenology

In both years, SWC was ~ 50 % (w/w) at the surface (0-7 cm) at the early planting (first and second sowing in 2016-17 and first sowing in 2017-18). For later sowings, the SWC was 43-47 % in 2016-17 and 31-43 % in 2017-18, respectively (Fig. 5S1). These variations in SWC affected sunflower emergence and density. In 2016-17, the initial higher SWC slightly delayed the emergence of the early planting (6-10 days) compared to the later planting (6-7 days) (Table 5S1A). In 2017-18, the decreased SWC for later sowings (10 and 25 January) delayed the emergence (9-15 days) relative to the early sowings (7-12 days) (Table 5S1B). Plant populations per square meter differed between emergence and harvest. In the first year, the last plantings (30 December) had 9 % lower plant densities at harvest than at emergence (Fig. S2a). In 2017-18, sowing on 25 November and 10 January had 22- 26 % lower plant populations during harvest than emergence because of waterlogging stress at the first sowing and surface soil dryness at the fourth sowing (Fig. 5S2b). In the first year, flower bud initiation started early for the first and second sowings (54-56 days) compared to the last three sowing (60-64 days), but for the second year, bud initiation started late for first, second and third sowing (61-65 days) compared to the last two sowing (57-60 days). In the second season, flowering was also delayed for the first, second and third sowing (72-76 days) relative to the last two sowing dates (65-72 days). In the first season, the longest crop growth duration was 113 days in the first sowing decreasing by 10 days for the last sowing (30 December). In the second year, the longest growth duration was 118 days for the first sowing (25 November) declining by 21 days for the last sowing (25 January). At all times of sowing, physiological maturity was delayed by 3-4 days for the RR treatment compared with the RS treatment.

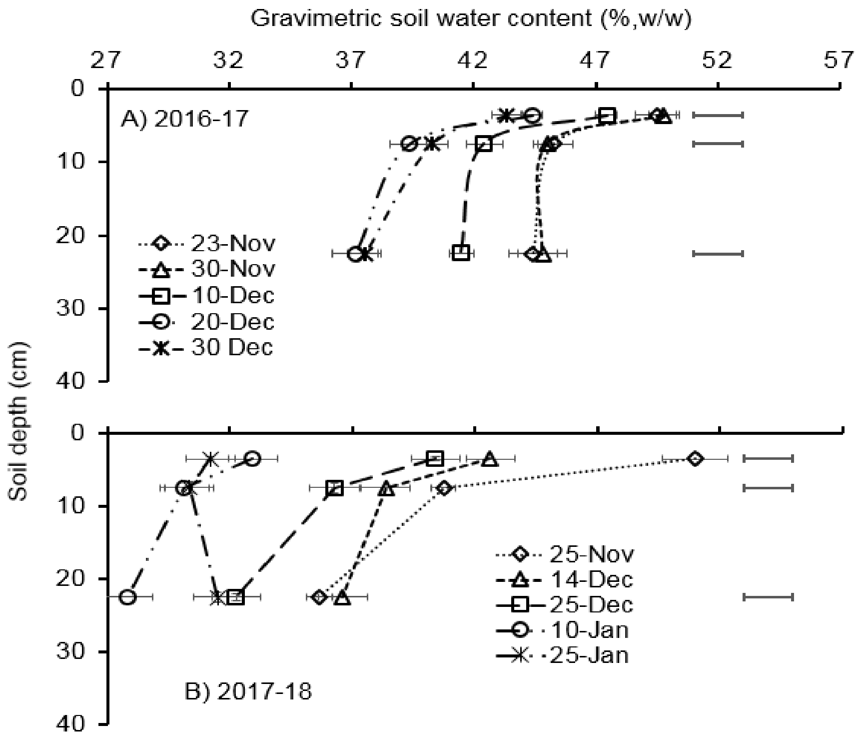

Fig. 5S1. The mean gravimetric soil water content (%, w/w) of the soil profiles during sunflower establishment at different sowing dates in (A) 2016-17, and (B) 2017-18. Error bars indicate the standard error of the means. The horizontal bars indicate the least significant difference at $P < 0.05$ in five times of sowing at three depths (0-7, 7-15 and 15-30 cm) of soils.

Table 5S1. Phenology of sunflower development at Pankhali, Dacope, Khulna Bangladesh in: (A) the 2016-17 and (B) the 2017-18 crop season.

Table 5S1A.

Sowing time	Mulching	Emergence (DAS)*	Bud initiation (DAS)*	First flowering (DAS)*	Physiological maturity (DAS)*
23 November	RS	6-10	55	75	113
	RR	6-10	56	75	113
30 November	RS	6-9	55	73	111
	RR	6-9	55	73	109
10 December	RS	6-8	61	76	112
	RR	6-8	62	77	109

20 December	RS	6-7	62	74	110
	RR	6-7	63	75	107
30 December	RS	6-7	59	72	105
	RR	6-7	60	73	103
Sowing (P-value)			0.001	0.001	0.001
LSD			0.87	1.09	0.64
Mulch (P-value)			0.05	NS	0.001
LSD			0.68	-	0.66
Sowing x Mulch			NS	NS	NS

Table 5S1B.

Sowing time	Mulching	Emergence (DAS)*	Bud initiation (DAS)*	First flowering (DAS)*	Physiological maturity (DAS)*
25 November	RS	7-10	63	75	114
	RR	7-10	63	75	118
14 December	RS	7-11	65	76	114
	RR	7-11	64	74	116
25 December	RS	7-12	61	73	106
	RR	7-12	61	72	109
10 January	RS	9-14	59	71	102
	RR	9-14	59	72	105
25 January	RS	9-15	56	65	94
	RR	9-15	57	67	97
Sowing (P-value)			0.001	0.001	0.001
LSD			0.99	2	2
Mulch (P-value)			NS	NS	0.001
LSD			-	-	0.75
Sowing x Mulch			NS	NS	NS

*DAS = Days after sowing; RS = Rice straw, RR = Rice residue; NS = Non-significant

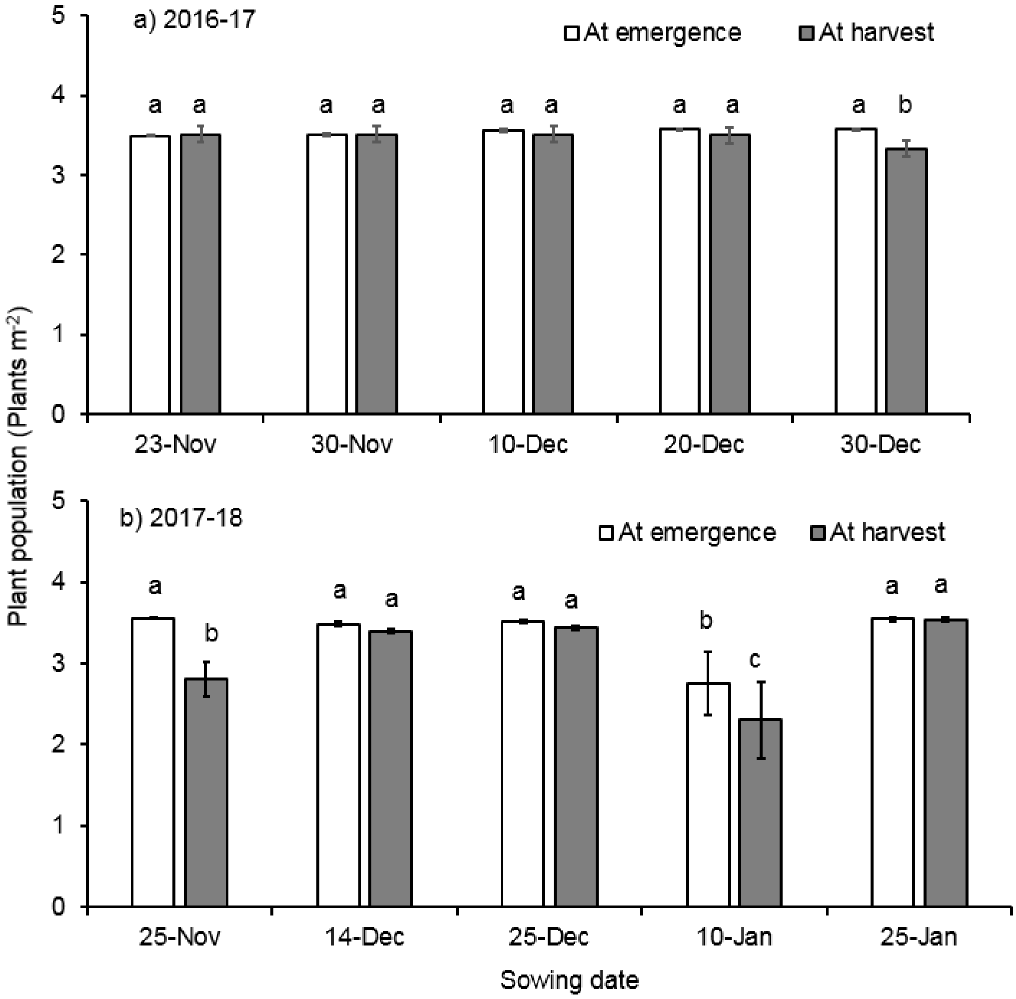

Fig. 5S2. Mean plant density per square metre at emergence and harvest in five times of sowing (a) 2016-17 and (b) 2017-18. Vertical bars indicate the standard error of the mean. The same letters are not significantly different at $P < 0.05$.

Section S2. Variation of soil water content, $EC_{1:5}$, and solute potential throughout each season

Soil water content (SWC) was higher during establishment and decreased with the progress of the season in all dates of sowing. The SWC was significantly affected by sowing dates, soil depth and time (DAS) in both years (Fig. 5S3). In 2016-17 during sowing, SWC at 0-7 cm depth was above field capacity for all dates of sowing, but in 2017-18, SWC was only above field capacity for first three dates of sowing and was below field capacity for last two sowing dates. In the first year, the SWC at 0-7 cm did not decline below the wilting point for the first three dates of sowing but was lower than the wilting point for the last two dates of sowing (Fig. 5S3A). In 2017-18, surface drainage after rainfall (59 mm) rapidly decreased the SWC. The average SWC of the first and second sowing declined from around 43-50 % at the establishment to 17-20 % at maturity at 0-7 cm (Fig. 5S3D). The SWC declined substantially after sowing on 25 December (third) and 10 January (fourth) which varied from 34-40 % at the establishment to 16 % at early maturity, but sowing on 25 January (fifth) maintained the greater SWC compared to third and fourth sowing mainly at the flowering and maturity as the land was rotary cultivated before dibbling and rainfall occurred later in the growing season. Throughout the season, the surface soil at 0-7 cm had higher SWC than the bottom depth at 7-15 and 15-30 cm (Fig. 5S3D, E and F).

The soil salinity ($EC_{1:5}$) increased with time for all dates of sowing at all soil depths up to 30 cm. In both years, $EC_{1:5}$ was significantly influenced by sowing dates, soil depth and time (DAS) (Fig. 5S4). In 2016-17, the crops sown on 23 and 30 November had lower $EC_{1:5}$ values than those sown on 20 and 30 December at all depths to 30 cm. The range of $EC_{1:5}$ at 0-7 cm (establishment to harvest) was affected by the time of sowing: for the first two sowings, this range was 0.5 to ~ 0.75 dS m^{-1}, while at the last time of sowing, this was 0.8 to 1.0 dS m^{-1} (Fig. 5S4A).

In 2017-18, $EC_{1:5}$ was slightly lower at all depths to 30 cm than 2016-17 season, however, an increasing trend of $EC_{1:5}$ was observed between sowing and harvest. Early sowing on 25 November and 14 December had mostly lower $EC_{1:5}$ than sowing on late 25 and 10 December. The range of $EC_{1:5}$ for first two sowing was about 0.5 dS m^{-1} at the establishment to 0.58 and 0.68 at maturity (March and early April), while $EC_{1:5}$ varied from 0.45 to 0.76 dS m^{-1} from the establishment to maturity (Mid-April to late April). Although the last sowing was on 25 January, $EC_{1:5}$ remained lower between establishment and harvest as soil was rotary tilled and there was rain at the end of the season. At any time, $EC_{1:5}$ was the highest at surface soil 0-7 cm than 7-15 an 15-30 cm depths (Fig. 5S4D-F).

The solute potential (SP) was significantly affected by sowing dates, soil depth and time (DAS) in both seasons (Fig. 5S5). In the first year, the SP of first two sowings was -248 kPa to -664 and for 728 kPa between establishment and harvest. The SP was more negative in third, fourth and fifth sowing which varied from -303 kPa to -800 kPa, -371 kPa to -977 kPa and -419 kPa to -1103 kPa at depth 0-7 cm, respectively (Fig. 5S5A-C). Throughout the season, the SP was far lower at 0-7 cm than depth 7-15 and 15-30 cm. A similar trend of the SP was observed in 2017-18 season, however, the SP was less negative than season 2016-17. The first sowing on 25 November and last sowing on 25 January (tilled soil) exhibited relatively higher SP than sowing on 14 December, 25 December and 10 January throughout the entire period. The SP in the first and last sowing was between -220 kPa and -685 kPa, and -256 kPa and -490 kPa from establishment to harvest. The SP was more negative on sowing 25 December and 10 January which declined from -240 kPa at establishment to -1142 kPa at flowering, and -310 kPa at establishment to -1108 kPa at maturity at depth 0-7 cm (Fig. 5S5D).

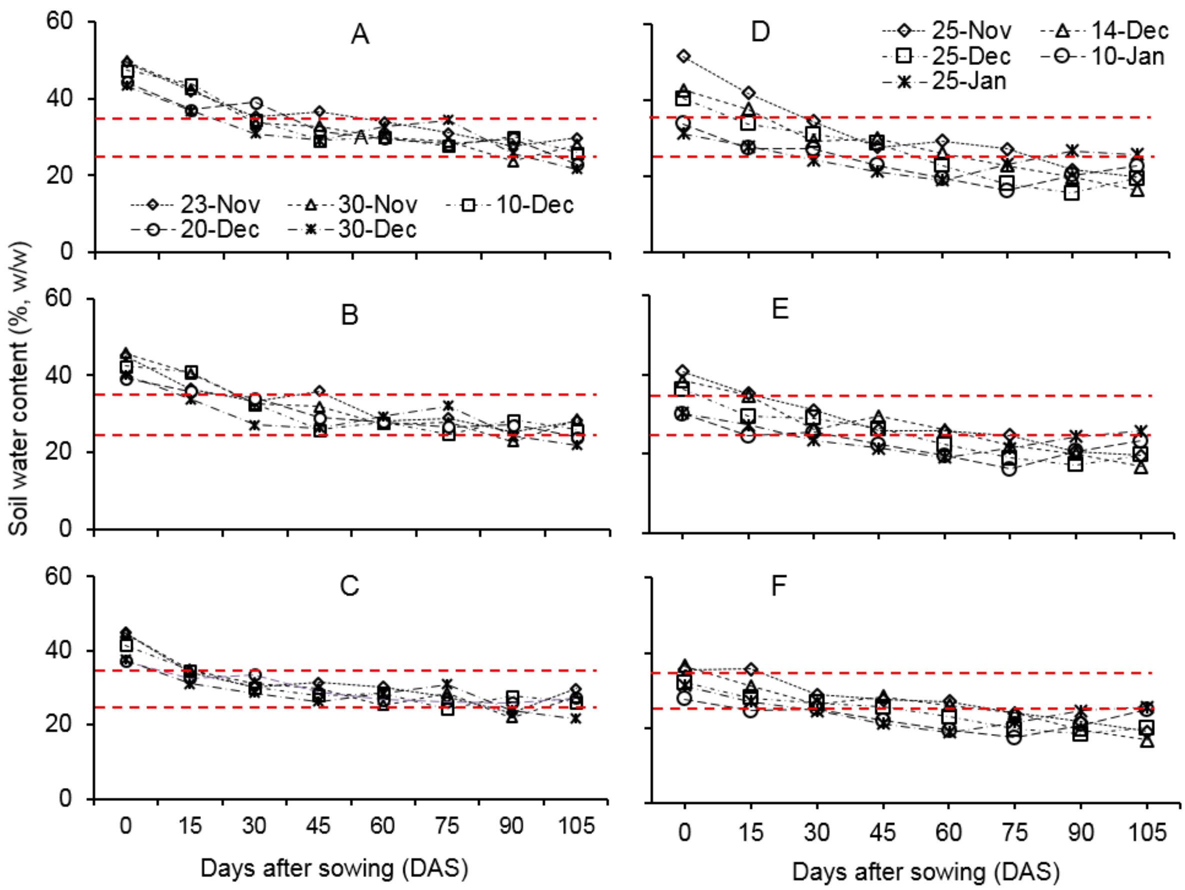

Fig. 5S3. Main effects of sowing time on SWC at: (A) 0-7 cm, (B) 7-15 cm and (C) 15-30 cm in the 2016-17 season and (D) 0-7 cm, (E) 7-15 cm and (F) 15-30 cm in the 2017-18 season. LSD (least significant difference) for different factor combinations are 2.85*** (Sowing date = S), 4*** (Soil depth = D), 2.5*** (Days after sowing = DAS), and 4* (S x D x DAS) in 2016-17. LSD for different factor combinations are 2.95*** (Sowing date = S), 1.69*** (Soil depth = D), 2.6*** (Days after sowing = DAS), and 2.95*** (S x D x DAS) in 2017-18. Values are the means of three replicates. *** indicate statistical significance at $P < 0.001$. Upper and lower dotted horizontal lines indicate gravimetric SWC at field capacity and wilting point.

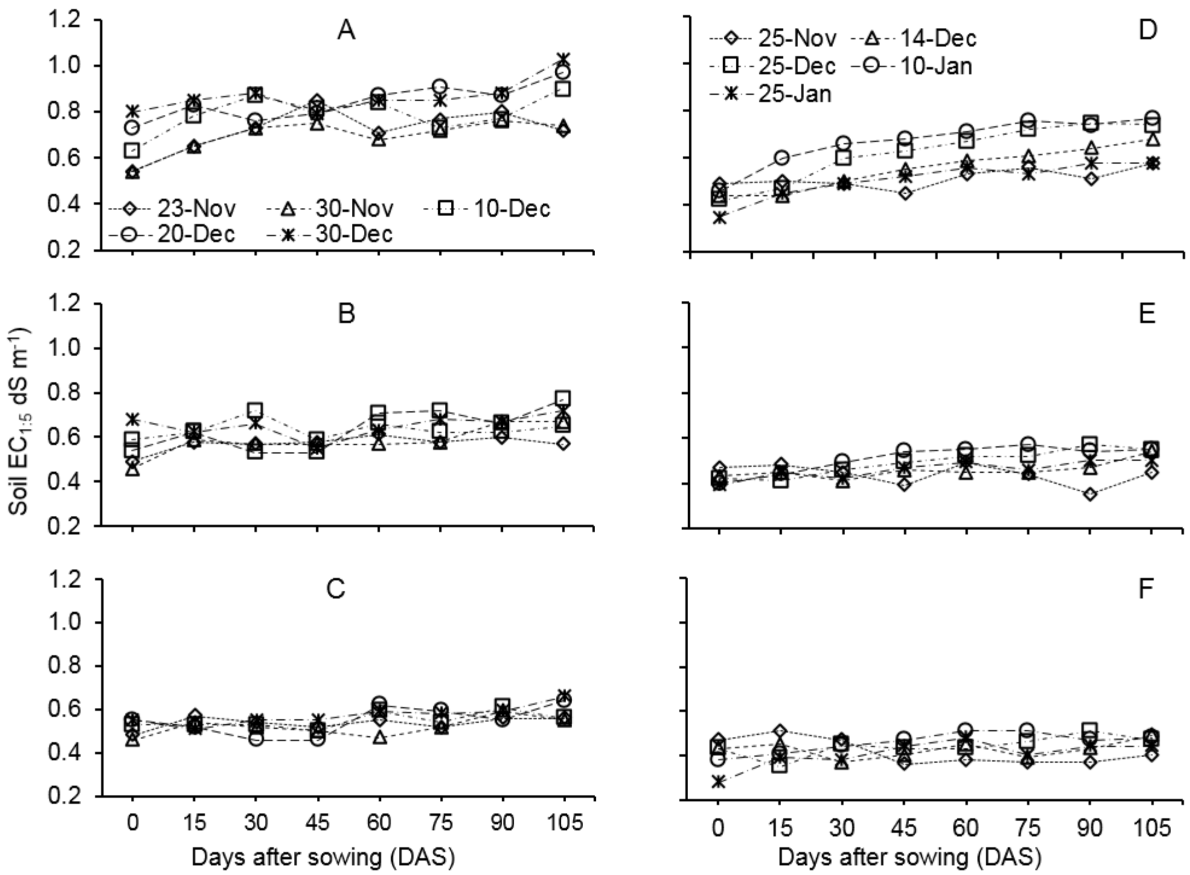

Fig. 5S4. Main effects of sowing time on $EC_{1:5}$ at: (A) 0-7 cm, (B) 7-15 cm and (C) 15-30 cm in 2016-17 season, and (D) 0-7 cm, (E) 7-15 cm and (F) 15-30 cm in 2017-18 season. LSD (least significant difference) for different factor combinations are 0.11*** (Sowing date = S), 0.06*** (Soil depth = D), 0.09*** (Days after sowing = DAS), and 0.11* (S x D x DAS) in 2016-17. LSD for different factor combinations are 0.08*** (Sowing date = S), 0.04*** (Soil depth = D), 0.07*** (Days after sowing = DAS), and 0.0.08* (S x D x DAS) in 2017-18. Values are the means of three replicates. *** indicate statistical significance at P < 0.001.

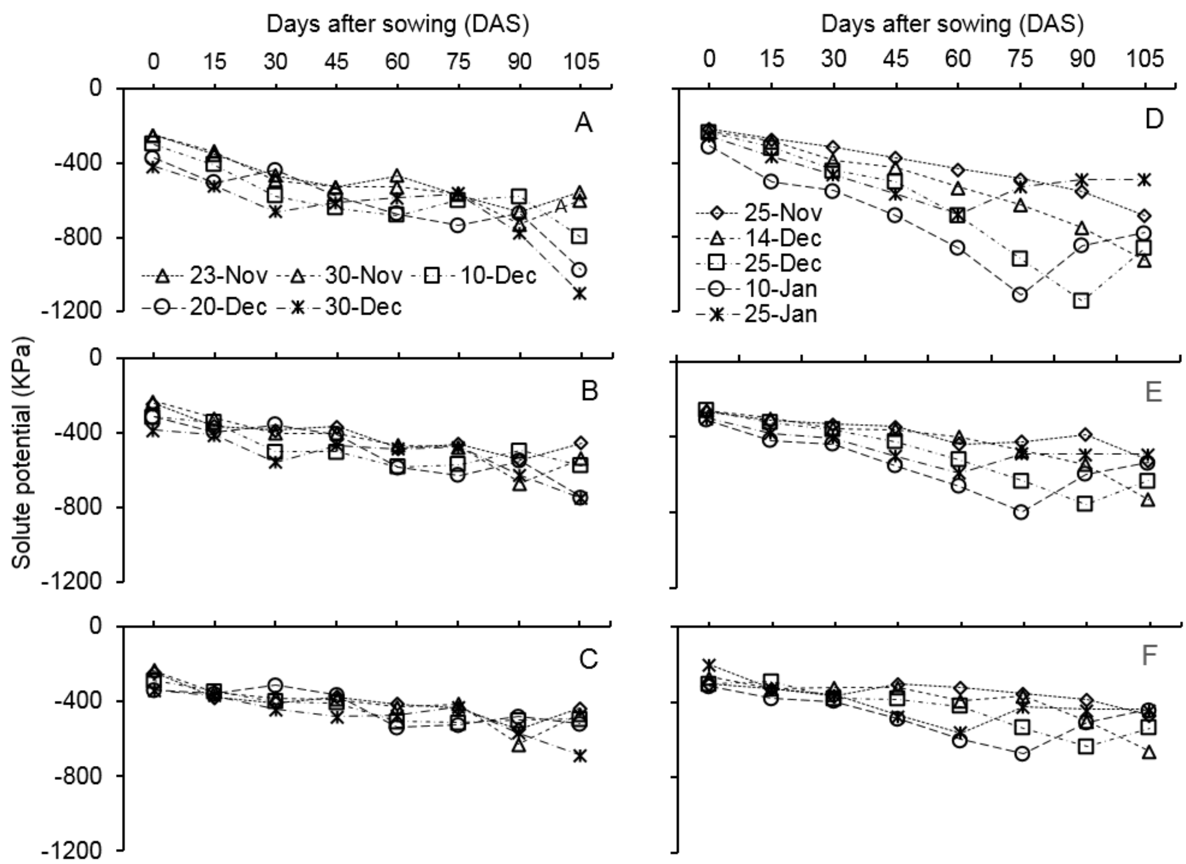

Fig. 5S5. Main effects of sowing time on solute potential at: (A) 0-7 cm, (B) 7-15 cm and (C) 15-30 cm in 2016-17 season, and (D) 0-7 cm, (E) 7-15 cm and (F) 15-30 cm in 2017-18 season. LSD (Least significant difference) for different factor combinations are 123*** (Sowing date = S), 68*** (Soil depth = D), 105*** (Days after sowing = DAS), and 123* (S x D x DAS) in 2016-17. LSD (Least significant difference) for different factor combinations are 69*** (Sowing date = S), 58*** (Soil depth = D), 91*** (Days after sowing = DAS), and 103*** (S x D x DAS) in 2017-18. Values are the means of three replicates. *** indicate statistical significance at $P < 0.001$.

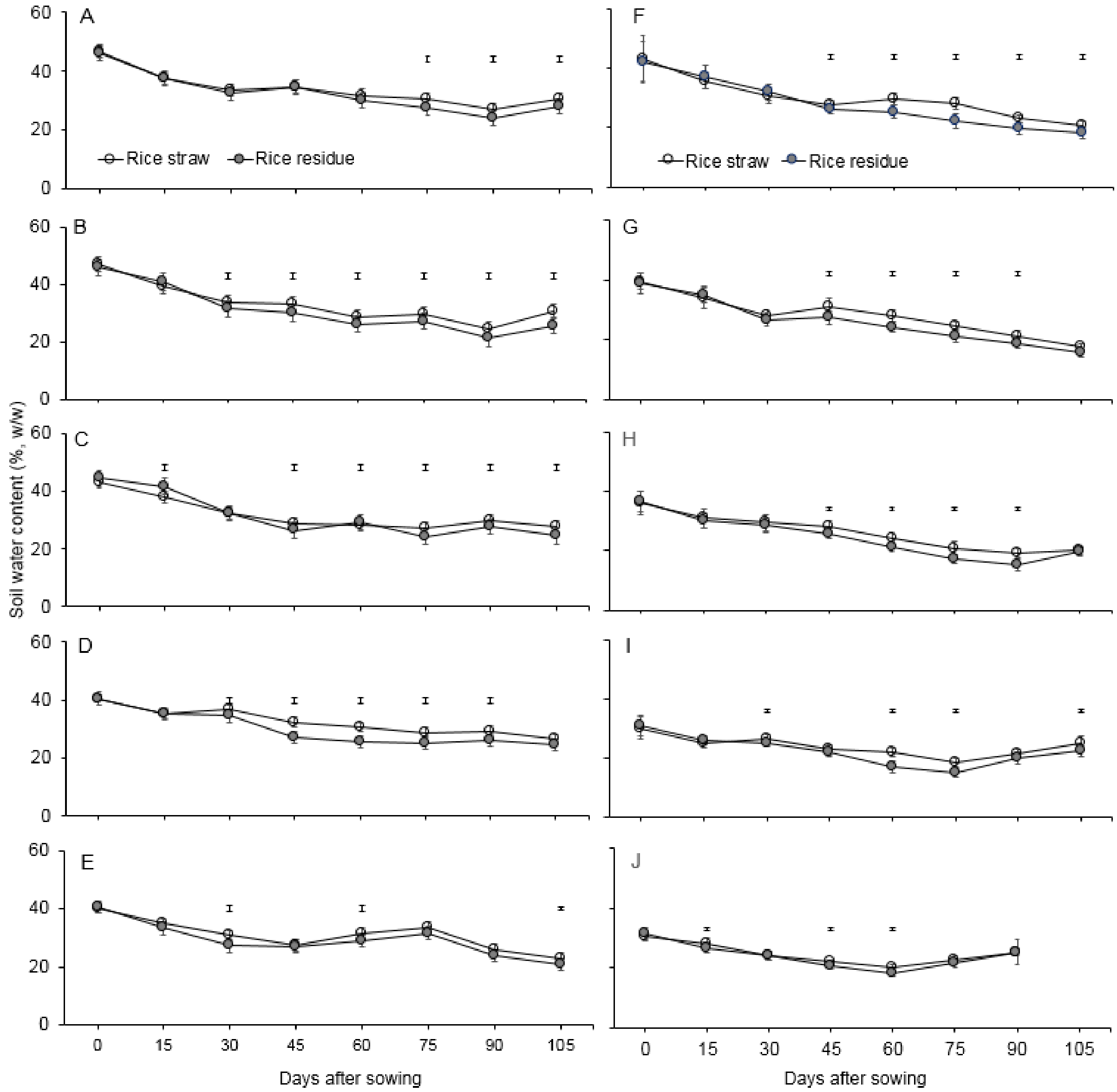

Fig. 5S6. Effect of RS (rice straw) treatment compared to RR (rice residue) on soil water content at five dates of sowing on: (A) 23 Nov, (B) 30 Nov, (C) 10 Dec, (D) 20 Dec and (E) 30 Dec in 2016-17, and (F) 25 Nov, (G) 14 Dec, (H) 25 Dec, (I) 10 Jan and (J) 25 Jan in 2017-18. Floating bars in each date of sampling indicate a significant difference between two mulching treatments at $P < 0.05$.

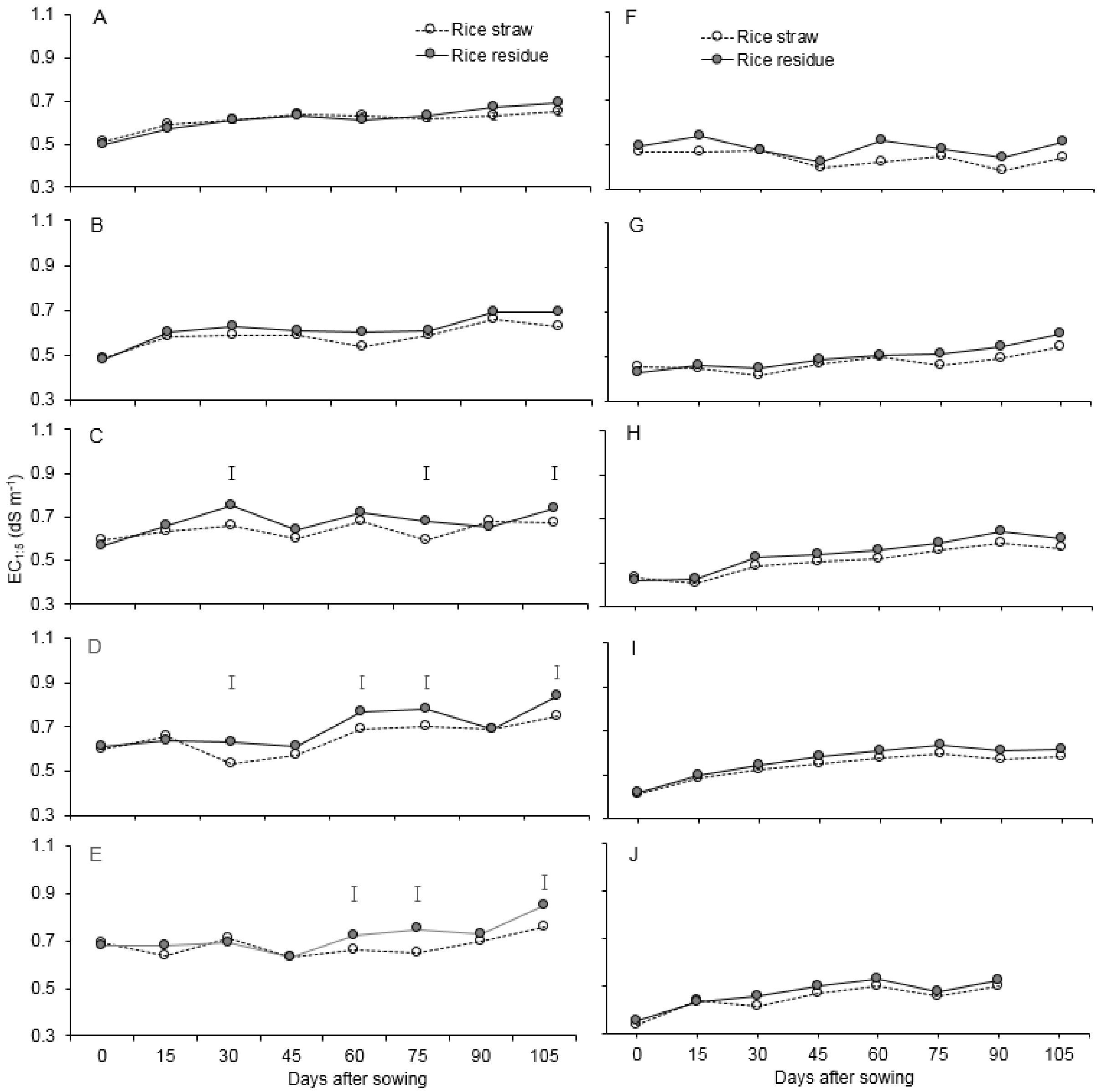

Fig. 5S7. Effect of RS (rice straw) treatment compared to RR (rice residue) on $EC_{1:5}$ at five dates of sowing on: (A) 23 Nov, (B) 30 Nov, (C) 10 Dec, (D) 20 Dec and (E) 30 Dec in 2016-17, and (F) 25 Nov, (G) 14 Dec, (H) 25 Dec, (I) 10 Jan and (J) 25 Jan in in 2017-18. Floating bars in each date of sampling for part A-F indicate a significant difference between two mulching treatments at $P < 0.05$. There was a significant interaction between mulch and time, but no interaction between sowing and mulch or sowing, mulch and time at $P > 0.05$ (Part F-J).

Chapter 6

Sunflower roots distribution in compacted and cracked clay-textured soil: effects of rice straw mulch

In Chapter 5, it was determined that sowing between 20 November and 15 December had a higher sunflower yield potential due to increased soil water content and solute potential, and decreased soil salinity. Sowing after 15 December decreased yield, which was associated with higher soil salinity and temperature. Across all sowing dates, the key driver of yield determination was $EC_{1:5}$ followed by temperature.

In Chapter 6, I investigated the role of root distribution in the soil profile (0 to 80 cm) in explaining sunflower responses to time of sowing, mulch and irrigation water supply. The root dry weight and total root length were significantly lower at 0-20 cm soil depth with the no-mulch than under the mulched plot. The lower values of root parameters under no-mulch plots may be influenced by soil compaction and cracking, but these soil parameters were not measured in the time of the sowing experiment (Chapter 5). In the present experiment, I measured soil penetration resistance and cracked dimensions in clay-textured soil under three mulching treatments and two irrigation regimes. The root distribution was quantified at three times during the growing season in the soil profile to 80 cm. Finally, I related the soil penetration resistance and cracked parameters to root growth and sunflower yield.

6 Sunflower root distribution in compacted and cracked clay-textured soil: effects of rice straw mulch

Priya Lal Chandra Paul [a, e, *], Richard W Bell [a], Edward G. Barrett-Lennard [a, b, d], Enamul Kabir [c]

[a] *Land Management Group, Agriculture Discipline, College of Science, Health, Engineering and Education, Murdoch University, WA-6150, Australia*

[b] *Department of Primary Industries and Regional Development, South Perth, WA-6151, Australia*

[c] *Agrotechnology Discipline, Khulna University, Khulna 9208, Bangladesh*

[d] *School of Agriculture and Environment, The University of Western Australia, Nedlands, WA 6009, Australia*

[e] *Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur-1701, Bangladesh and* [*]*Corresponding author: Tel.: +8801716617378, +610470569881; E-mail: plcpauliwm@yahoo.com*

6.1 Abstract

In the salt-affected coastal zone of the Ganges delta, puddling clay soil as part of intensive tillage for rice cultivation causes loss of soil structure and vertical shrinkage cracks that are hypothesised to hamper sunflower root growth in the following dry season. In order to alleviate soil physical constraints for root growth, the effects of three levels of mulch and two irrigation regimes on sunflowers were examined in the 2018-19 season. These treatments were: no-mulch (NM), rice straw mulch at 5 t ha^{-1} (RS5) and rice straw mulch at 10 t ha^{-1} (RS10) and irrigation applied to raise soil water to field capacity up to 60 cm depth (I1) or double the water supply of treatment I1 (I2) at 30, 55 and 70 days after sowing. Mean dry root weight, total root length, and root length density were higher with the RS5 and RS10 treatments at 0-20 cm depth, but there was a higher total root length at 60-80 cm with the NM treatment. The improved soil physical condition and better root development with the rice straw mulch increased sunflower yield by 23 %. The rice straw mulch significantly increased soil water content at 0-30 cm relative to the no-mulch treatment, and reduced soil cracking and penetration resistance. The RS5 and RS10 treatments significantly reduced crack volume, cross-sectional area, crack length density, depth and width, 84-91 %, 63-69 %, 57-70 %, 42-52 %, and 42 %, respectively, relative to the NM treatment. With RS5 and RS10 treatments, the average soil resistance decreased by 77 %, 49 % and 28 % at 0-7, 7-15 and 15-30 cm depths, respectively, compared to the NM treatment. No benefit further decrease in soil penetration resistance or crack volume was obtained from increasing the level of mulch 5 t ha^{-1} to 10 t ha^{-1} or doubling of the level of irrigation. It is concluded that ameliorating soil physical constraints possibly led to better root growth and yield on this moderately saline clay-soil and that rice straw mulch of ~ 5 t ha^{-1} under no-tilled conditions was an effective treatment.

Keywords: Crack dimension soil water content, soil penetration resistance, sunflower yield.

6.2 Introduction

In the salt-affected coastal zone of the Ganges delta, as in many parts of Asia that grow wetland rice, puddling of clay soil through intensive tillage for rice establishment in the wet season damages soil structure, which during the following dry season lead to soil compaction and abundant vertical shrinkage cracks (Mondal et al., 2015a; Paul et al., 2020a). The soils typically have a massive apedal structure when puddled, a compacted layer below the puddled layer and high soil strength when soil water decreases during the dry season (Adachi, 1990; Kirchhof et al., 2000; So and Ringrose-Voase, 2000). An ideal soil pore space usually holds 25 % water and 25 % air by volume, but soil compaction due to puddled tillage with the dispersion of soil aggregates reduces this pore space in the dry season, which causes a dense soil with impeded internal drainage and aeration (Bayhan et al., 2002). As a result of lowered porosity and deficiency of oxygen level in compacted soils, root penetration and elongation are impaired, and expansion of the root tip is decreased, which results in poor plant growth and development (Cambi et al., 2018; Kozlowski, 1999). Cook et al. (1995), who conducted experiments in clay soil in growth chambers and the field at Los Banos, in the Philippines, reported that high soil penetration resistance in dry soil was the major soil physical constraint affecting the seedling emergence of mungbean. So and Woodhead (1987) reported that increasing soil mechanical resistance decreased the root elongation of legume species and root growth ceased when soil resistance was greater than 3 MPa. Goodman and Ennos (1999) found that sunflower and maize growing in strong (bulk density: 1.4 Mg m^{-3}) and weak soil (bulk density: 1.0 Mg m^{-3}) had no difference in the number or weight of first-order lateral roots systems, but there was a significant effect on the fresh and dry weights of shoots of both crops.. Another experiment conducted by Bayhan et al. (2002) reported that root development and growth of sunflower were reduced by about 22 % with a soil penetration resistance of 1.6 -1.8 MPa (0-20 cm) caused by wheel traffic. Although increases in soil penetration resistance have been reported to affect plant growth and root development in the literature, little work has been done on the sunflower root distribution down the soil profile in the saline clay-textured soil of the Ganges delta.

In soils of the Ganges Delta, the predominant clay minerals are smectite and mica (Moslehuddin et al., 1999), and the drying of these can cause soil shrinkage and vertical cracking (Cabangon and Tuong, 2000). Cracks in the soil can cause bypass water flow from the soil surface to depth after rain or irrigation and can also cause an increase in water loss from soil profiles because the soils are more exposed to evaporation (Tuong et al., 1996). After irrigation, water moves quickly into the crack networks and irrigation water can be lost from the root-zone through sub-soil infiltration and lateral drainage (Tuong et al., 1996; Wopereis et al., 1994). Cracks in the soil profile are said to impair the development and distribution of roots and grain yield (Ringrose-Voase and Sanidad, 1996; Taylor and Brar, 1991; Whitmore and Whalley, 2009), but effects may vary between crops. For example, there are also evidence that soybean roots can grow down crack walls and extract subsoil water (Hasegawa et al., 1985).

In this experiment, measurements were made of water extraction by roots growing adjacent to soil cracks to 60 cm, but measurements were not made of the effects of cracks on root dry weight, total root length or root density at different depths in the soil profile. Application of straw mulch to a soil surface can stimulate the restoration of soil structure in compacted soils (Jourgholami et al., 2018; Paul et al., 2020b). For instance, mulches increased soil water content, stabilized soil aggregation and improved infiltration rate, all of which can prevent or mitigate the increase of soil penetration resistance (Fang et al., 2011; Mulumba and Lal, 2008). Studies have shown that straw mulch is effective in increasing soil water content (Paul et al., 2020b), thus reducing soil compaction (Lal and Latham, 1987) and crack development (Cabangon and Tuong, 2000) and improving crop productivity (Mitchell et al., 2013). With sunflower, previous studies have investigated the effect of soil compaction on sunflower root growth and yield (Bayhan et al., 2002; Tracy et al., 2011), but there have been no detailed studies on sunflower root distribution down the soil profile under compacted and cracking conditions in clay-textured soils. A recent study conducted by Paul et al. (2020b) showed that mulching with rice straw increased sunflower yield and this was attributed to increased soil water and a lower $EC_{1:5}$ in surface soil layers, but the effects on root growth in this work were not reported. This study aimed to determine the effect of rice straw mulch together with different amounts of irrigation water on soil penetration resistance, crack dimension and sunflower root distribution in the profile of a moderately saline, clay soil with a shallow water table. Some of the measurements made here are supported by additional data from a preliminary investigation conducted a year earlier on the same site; these are reported in the Supplementary Materials.

6.3 Materials and methods

6.3.1 Site description

The experiment was established in a farmer's field at Pankhali, Dacope Khulna Bangladesh (22^0 37' 55" N and 89^0 30' 10" E) in the 2018-19 season. This area is low-lying with an elevation of 2 - 3 m above mean sea level (Mondal et al., 2015b) within the Ganges Tidal Floodplain agro-ecological zone (Paul et al., 2020a). The climate in this region is sub-tropical with an average annual rainfall of ~1,800 mm of which 80 % fall in the wet season. There is a cool dry winter from November to February and a hot and humid summer from March to June. The soil texture was silty clay (0-30 cm) overlying clay (30-60 cm). The soil (0-15 cm) had a bulk density of 1.4 Mg m^{-3}, a pH of 7.5, an organic carbon content of 12 g kg^{-1} (Paul et al., 2020b). Groundwater depth varied from 0.7 to 1.8 m below the soil surface, and the water was moderately saline (EC_w: 2.0 - 3.5 dS m^{-1}). A medium duration high-yielding monsoon-season rice variety was grown in the wet season and was harvested in the third week of November. The excess standing water on the land was removed by surface drainage to prepare the plots for planting. Irrigation water was conserved in an adjacent canal by constructing an embankment between the river and canal before the river water turned saline.

6.3.2 Experimental details and crop management

The experiment tested three mulching treatments: no-mulch (NM), rice straw mulch at 5 t ha^{-1} (RS5) and rice straw mulch at 10 t ha^{-1} (RS10), and two irrigation regimes: I1 [(irrigation water was applied to raise soil water in the 0-60 cm layer to field capacity at 30, 55 and 70 days after sowing (DAS) and I2 (irrigation water applied at double the amounts of treatment I1 at 30, 55 and 70 DAS)]. The experiment was laid out in a split-plot design with three replications where irrigation was in main plots and mulch in subplots. The plot size was 7 × 5 m, and sunflower seeds (cv. Hysun-33, hybrid) were dibbled into the no-tilled wet soil on 7 December by making a hole with a round stick to a depth of 2 - 3 cm. There was a plant to plant spacing of 40 cm and a row to row spacing of 70 cm. Plots were surrounded by thick polythene sheets inserted vertically beside a bund to 50 cm depth. In addition, a 1 m buffer zone between plots was maintained in order to prevent runoff or lateral seepage of irrigation water. The fertilizer application was at 200-200-170-170-10-12 kg ha^{-1} as urea-triple superphosphate-muriate of potash-gypsum-zinc sulphate-boric acid. All fertilizers except 75% of urea were applied at sowing by adding to a hole (5-7 cm deep) on both sides of the plant (~ 5 cm distance) along the rows, and the rest of the urea was top-dressed in equal splits during irrigation events. For pre-plant weed control, Roundup$^{(R)}$ (Glyphosate 62 %) was sprayed seven days before sowing, and a hand weeding was done at 25 DAS. Nitro (Cypermethrin Chlorpyriphos) was sprayed three times during the season to control hairy caterpillar. Irrigation water was applied by hose pipe during urea top dressing at 30, 55 and 70 DAS and volumetric water supply was measured. Fig. 6.1 shows the soil condition and crop performance under three mulching treatments. Before maturity, an overhead net was set up to prevent damage to crops by birds. Physiological maturity was determined when all seeds had turned black and shiny. Crop emergence rate, crop growth and development, bud initiation, first flowering and physiological maturity were recorded. Ten plants were randomly selected to measure plant height, stem diameter, head diameter, head weight, number of seeds per head and 1000 seed weight at harvest. The final grain yield was calculated (t ha^{-1}) at an adjusted moisture content of 9 % (w/w).

6.3.3 Root measurements

Sunflower root distribution in the soil profile was observed at 25, 58 and 90 DAS. At 25 DAS (seedling stage), shoots were separated from four selected plants in each plot and the roots of each plants were excavated to a depth 20 cm. One plant was selected in each plot at 58 DAS (stage of maximum vegetative growth), and at 90 DAS (flowering stage). Shoots were excised and roots were excavated in a block 20 cm along the row, 20 cm across the row and in 20 cm deep increments to 60 cm at 58 DAS and down to 80 cm at 90 DAS. Each block of soil was soaked in a bucket for 5-6 hours. Roots were then separated from the slurry and washed out on a 2 mm sieve. Finally, the non-root materials were picked out of the samples. For each soil block, total root length (TRL) was measured manually using a ruler. Root dry weight (RDW) were measured after oven drying at 65 ^{0}C to reach a constant weight. Root length density (RLD) (root length/soil volume) and specific root length (SRL) (root length/ root dry weight) were then calculated for each soil depth.

Root distribution was also observed at the flowering stage in an experiment conducted in the previous year on the same site (the experiment is described in Chapter 5). Details of the root measurements in this experiment are reported in the Supplementary Materials (Section 2 and Fig. S2-4).

6.3.4 Soil penetration resistance

After sowing, soil penetration resistance was measured using a cone penetrometer (Hand penetrometer Eijkelkamp) at the 0-7, 7-15 and 15-30 cm depths. Different sizes of cones (1 to 5 cm^2 base area) were fitted to the extension rod as required to ensure that a uniform pressure could be applied to push the cone into the soil. In each measurement, the manometer reading in kN (kilo Newton) was recorded. The resistance was then converted to MPa (MegaPascal) based on the surface area of the cone.

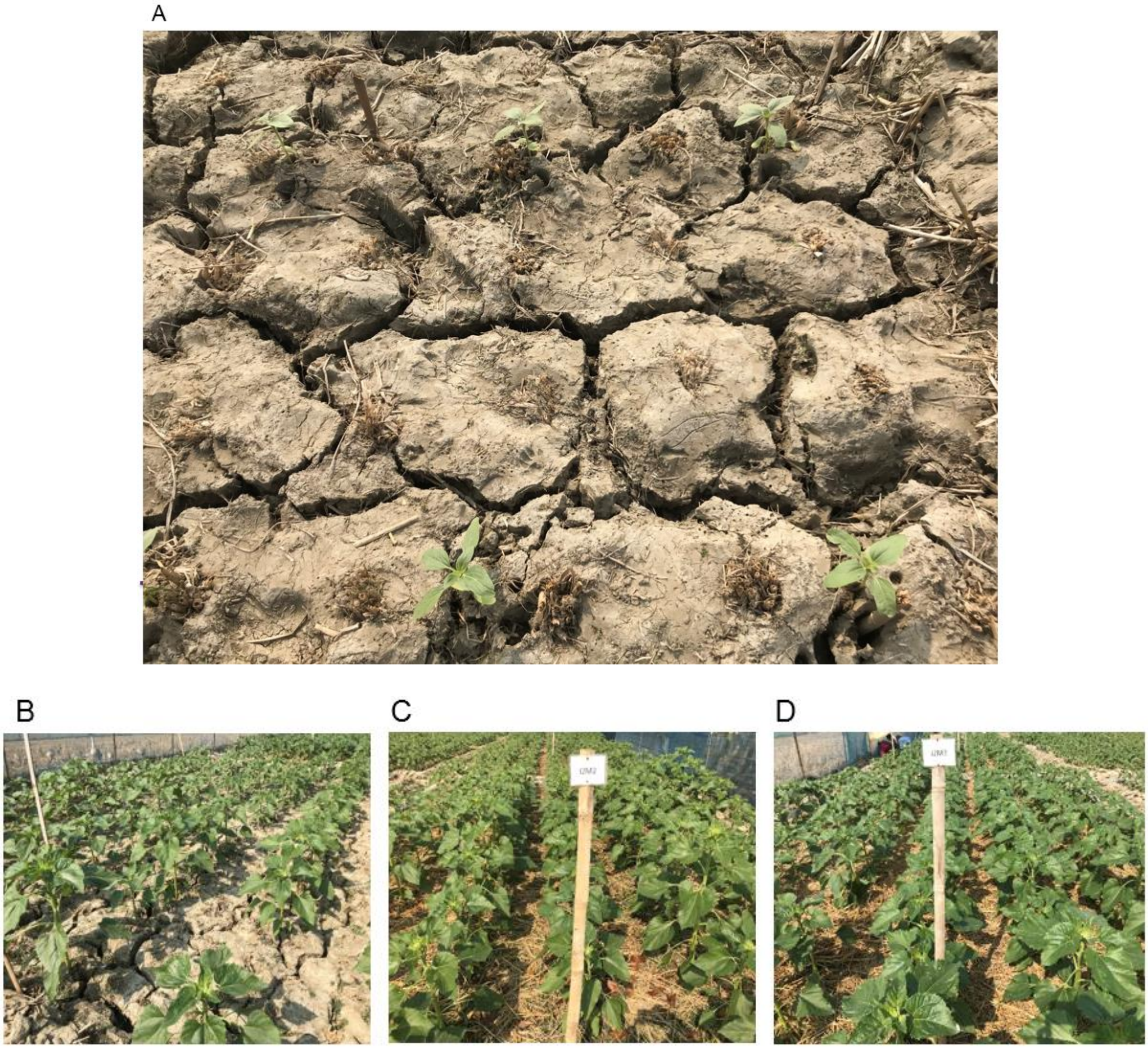

Fig. 6.1. Pictorial view of cracked soil during sunflower growth (A), and the effects of mulch treatments on sunflower growth: (B) no-mulch, (C) mulch at 5 t ha^{-1} and (D) mulch at 10 t ha^{-1}.

6.3.5 Soil crack dimension

Soil surface cracks were measured in each plot using a transect method (Ringrose-Voase and Sanidad, 1996). The transect involved a series of six connected semi-circles of 1 m diameter. Each semi-circle was placed on the soil surface and the number of intercepts was recorded to measure the length of crack per unit area (L_A). The average depth (D) and width (W) of cracks intercepted by each semi-circle were counted from the first five cracks intercepted with each ring using a flexible ruler (i.e., there were 60 pairs of total measurements). The cross-sectional area ($\overline{X}$) of cracks (assuming a triangular cross-section) was calculated using the average depth and width. Finally, the volume of the crack per unit area (V_A) was estimated as $L_A \times \overline{X}$.

6.3.6 Soil water content

Soil samples were collected at 0-7, 7-15, 15-30, 30-45 and 45-60 cm depths at two-week intervals between sowing and harvest to measure gravimetric soil water content (SWC). A hand-held auger was used to collect samples from each depth, and soils were placed immediately in sealed polyethylene bags. The wet weight of the samples was measured immediately, and they were then oven-dried to constant weight. The SWC was calculated from the difference between soil wet and dry weight. The volumetric soil water content was calculated by multiplying the gravimetric soil water content by the bulk density of the respective soil layers.

6.3.7 Statistical analysis

Data for all parameters were analysed with two-way ANOVA using STAR software (Version 2.0.1). The effects of mulch and irrigation on soil water content, resistance and crack properties were determined using four-way factorial ANOVA models that also took account of the effects of mulch, soil depth and date after sowing (time) as repeated measures. The comparison of means was tested using the least significant difference (LSD) at the 95 % confidence level. The relationship between soil water content and soil parameters (soil resistance and crack properties) or yield and soil parameters (soil resistance and crack properties) were tested by a single factor regression model.

6.4 Results

6.4.1 Weather data

There was no rainfall during crop growth until 22 February, but from flowering to maturity about 352 mm of rain fell (Fig. 6.2A). About half of the total season rainfall occurred in the last week of February, which inundated the plots and damaged some plants due to waterlogging stress. The temperature was lower in December and January (minimum average 12-14 ^{o}C) and higher in March and April (maximum average 31.8-33.9 ^{o}C). The lowest and highest temperature was 8 ^{o}C and 35.5 ^{o}C in December and April, respectively (Fig. 6.2B).

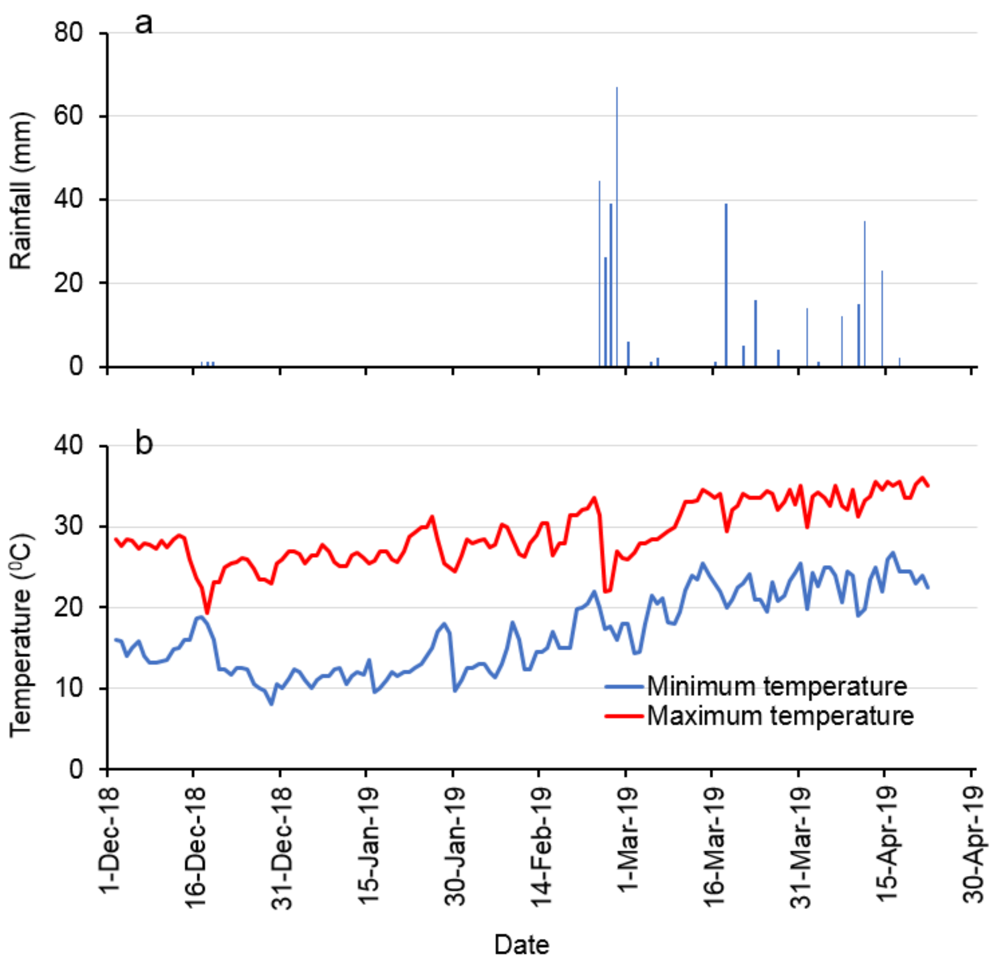

Fig. 6.2. Weather details for the 2018-19 growing season at Pankhali, Dacope Khulna, Bangladesh: (a) daily rainfall and (b) minimum and maximum temperature.

6.4.2 Sunflower yield and yield components

There were significant effects of mulch treatments on yield and yield components (Table 6.1). The M2 and M3 treatments had a 0.5 - 0.6 t ha^{-1} higher yield than the M1 treatment. With the M2 and M3 treatments, thousand seed weight, number of seeds per head, and head diameter were also significantly higher relative to the M1 treatment (Table 6.1). However, there was no difference in yield or yield components between the M2 and M3 treatments. Irrigation treatments did not affect the yield and yield components except thousand seed weight, where there was higher seed weight in the I2 treatment than I1 treatment (Table 6.1). Sunflower yield was negatively correlated with all crack parameters (P <0.001; Table 6.2), increasing soil resistance (P < 0.01) and with SWC (P < 0.05). For crack parameters, crack width explained the most yield variation (r^2 = 0.75), while crack depth explained the least yield variation (r^2 = 0.53) (Table 6.2, Sl no 1 and 5). Crack length density, crack area and crack volume accounted for 55-59 % variation in the yield. Soil resistance and SWC accounted for about 34 % and 32 % variation in the yield (Table 6.2, SL no. 6 and 7).

There was also a significant relationship between yield and root parameters during bud formation and flowering at different depths in the soil (Table 6.3). The most significant impacts on yield were RDW at 0-20 cm soil depth at bud formation (P < 0.001) and flowering (P < 0.01) stages, while below this depth there was no effect. During bud formation, TRL and RLD were significantly (P < 0.05) correlated with yield at 0-40 cm, but at flowering these factors as well as SRL, were only significant (P < 0.05) at 60-80 cm depth (Table 6.3).

Table 6.1. Yield and yield attributes of sunflower under different mulch treatments and irrigation regimes in Pankhali, Dacope, Bangladesh in 2018-19.

Irrigation regimes	Mulch treatments	Yield (t ha^{-1})	Thousand seed weight (g)	Seeds per head	Head diameter (cm)
I1	M3	3.1	82.0	1505	20.4
	M2	3.0	81.5	1479	20.3
	M1	2.5	74.0	1285	18.6
I2	M3	3.3	87.0	1582	21.1
	M2	3.2	84.5	1557	20.6
	M1	2.8	79.0	1345	19.2
Treatment means					
I1		2.9	79.0	1423	19.8
I2		3.1	84.0	1495	20.3
RS10		3.2	85.0	1544	20.8
RS5		3.1	83.0	1518	20.5
NM		2.6	76.5	1315	18.9
P-values					
Irrigation		NS	0.05	NS	NS
Mulch		0.05	0.05	0.01	0.05
Irrigation x Mulch		NS	NS	NS	NS
$LSD_{0.05}$					
Irrigation		-	2.0	-	-
Mulch		0.3	6.2	109	1.3
Irrigation x Mulch		-	-	-	-

I1 = irrigation up to field capacity, I2 = Irrigation double than treatment I1; NM = no-mulch, RS5 = rice straw ~ 5 t ha^{-1}, RS10 = rice straw ~ 10 t ha^{-1}; NS = non-significant.

Table 6.2. Relationship between grain yield and soil factors (soil crack, penetration resistance water content)

Serial number (SL)	Soil factors	Regression equation	Coefficient determination (r^2)
	Crack parameters		
1	Width, W (cm)	Y = -0.42 W + 3.65	0.75^{***}
2	Cross-sectional area, A (cm^2)	Y = -0.04 A + 3.34	0.59^{***}
3	Length density, LA ($m\ m^{-2}$)	Y = -0.104 LA + 3.43	0.58^{***}
4	Volume, V ($m^3\ m^{-2}$)	Y = - 43.96 V + 3.2	0.55^{***}
5	Depth, D (cm)	Y = -0.085 D + 3.77	0.53^{***}
6	Soil resistance, SR (MPa)	Y = -0.50 SR + 3.43	0.34^{**}
7	Soil water content (SWC, %)	Y = 0.13 SWC – 1.49	0.32^{*}

Table 6.3 Significance of the relationships between yield and root parameters at 0-60 cm (at 58 DAS) and 0-80 cm (at 90 DAS)

Soil depth (cm)	At bud formation (58 DAS)				At flowering (90 DAS)			
	P-values and r^2 values in brackets				*P*-values and r^2 values in brackets			
	RDW	TRL	RLD	SRL	RDW	TRL	RLD	SRL
0-20	*** (0.52)	* (0.31)	* (0.31)	NS	** (0.34)	NS	NS	* (0.24)
20-40	NS	* (0.26)	* (0.26)	NS	NS	NS	NS	NS
40-60	NS	NS	NS	NS	NS	NS	NS	NS
60-80	-	-	-	-	NS	* (0.22)	* (0.22)	** (0.35)

*, ** and *** indicate significant at 5 %, 1 % and 0.1 % probability level. NS= non-significant.

6.4.3 Root distribution

At the seedling stage (25 DAS), there was no effect of mulch on root distribution (data not shown), but at bud formation (58 DAS) and at flowering (90 DAS) all measures of root distribution were significantly affected by mulch treatments, soil depth and the interaction between mulch and depth, except that mulch had no effect on SRL at flowering (Fig. 3 and 4).

At bud formation and flowering, the RDW, TRL and RLD values were highest at 0-20 cm and were 71- 97 % lower at the deepest depth measured (40-60 cm at bud formation; 60-80 cm depth at flowering). The RS5 and RS10 treatments significantly increased RDW, TRL and RLD values at 0-20 cm at bud formation, but only increased RDW at 0-20 cm at flowering (Fig. 6.3 and 6.4). On average, the RS5 and RS10 treatments had 22-38 % higher RDW compared with NM treatment. During bud formation, the TRL was higher with RS5 and RS10 treatments than with the NM treatment at 0-20 cm depth, but at depth 40-60 cm the TRL was significantly higher with NM treatments than RS5 and RS10 treatments (Fig. 6.3B). On the other hand, at flowering, the NM treatment had a higher TRL at 0-20 and 60-80 cm than with the RS5 and RS10 treatments; the reason for the increase in shallow roots in NM plots was the huge number of new adventitious roots formed near the surface after the soil was inundated due to heavy rainfall. The SRL increased with depth at bud formation and flowering. However, mulch had no effect on SRL at 0-20 cm at bud formation or at all depths at flowering (Fig. 6.3D and 6.4D).

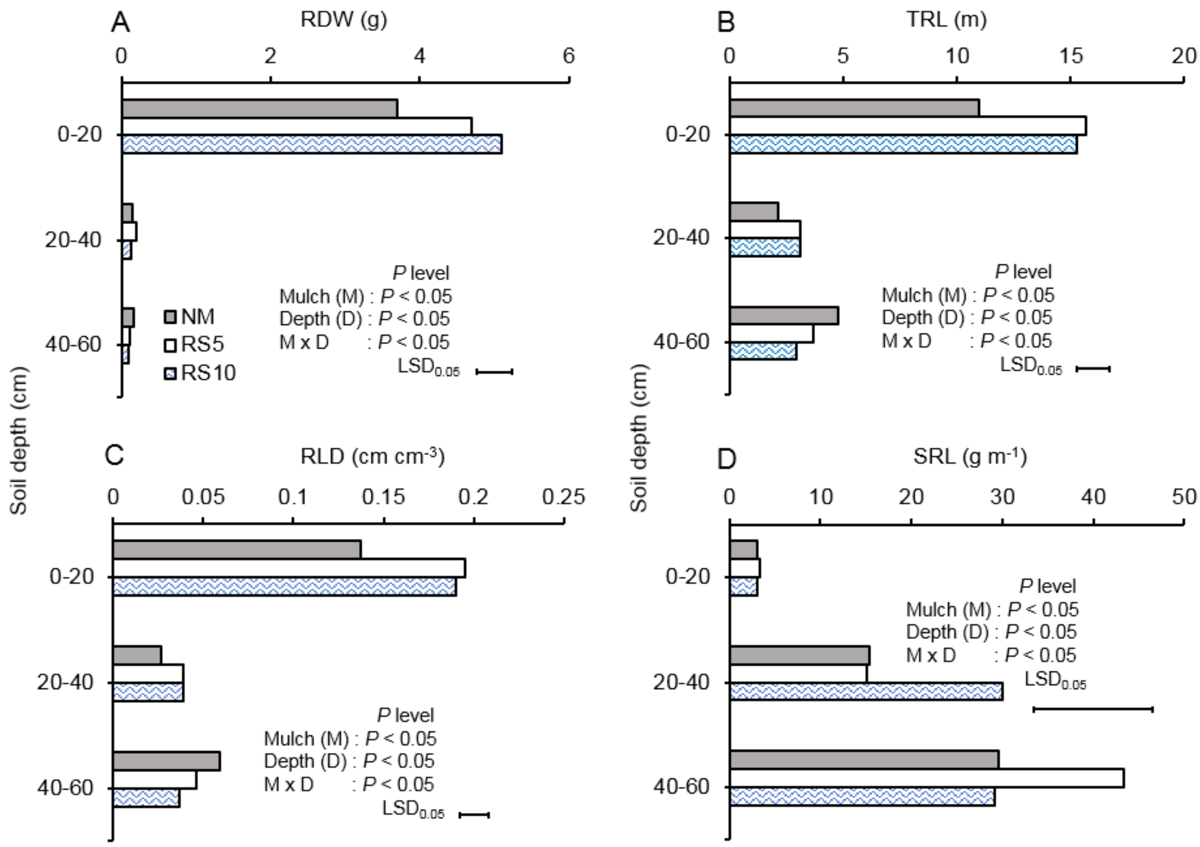

Fig. 6.3. Effects of three mulch treatments on root parameters at different soil depths at bud formation (6 February at 58 DAS) in 2018-19: (A) mean root dry weight (RDW), (B) total root length (TRL), (C) root length density (RLD), and (D) specific root length (SRL). $LSD_{0.05}$ is the least significant difference of the interaction between mulch and depth. NM = no-mulch, RS5 = rice straw ~ 5 t ha^{-1}, RS10 = rice straw ~ 10 t ha^{-1}

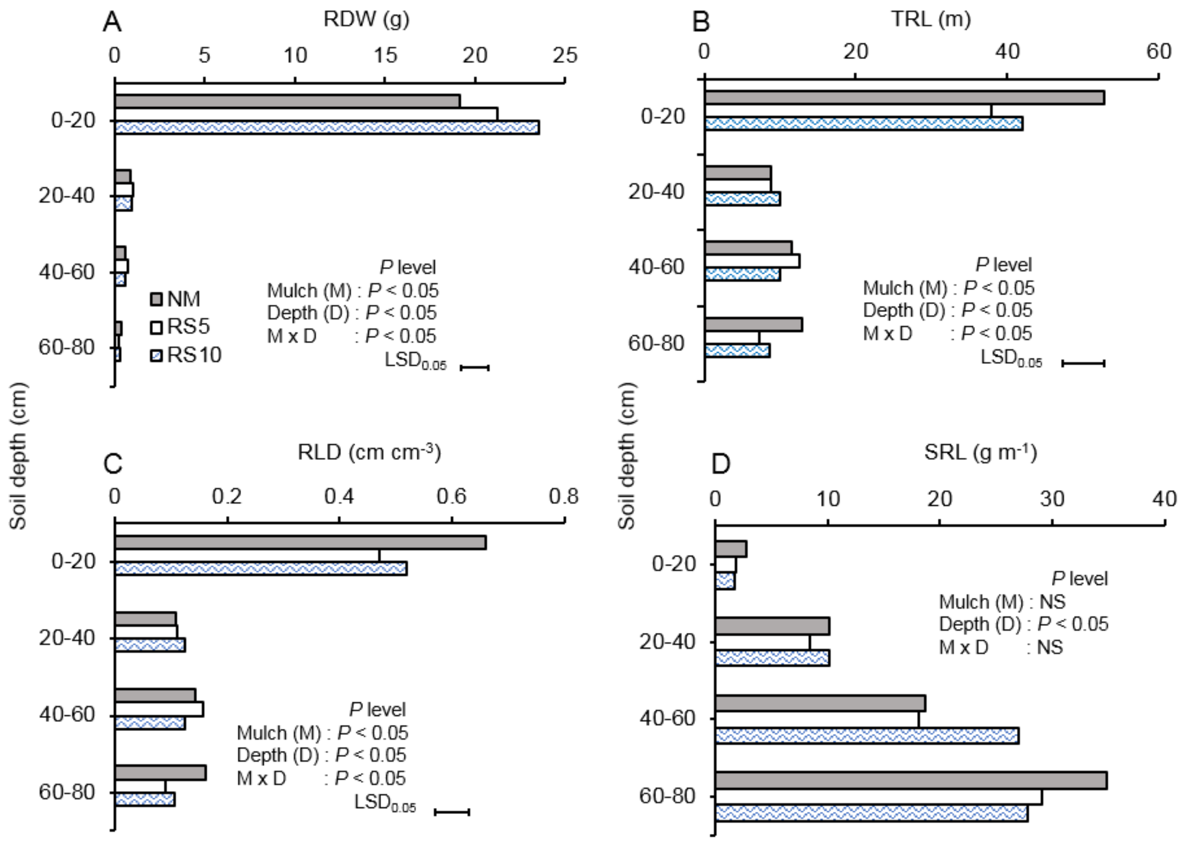

Fig. 6.4. Effects of three mulch treatments on root parameters at different soil depths at flowering (5 March at 90 DAS) in 2018-19: (A) mean root dry weight (RDW), (B) total root length (TRL), (C) root length density (RLD), and (D) specific root length (SRL). $LSD_{0.05}$ is the least significant difference of the interaction between mulch and depth. NM = no-mulch, RS5 = rice straw ~ 5 t ha^{-1}, RS10 = rice straw ~ 10 t ha^{-1}.

6.4.4 *Soil water content*

Gravimetric SWC was significantly affected by mulch treatments, soil depth and date after sowing (time), and there was a significant interaction between mulch and time (Fig. 6.5A), and mulch and soil depth (Fig. 6.5B). At 30 DAS (5 January), there was no difference in SWC among the mulch treatments. The SWC was significantly lower from 45 DAS to 70 DAS (20 Jan to 16 Feb) in the NM treatment (22-33 %) than with the RS5 and RS10 treatments (36-28 %) (Fig. 6.5A). From flowering to maturity (6 to 28 Mar), SWC did not differ between treatments due to the seasonal rainfall. The greater change of SWC was at 0-30 cm and below this depth, there was little change (Fig. 6.5B). The average SWC was high (31-34 %) at 0-15 cm, decreased to about 29 % at 30 cm, and then increased again (33 %) at 60 cm. The RS5 and RS10 treatments had significantly higher SWC at 0-30 cm depth than the NM treatment.

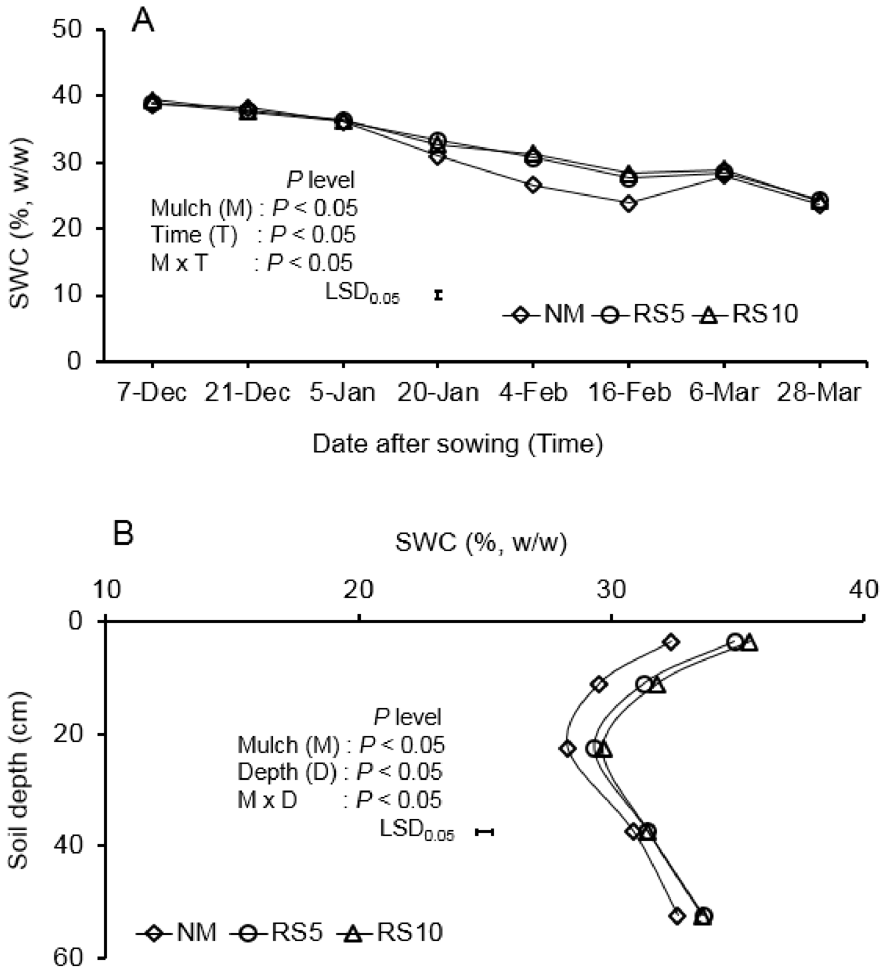

Fig. 6.5. Effects on soil water content (SWC) in the 2018-19 season: (A) effect of mulch and the interaction between mulch and time, and (B) interaction between mulch and soil depth. $LSD_{0.05}$ is the least significant difference of the interaction between mulch and time (A), and mulch and soil depth (B). Part A is the average for the five soil depths. Part B is the average of values at eight times. NM = no-mulch, RS5 = rice straw at ~ 5 t ha^{-1}, RS10 = rice straw at ~ 10 t ha^{-1}.

6.4.5 *Soil crack development*

Crack measurements were started 15 days after the application of rice straw mulch. Cracks developed in all mulch treatments but with significant differences. Initially, the length of crack per unit area (L_A) rose rapidly to a maximum of 8 - 9 m m^{-2} with the NM treatment and afterward decreased slightly (Fig. 6.6A). Crack length increased at a lower rate up to a peak value of 3.8 and 2.9 m m^{-2} under RS5 and RS10 treatments. However, the RS10 treatment (mulch at 10 t ha^{-1}) had significantly reduced crack length compared with the RS5 treatment (mulch at 5 t ha^{-1}). From the first measurements with the NM treatment, the mean crack width and depth were much bigger than with the other mulch treatments and reached peaks at 3 cm (width) and 17 cm (depth). By contrast, cracks were both shallower and narrower with the RS5 and RS10 treatments with values that varied respectively from 1.0-1.6 cm and 1.0-1.3 cm (width), and 6.8 - 9.3 cm and 6.4 - 8.2 cm (depth), respectively (Fig. 6.6B and 6.6C). The larger crack width and depth under the NM treatment exposed a much greater surface area of cracks compared to the RS5 and RS10 treatments (Fig. 6.6D). From the first sampling, the rate of increase in crack volume was much faster with the NM treatment which increased from 0.005 at initial (5 January) to 0.02 m^3 m^{-2} at peak (27 January) (Fig. 6.6E). By contrast, with the RS5 and RS10 treatments, crack volume increased from 0.0009 m^3 m^{-2} to 0.0023 m^3 m^{-2} (from 5 January to 27 January). Irrigation treatments only affected the length per unit area (L_A); the I2 treatment had significantly lower L_A (4.1 m m^{-2}) than the I1 treatment (4.5 m m^{-2}) (data not presented). There was a significant negative correlation between crack parameters (mean depth, cross-sectional area and volume) and SWC at 0-30 cm soil depth. The SWC accounted for 87 %, 75 % and 70 % variations in the crack depth, crack cross-sectional area and crack volume, respectively (Table 6.3).

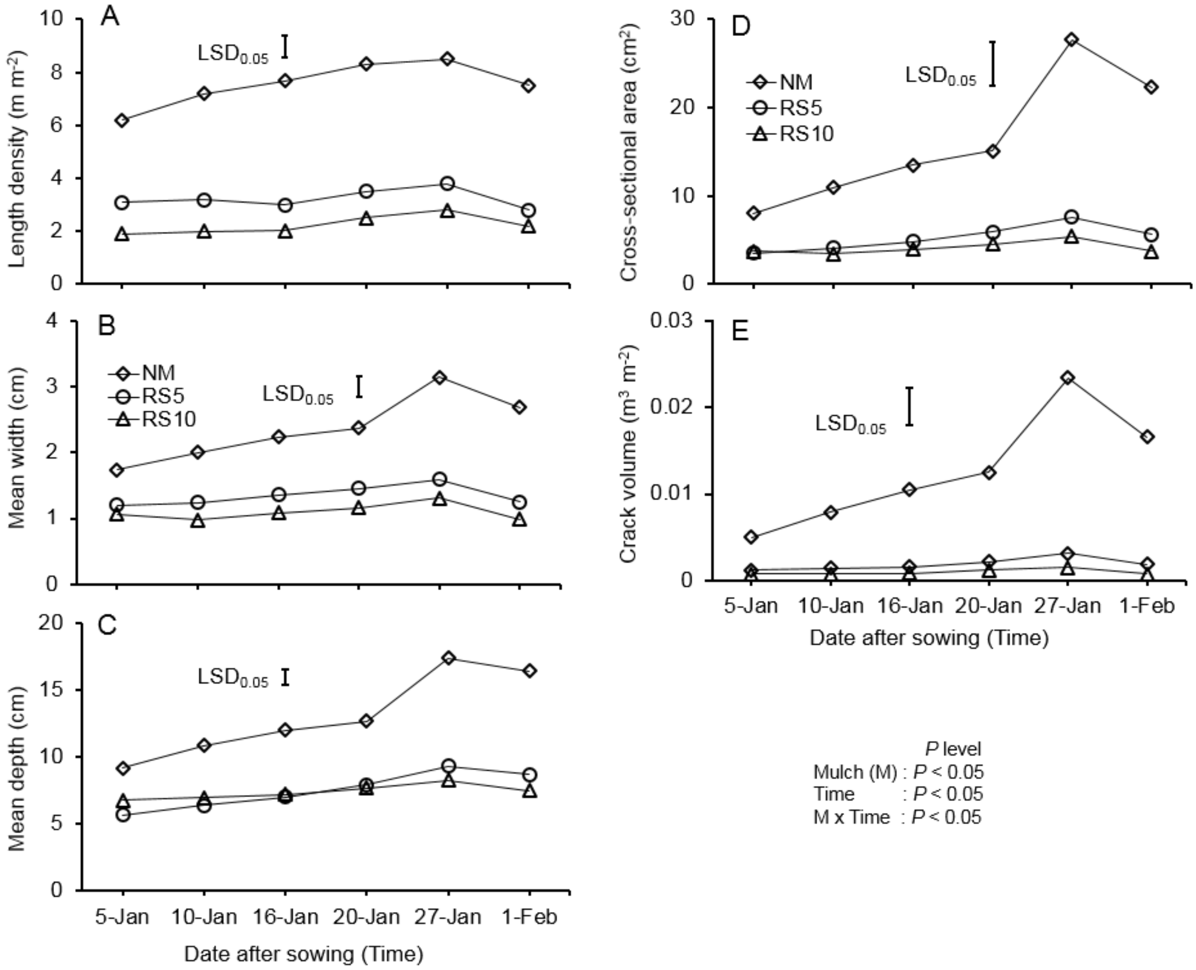

Fig. 6.6. Effects of mulch treatments on crack parameters: (A) length per unit area, (B) mean width, (C) mean depth, (D) mean cross-sectional area, and (E) crack volume per unit area. $LSD_{0.05}$ is the least significant difference of the interaction in each graph at a *P*-value of 0.05. NM = no-mulch, RS5 = rice straw at ~ 5 t ha^{-1}, RS10 = rice straw at ~ 10 t ha^{-1}.

Table 6.4. Significance of relationships between crack parameters and SWC (%, w/w) at 0-30 cm

Crack parameters	Regression equation	Coefficient determination (r^2)
Depth, D (cm)	D = -2.73 SWC + 59	0.87^{**}
Cross-sectional area, A (cm^2)	A = -1.37 SWC + 45.37	0.75^{*}
Volume, V ($m^3\,m^{-2}$)	V = - 1632 SWC + 42	0.70^{*}

* and ** indicate significant at 5 % and 1 % probability level

6.4.6 Soil penetration resistance

After crop establishment, there was an increasing trend of soil penetration resistance in all mulching treatments, however rice straw mulch significantly limited the increase in soil penetration resistance (Fig. 6.7). From the first week of January, soil penetration resistance was 2-fold higher without mulch (NM treatment) than with mulch (RS5 and RS10 treatments), but there was no difference between the RS5 and RS10 treatments (Fig. 6.7A, 6.7B and 6.7C). With the NM treatment, the average soil penetration resistance was highest (~5.2 MPa) at 0-7 cm and lower (2.8 and 3.1 MPa) at 7-15 and 15-30 cm depth on 30 January (Fig. 6.7A, 6.7B and 6.7C). By contrast, with RS5 and RS10 treatments, average soil resistance was lowest (1.0 MPa) at 0-7 cm and increased to 1.8 and 2.1 MPa at 7-15 and 15-30 cm. Throughout the season, the average soil resistance decreased by 77 %, 49 % and 28 % at 0-7, 7-15 and 15-30 cm depths, respectively, with the RS5 and RS10 treatments compared to the NM treatment. Increasing irrigation volumes applied had no effect on soil resistance. There was a significant negative correlation between soil resistance and SWC (Fig. 6.8). Soil resistance increased with decreasing SWC, and about 62 % of the variation in soil resistance could be explained by SWC.

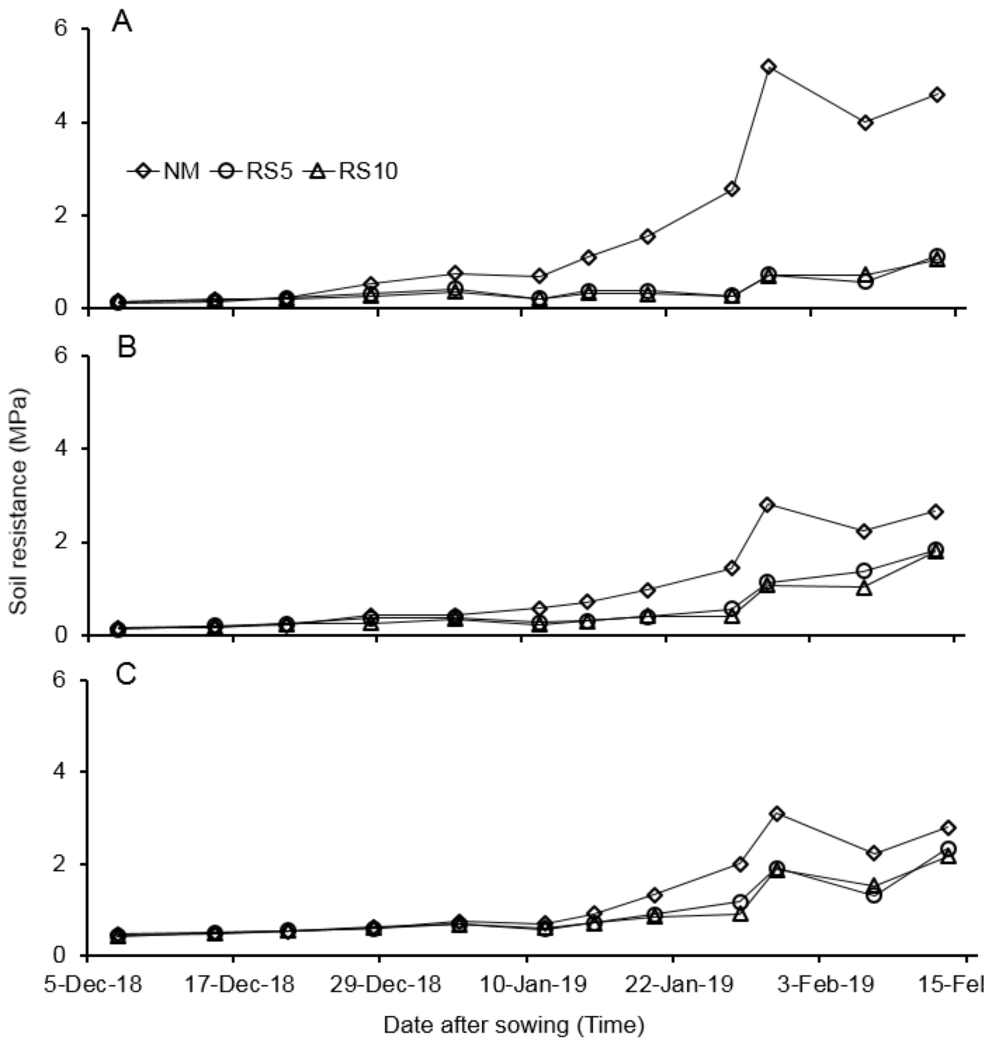

Fig. 6.7. Effects of mulch on soil penetration resistance in the 2018-19 season: (A) at 0-7 cm, (B) 7-15 cm, and (C) 15-30 cm. $LSD_{0.05}$ is the least significant difference of the interaction between mulch, depth and time in each graph at a P-value of 0.05. NM = no-mulch, RS5 = rice straw at ~ 5 t ha^{-1}, RS10 = rice straw at ~ 10 t ha^{-1}. Note: 7 December was the sowing date for sunflower.

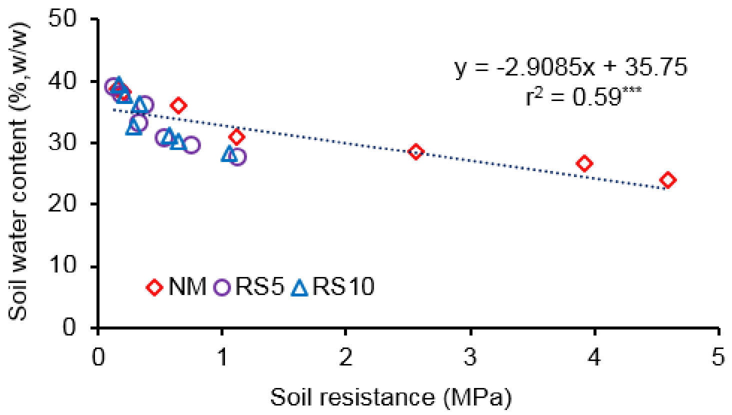

Fig. 6.8. Relationship between average soil water content and average soil resistance (0-30 cm soil depth) from sowing to bud formation. NM = no-mulch, RS5 = rice straw at ~ 5 t ha^{-1}, RS10 = rice straw at ~ 10 t ha^{-1}.

6.4.7 Effects of cracks and soil penetration resistance on root distribution

In general, crack parameters (width, length density, depth, cross-sectional area and volume) had negative effects on the dry root weight and total root length at bud formation but not at flowering; the single exception was an effect of crack depth at flowering on total root length (Table 6.5). Among the crack parameters, crack width and length area had the strongest relationships with root dry weight (r^2 = 0.72 and 0.73), while there was the greater influence of crack volume on TRL (r^2 = 0.54) at bud formation (Table 6.5). Soil penetration resistance was also negatively correlated with the root distribution of sunflower. Increasing soil penetration resistance significantly reduced the RDW and TRL at bud formation (Fig. 6.9A and 6.9B). At flowering, RDW was also decreased with increasing soil penetration resistance, but there was no relation with TRL (Fig. 6.9C and 6.9D).

Table 6.5. Significance of relationships of crack parameters to root dry weight and total root length at bud formation (average 0-60 cm) and flowering stage (average 0-80 cm soil depth)

Crack parameters	Total root dry weight at bud formation	Total root dry weight at flowering	Total root length at bud formation	Total root length at flowering
		P-values with r^2 values in brackets		
Width (W)	** (0.73)	NS	NS	NS
Length area (LA)	** (0.72)	NS	* (0.44)	NS
Depth (D)	** (0.68)	NS	* (0.48)	* (0.44)
Cross-sectional area (A)	** (0.67)	NS	* (0.47)	NS
Volume (V)	** (0.66)	NS	* (0.54)	NS

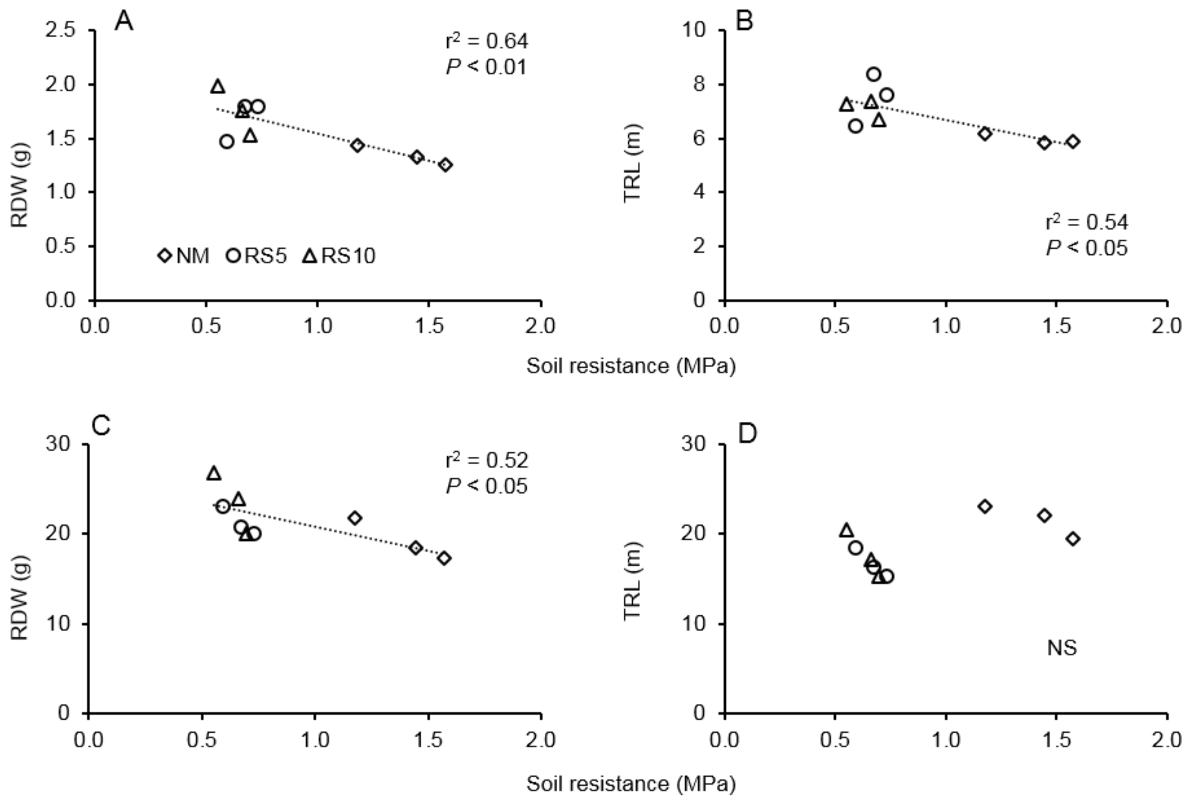

Fig. 6.9. Relationship between soil resistance and root parameters: (A) total root dry weight (B) total root length at bud formation, and (C) total root dry weight, (D total root length at flowering in 2018-19. NM = no-mulch, RS5 = rice straw ~ 5 t ha^{-1}, RS10 = rice straw ~ 10 t ha^{-1}; NS = non-significant.

6.5 Discussion

Roots are difficult to extract from clay soils in the field. As a result, relatively few field datasets exist for clay soils in which changes in rooting patterns due to subsoil constraints can be correlated with variation in crop grain yield. Fig. 6.10 summarises for the present study the key interactions between soil water, cracks and soil resistance, the production of roots and grain yield. This schematic 'roadmap' shows that while soil water content was significantly correlated with grain yield (r^2 = 0.32; $P < 0.01$), the mechanism through which this occurred may have been through the development of cracks (SWC against crack depth r^2 = 0.87; $P < 0.001$) which affected the formation of roots (crack width against total root weight at 0-60 cm r^2 = 0.73; $P < 0.01$). The r^2 of relationships between crack or root parameters and grain yield (0.75 and 0.52 respectively) were greater than the r^2 of the relationship between soil water content and yield.

In the present work, straw mulches decreased soil cracking, decreased soil penetration resistance and increased soil water content; these changes were associated with the increased formation of shallow roots (0-20 cm depth), and a 23% increase in the yield of sunflower. This discussion focuses on the effects of mulch and soil parameters on root distribution, the effects of mulch on crack development and soil penetration resistance, and the effects of mulch and soil parameters on yield.

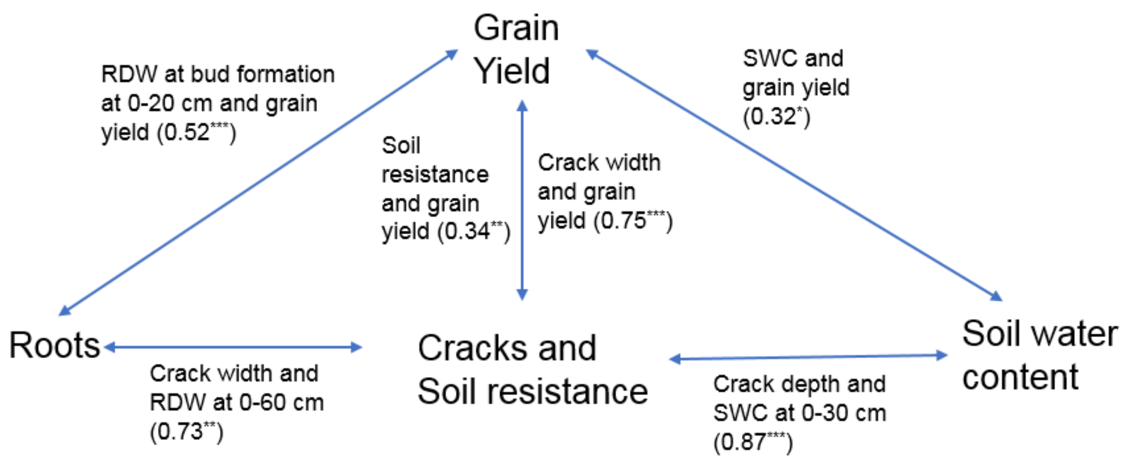

Fig. 6.10. Schematic diagram summarising the best relationships between the various factors studied in this paper. The brackets indicate the r^2 and significance of the simple linear regression between the two named variables.

6.5.1 Root distribution

Data presented in this paper show that sunflower roots on clay soil are distributed according to several principles: (a) root dry mass, root length and root length density are greater at 0-20 cm than at depths in the soil profile, and mulches can increase root dry mass at 0-20 cm which was related to increases grain yield, (b) roots can penetrate to considerable depths (to 80 cm) in this clayey, seasonally anaerobic soil, and (c) these effects occur despite or because of the presence of soil cracks and very high soil resistances.

Around 90-95 % of total sunflower root biomass and 70-80 % of total root length were concentrated in the 0-20 cm depth. Plant yield was most affected by total root dry mass at 0-20 cm depth at the bud formation stage ($r^2 = 0.52$; $P < 0.001$) (Table 3). The mulch treatments (RS5 and RS10) increased this root dry mass by 20-28 % compared to the NM treatment. Our unpublished results from this site with a range of planting dates in the previous year

(Supplementary Materials Section S2 and Fig. 6S2-4) suggest that these effects are reasonably typical. In this previous work, sunflower root growth was assessed over depth intervals of 0-10, 10-20, 20-40, 40-60 and 60-80 cm. THE highest RDW occurred at the 0-10 cm depth and rice straw mulch at 5 t ha^{-1} enhanced sunflower RDW by 13 – 83 %. Moreover, the percentage gain in RDW with mulch increased with the lateness of sowing (see appendix; Section 8.2 and Fig. 8.2).

At 58 and 90 DAS some roots were found at 40-80 cm depth; these were not a large proportion of total root weight (3 % of those at 0-20 cm depth), but they were substantially finer roots at 40-80 cm than the roots at 0-20 cm, which increased SRL at 40-80 cm depth (Fig. 6.3D and 6.4D). Indeed, the greater development of fine roots in non-mulched soil may suggest that the cracks aid in deeper penetration of sunflower roots. These fine roots with a high surface area to volume ratio may be functionally important for extracting nutrients and water from the deeper layers of clay-textured soil (Ostonen et al., 2007), but may also have been better equipped than thick roots to glean oxygen from this hypoxic soil environment. Overall, sunflower yield was best related to the shallow roots (0-20 cm) (Table 6.3). Similar root development associated with higher TRL in the no-mulch plots and higher SRL at 60-80 cm was also observed in our previously unpublished results on the same soil in the previous year (see appendix; Section 8.2 and Fig. 8.3 and 8.4).

In our study, root distribution down the soil profile was influenced by soil cracking and soil penetration resistance (Table 6.5 and Fig. 6.9). How is it that fine roots are able to grow to depths of 80 cm in this massive soil that is anaerobic immediately after the rice phase and presumably also anaerobic at depth in the rabi season? We wonder if the development of cracks as the soil dries provides an opportunity for roots to receive sufficient oxygen for metabolism from the soil adjacent to the crack void and if a low soil strength in the wet sub-soil allows root to elongate. Given this, we might expect that roots would be located in the soil close to the cracks within the massive tables of clay between the cracks.

Was there a plough pan in this soil that impeded root growth? Although we saw no direct evidence for the presence of a pan in the soil from measures of soil resistance, we wonder if this can be inferred from the root measurements. In 2018/19, the TRL and RLD in the non-mulched soil appeared to be restricted in the 20-40 cm layer compared to the deeper soil layers, whereas such a restriction was not evident in the mulched soil (Fig. 6.3). If anything, these effects were even stronger at 10-20 cm in the experiment of the previous years (appendix; Fig. 8.3).

One interesting feature of the current experiment was how late-season waterlogging affected root growth. Waterlogging due to heavy rainfall can change root distribution (Grzesiak et al., 2014). In the present work, after the heavy rain (175 mm) at flowering, adventitious roots were produced more abundantly at 0-20 cm on the no-mulch plot resulting in a higher TRL and RLD than in the mulched plots. Despite this adventitious root formation, RDW was still greater with the RS5 and RS10 treatments than the NM treatment at 0-20 cm. At bud formation and flowering, the NM treatment generated greater root length at 40-80 cm depth than RS5 and RS10 treatments. However, despite the greater abundance of fine roots at 40-80 cm in the no-mulch plots, they were not able to compensate for lower root growth in the 0-20 cm layer, possibly because the deeper roots formed too late in the growing season. Compared with the present work, there was higher TRL and SRL at depth 60-80 cm in the previous work (see appendix; Fig. 8.4 and 8.5). These higher values may have occurred because there was no waterlogging at flowering in the previous year.

Although root growth is negatively affected by compacted soil, there is good evidence that plants have adaptations to cope with increasing soil strength (Clark et al., 2003). In strong soil, the primary roots of plants can be thicker and shorter and taproots can be grown more rapidly than in normal soil (Goodman and Ennos, 1999; Tracy et al., 2011). However, lateral roots can be thinner which enables the tips to find cracks, void and smaller pores to penetrate through hard layers, including plough pans (Atwell, 1989; Croser et al., 1999; Goss, 1977). As the highest soil strength was at 0-7 cm and decreased to down the soil profile in the no-mulch plot, roots grew into the weaker sub-soil after exiting the surface layer of strong soil because of increasing the availability of soil water with depth. Beyond root distribution, soil compaction can also affect shoot biomass, leaf area, and stomatal conductance (and hence photosynthesis) (Masle et al., 1990; Tardieu et al., 1992; Tubeileh et al., 2003). In our study, the increased penetration resistance in clay soils without mulch had lower chlorophyll content and stomatal conductance, which may be attributed to the limited water supply from soil to the plant (see appendix; Section 8.1, Fig. 8.1). This again suggests that the greater abundance of deeper roots in the no-mulch plots were insufficient to offset the decrease in surface SWC and decreased root density in that layer.

6.5.2 Crack development and soil penetration resistance

In the current study, grain yield was most strongly affected by the presence of cracks and then by changes in soil resistance, and mulch impacted on both these. Furthermore, the use of mulch was more effective at suppressing crack formation than the use of irrigation; plots without mulch developed a substantial crack network even with two irrigation events but plots with rice straw mulch had decreased cracks using all the parameters we measured. The decrease in crack formation under rice straw mulch was associated with a higher content of surface soil water. A previous study conducted by Bandyopadhyay et al. (2003) for clay textured soil in India reported that crack depth, width, area, and volume increased with decreasing SWC at 0-15 cm soil depth. Another study at Los Banos, Philippines, reported that straw mulch at 5 t ha^{-1} in a fallow rice field reduced mean crack width by 32 % but did not reduce mean crack depth compared to the no-mulch plot (Cabangon and Tuong, 2000).

Soil resistance was another factor altered by mulches. In the absence of surface cover, no-tillage cultivation in clayey soils is problematic for soil structure and crop production (Paul et al., 2020a). Puddled clay soils with a high content of swell-shrink clay minerals become strong and compacted when dried. During the seedling stage at 22 DAS (28 December), there was a little difference in soil penetration resistance between mulched and no-mulch plots, and values were below 0.5 MPa and non-limiting to root growth. Soil penetration resistance was highest at the maximum vegetative stage at 55 DAS (30 January), when values exceeded 5 MPa in no-mulch plots but were 1 MPa in mulched plots at 0-7 cm. Although previous literature (Passioura, 2002) pointed out that root growth was slowed by soil resistance of 1 MPa and completely ceased at 5 MPa, the high values in the current study did not limit the RDW and TRL, presumably because before soil resistance was high tap roots were able to penetrate the compacted layer (0-20 cm) and had started development into the deeper soil profile at 40-60 cm.

Throughout the season, the average resistance of soil to penetration was 67 % lower with the RS5 and RS10 treatments than with the NM treatment. The cause of the higher soil penetration resistance with the NM treatment was mainly related to decreased soil water content (Fig. 6.8). In line with the current study, several previous studies have reported that using mulch on bare soil can reduce soil resistance by enhancing soil water holding capacity, increasing soil porosity and improving microbial activities (Jourgholami et al., 2019; Liu et al., 2018; So and Ringrose-Voase, 2000). In addition, mulch has been noted to improve the mineralization of soil organic carbon and nitrogen which leads to the stabilization of soil aggregates and the amelioration of soil compaction (García-Orenes et al., 2012; Jordán et al., 2010). Increasing the level of mulch from 5 t ha^{-1} to 10 t ha^{-1} and increasing the volume of irrigation water applied to above field capacity did not affect soil penetration resistance throughout the study period.

6.5.3 Sunflower growth and yield

In the present work, applying rice straw mulch on this poorly structured soil increased sunflower yield by around 23 % and increased seeds per head by 15 % compared to the no-mulch treatment. The higher yield and yield components under straw mulch were attributed to the decreased crack formation and lower soil resistance (associated with higher soil water content), which enhanced dry root weight and total root length. The variation of grain yield was highly correlated with crack width and RDW at 0-20 cm soil depth, and to a lesser extent soil resistance and SWC (Fig. 6.10). This yield improvement is of similar scale to other examples in the literature. At the same location, a previous study showed that straw mulch at ~5 t ha^{-1} boosted sunflower yield by 16-26 % relative to no-mulch (Paul et al., 2020b). Bunna et al. (2011) and So and Ringrose-Voase (2000) reported that using rice straw mulch at 1.5 t ha^{-1} and 5 t ha^{-1} in strongly compacted soil increased mungbean yield by 35 % and 30 % in Cambodia and Indonesia, respectively.

6.6 Conclusions

Soil shrinkage and crack development during drying of puddled clay soil were related to increasing soil penetration resistance and reduced root growth and development in the upper 20 cm of soil. In the present work, rice straw mulch at 5 t ha^{-1} increased soil water content while also reducing soil penetration resistance and cracking in the surface soil. Rice straw mulch significantly increased the dry root weight and total root length at 0-20 cm depth, but the total root length was higher at 60-80 cm depth under the no-mulch condition, which may be associated with the root penetration around wider and deeper soil cracks to greater soil depth. Improvement of soil quality and higher root biomass in 0-20 cm soil depth under rice straw mulch increased the sunflower yield by 23 %. No further benefits (for soil penetration resistance, cracking and sunflower growth and yield) were obtained by increasing mulch level from 5 to 10 t ha^{-1} or by increasing the volume of irrigation water. Thus, ameliorating soil physical constraints of these saline clay soils of the coastal zone of the Ganges Delta increased root growth at the 0-20 cm depth and consequently increased sunflower yield.

6.7 References

Adachi, T. (1990). Effects of rice-soil puddling on water percolation. *In* "Transactions of the 14th International Congress of Soil Science, Kyoto, Japan, August 1990.", pp. 146-151.

Atwell, B. (1989). Physiological responses of lupin roots to soil compaction. *In* "Structural and Functional Aspects of Transport in Roots," pp. 251-255. Springer.

Bandyopadhyay, K., Mohanty, M., Painuli, D., Misra, A., Hati, K., Mandal, K., Ghosh, P., Chaudhary, R., and Acharya, C. (2003). Influence of tillage practices and nutrient management on crack parameters in a Vertisol of central India. *Soil Tillage Res.* **71**, 133-142.

Bayhan, Y., Kayisoglu, B., and Gonulol, E. (2002). Effect of soil compaction on sunflower growth. *Soil Tillage Res.* **68**, 31-38.

Bunna, S., Sinath, P., Makara, O., Mitchell, J., and Fukai, S. (2011). Effects of straw mulch on mungbean yield in rice fields with strongly compacted soils. *Field Crops Res.* **124**, 295-301.

Cabangon, R. J., and Tuong, T. P. (2000). Management of cracked soils for water saving during land preparation for rice cultivation. *Soil Tillage Res.* **56**, 105-116.

Cambi, M., Mariotti, B., Fabiano, F., Maltoni, A., Tani, A., Foderi, C., Laschi, A., and Marchi, E. (2018). Early response of Quercus robur seedlings to soil compaction following germination. *Land Degrad. Dev.* **29**, 916-925.

Clark, L. J., Whalley, W. R., and Barraclough, P. B. (2003). How do roots penetrate strong soil? *Plant Soil.* **255**, 93-104.

Cook, S., Gupta, S. C., Woodhead, T., and Larson, W. (1995). Soil physical constraints to establishment of mungbeans (Vigna radiata L. Wilczek) in paddy rice (Oryza sativa L.) soils. *Soil Tillage Res.* **33**, 47-64.

Croser, C., Bengough, A. G., and Pritchard, J. (1999). The effect of mechanical impedance on root growth in pea (Pisum sativum). I. Rates of cell flux, mitosis, and strain during recovery. *Physiol. Plant.* **107**, 277-286.

Fang, S., Xie, B., Liu, D., and Liu, J. (2011). Effects of mulching materials on nitrogen mineralization, nitrogen availability and poplar growth on degraded agricultural soil. *New Forest.* **41**, 147-162.

García-Orenes, F., Roldán, A., Mataix-Solera, J., Cerdà, A., Campoy, M., Arcenegui, V., and Caravaca, F. (2012). Soil structural stability and erosion rates influenced by agricultural management practices in a semi-arid Mediterranean agro-ecosystem. *Soil Use Manage.* **28**, 571-579.

Goodman, A., and Ennos, A. (1999). The effects of soil bulk density on the morphology and anchorage mechanics of the root systems of sunflower and maize. *Ann. Bot.* **83**, 293-302.

Goss, M. (1977). Effects of mechanical impedance on root growth in barley (Hordeum vulgare L.) I. Effects on the elongation and branching of seminal root axes. *J. Exp. Bot.* **28**, 96-111.

Grzesiak, M. T., Ostrowska, A., Hura, K., Rut, G., Janowiak, F., Rzepka, A., Hura, T., and Grzesiak, S. (2014). Interspecific differences in root architecture among maize and triticale genotypes grown under drought, waterlogging and soil compaction. *Acta Physiol. Plant* **36**, 3249-3261.

Hasegawa, S., Thangaraj, M., and O'Toole, J. (1985). Root behavior: field and laboratory studies for rice and nonrice crops. *Soil physics and rice*, 383-395.

Jordán, A., Zavala, L. M., and Gil, J. (2010). Effects of mulching on soil physical properties and runoff under semi-arid conditions in southern Spain. *Catena* **81**, 77-85.

Jourgholami, M., Fathi, K., and Labelle, E. R. (2019). Effects of litter and straw mulch amendments on compacted soil properties and Caucasian alder (Alnus subcordata) growth. *New Forests*.

Jourgholami, M., Nasirian, A., and Labelle, E. (2018). Ecological restoration of compacted soil following the application of different leaf litter mulches on the skid trail over a five-year period. *Sustainability* **10**, 2148.

Kirchhof, G., So, H., Adisarwanto, T., Utomo, W., Priyono, S., Prastowo, B., Basir, M., Lando, T., Dacanay, E., and Tan-Elicano, D. (2000). Growth and yield response of grain legumes to different soil management practices after rainfed lowland rice. *Soil Tillage Res.* **56**, 51-66.

Kozlowski, T. T. (1999). Soil Compaction and Growth of Woody Plants. *Scand. J. Forest Res.* **14**, 596-619.

Lal, R., and Latham, M. (1987). Management of soil compaction and soil-water after forest clearing in upland soils of humic tropical Asia. *Soil management under humid conditions in Asia and Pacific, Proceeding* **5**, 273-296.

Liu, T., Wang, B., Wang, R., Xiao, H., Yang, B., Cao, Q., and Cao, Y. (2018). Differentially improved soil microenvironment and seedling growth of Amorpha fruticosa by plastic, sand and straw mulching in a saline wasteland in northwest China. *Ecol. Eng.* **122**, 126-134.

Mahata, K., Sen, H., Pradhan, S., and Mandal, L. (1990). No-tillage and dry ploughing compared with puddling for wet-season rice on an alluvial sandy clay–loam in eastern India. *The J. Agric. Sci.* **114**, 79-86.

Masle, J., Farquhar, G., and Gifford, R. (1990). Growth and carbon economy of wheat seedlings as affected by soil resistance to penetration and ambient partial pressure of CO2. *Funct. Plant Biol.* **17**, 465-487.

Mitchell, J., Cheth, K., Seng, V., Lor, B., Ouk, M., and Fukai, S. (2013). Wet cultivation in lowland rice causing excess water problems for the subsequent non-rice crops in the Mekong region. *Field Crops Res.* **152**, 57-64.

Mondal, M., Saha, N., Ritu, S., Paul, P., Sharifullah, A., Humphreys, E., Tuong, T., and Rashid, M. (2015b). Optimum sowing window for boro cultivation in the coastal zone of Bangladesh. In:Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF), pp 449–476.

Mondal, M. K., Paul, P., Humphreys, E., Tuong, T., Ritu, S., Rashid, M., Humphreys, E., Buisson, M., Pukinskis, I., and Phillips, M. (2015a). Opportunities for cropping system intensification in the coastal zone of Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo. SriLanka: CGIAR Challenge Program on Water and Food (CPWF). pp. 449–476.

Moroke, T., Schwartz, R., Brown, K., and Juo, A. (2005). Soil water depletion and root distribution of three dryland crops. *Soil Sci. Soc. Am. J.* **69**, 197-205.

Moslehuddin, A. Z., Hussain, M. S., Saheed, S., and Egashira, K. (1999). Clay mineral distribution in correspondence with agroecological regions of bang adesh soils. *Clay Sci.* **11**, 83-94.

Mulumba, L. N., and Lal, R. (2008). Mulching effects on selected soil physical properties. *Soil Tillage Res.* **98**, 106-111.

Ostonen, I., Püttsepp, Ü., Biel, C., Alberton, O., Bakker, M. R., Lõhmus, K., Majdi, H., Metcalfe, D., Olsthoorn, A. F. M., Pronk, A., Vanguelova, E., Weih, M., and Brunner, I. (2007). Specific root length as an indicator of environmental change. *Plant Biosyst.*

141, 426-442.Passioura, J. B. (2002). Soil conditions and plant growth. *Plant Cell Environ.* **25**, 311-318.

Paul, P. L. C., Bell, R. W., Barrett-Lennard, E. G., and Kabir, E. (2020a). Variation in the yield of sunflower (Helianthus annuus L.) due to differing tillage systems is associated with variation in solute potential of the soil solution in a salt-affected coastal region of the Ganges Delta. *Soil Tillage Res.* **197**, 104489.

Paul, P. L. C., Bell, R. W., Barrett-Lennard, E. G., and Kabir, E. (2020b). Straw mulch and irrigation affect solute potential and sunflower yield in a heavy textured soil in the Ganges Delta *Agric. Water. Manage.* ***239***, 106211.

Ringrose-Voase, A. J., and Sanidad, W. B. (1996). A method for measuring the development of surface cracks in soils: application to crack development after lowland rice. *Geoderma.* **71**, 245-261.

So, H., and Ringrose-Voase, A. (2000). Management of clay soils for rainfed lowland rice-based cropping systems: an overview. *Soil Tillage Res.* **56**, 3-14.

So, H., and Woodhead, T. (1987). Alleviation of soil physical limits to productivity of legumes in Asia. *In* "ACIAR Proceedings," Vol. 18, pp. 112.

Tardieu, F., Zhang, J., Katerji, N., Bethenod, O., Palmer, S., and Davies, W. (1992). Xylem ABA controls the stomatal conductance of field-grown maize subjected to soil compaction or soil drying. *Plant Cell Environ.* **15**, 193-197.

Taylor, H., and Brar, G. (1991). Effect of soil compaction on root development. *Soil Tillage Res.* **19**, 111-119.

Tracy, S. R., Black, C. R., Roberts, J. A., and Mooney, S. J. (2011). Soil compaction: a review of past and present techniques for investigating effects on root growth. *J. Sci. Food Agric.* **91**, 1528-1537.

Tubeileh, A., Groleau-Renaud, V., Plantureux, S., and Guckert, A. (2003). Effect of soil compaction on photosynthesis and carbon partitioning within a maize–soil system. *Soil Tillage Res.* **71**, 151-161.

Tuong, T., Cabangon, R., and Wopereis, M. (1996). Quantifying flow processes during land soaking of cracked rice soils. *Soil Sci. Soc. Am. J.* **60**, 872-879.

Vance, W. (2013). Overcoming soil water constraints to chickpea yield in rainfed environments of Western Australia and Bangladesh. PhD Thesis, Murdcoh University, WA, Australia.

Varade, S. (1990). Establishment of non-rice crops in previously puddled soils. *In* "Transactions of the 14th International Congress of Soil Science, Kyoto, Japan, August 1990.", pp. 170-174.

Whitmore, A. P., and Whalley, W. R. (2009). Physical effects of soil drying on roots and crop growth. *J. Exp. Bot.* **60**, 2845-2857.

Wopereis, M., Bouma, J., Kropff, M., and Sanidad, W. (1994). Reducing bypass flow through a dry, cracked and previously puddled rice soil. *Soil Tillage Res.* **29**, 1-11.

Chapter 7

General Discussion and Conclusions

7 General discussion and conclusions

Rabi crop establishment in the low-lying coastal saline area of Bangladesh is hampered by excess soil moisture after harvest of the previous rice crop, which constraints timely soil preparation, while delays in sowing expose the crop later in the season to soil dryness, salinity, soil compaction and cracking and high temperatures. This thesis, therefore, examined agronomic practices (zero tillage through to full tillage; mulch, irrigation frequency, and time of sowing) to enhance the success of early dry season (rabi) crop establishment on wet soil and their implications for alleviating late season crop stresses. Early sowing of rabi crops (for example sunflower) to improve cropping system productivity in this area had been previously tested (Mondal et al., 2015), but these previous studies did not define the optimum sowing window nor the tillage techniques and agronomic management practices required to achieve success with early sowing, nor did they examine the dynamics of soil water and salinity in the soil profile throughout the growing season for rabi crops. In this present study with sunflower as a promising rabi crop for Southern Bangladesh, we identified when sunflower is best sown in the rabi season with a range of soil disturbance regimes (from zero tillage to full tillage), and the risk associated with early sowing. We also assessed the role of rice straw mulch in increasing soil water availability and water uptake by plants and overcoming physical constraints such as cracking and high soil strength.

A major contribution of this research is the identification of soil water solute potential as a significant driver of yield reduction of early-sown sunflower rather than soil salinity or soil water content alone. Furthermore, the effect of lower temperature (both minimum and maximum) during the growing season was identified as a factor enhancing sunflower yield with early sowing time compared to the conventional sowing. This chapter synthesizes and discusses these main themes of this thesis: the role of tillage in crop establishment on wet soils (section 7.1), the benefits of straw mulch in alleviating low solute potential in the upper root zone and the effects of soil strength and cracking on root growth and sunflower yield on the clays soils (section 7.2), and the trade-off with early sowing between increased waterlogging risk at establishment versus decreasing heat and crop water stress later in crop growth (section 7.3).

7.1 Sunflower establishment on wet soils: no-tillage versus reduced tillage

On wet-clay soil in the saline area of the Ganges delta, increasing mechanised soil disturbance (BP, SPST and DP) was more effective for achieving highest yields than mechanised minimum soil disturbance (ZT, NST and WST). This was due to improved soil water storage and decreased solute potential of the soil water (Chapter 3). By contrast, in later studies (Chapter 5) with the zero-tillage establishment by dibbling of seeds into wet soils, reliable crop establishment was achieved, leading to high seed yields. Variations in the response of crop establishment to soil disturbance levels caused by tillage techniques or zero-tillage may be related to soil water and oxygen levels around the seed: these in turn are affected by soil texture, soil structure, soil microtopography, local hydrology, crop residue levels and weather. On wet clay soils, soil disturbance by different means of mechanised tillage alters soil water, soil aeration, and soil strength around the seed, which directly influences germination and emergence (Guérif et al., 2001). However, substantial soil disturbance (for example, SPST, BP and DP) on the wet clay soils left a very cloddy seed bed, which actually slowed the initial emergence of sunflower due to poor seed-soil contact. Hence the more aggressive tillage for seedbed preparation might be better in terms of finer size of aggregates if the SWC is below field capacity. By contrast, ZT (zero tillage) was carried out by a furrow opener, which was pulled through the wet soil and opened a slot in the soil. The ST (strip tillage) produced soil disturbance in the seed furrow only, but the cultivated soil in the strip is often remoulded into clods rather than shattered into peds. In both ZT and ST systems, wet soil (gravimetric SWC varied from 32-35 %) was associated with wheel slip and high draft for the 2-wheel tractor. In addition, it caused visible compaction and smearing by the force of the furrow opener. In these tillage systems, the uncovered soil and smearing of the furrow wall accelerated drying of the smeared soil into a hard layer, which did not impede germination and emergence but restricted subsequent root growth and elongation, resulting in poor growth and development of crops.

The size of aggregates generated by different tillage systems depends on the surface soil water content. Tillage in moist soil (soil water content less than field capacity) can generate finer aggregates than in wet clay soil (Vance, 2013). The change of soil physical and chemical properties for rabi crop establishment in saline clay soil under different tillage systems needs to be examined. There have been many combinations of tillage systems in crop cultivation, but the selection of tillage type should be considered according to the local constraints (Guérif et al., 2001; Strudley et al., 2008). In wet soil, the furrow opener in zero tillage may achieve suitable seed-soil contact in the furrow floor and wall, so that there is enough water imbibed by the seed for seed germination and emergence, but at the same time without soil covering in the furrow soil water is prone to rapid vapour loss, which associated with rapid soil drying that generates a hard crust on the furrow base and walls. The strength of the crust can restrict root penetration and proliferation into the deeper soils (Minhas et al., 2020; Soane et al., 2012), and this seems to be a plausible explanation for the restricted sunflower growth under mechanised zero tillage and strip tillage planting (Chapter 3). Notwithstanding the discussion above, practicing mechanised zero or strip tillage in wet soil achieved an average sunflower yield of ~ 3 t ha^{-1} which was satisfactory and even higher than the late planting after 30 December (~ 2 t ha^{-1}) (Chapter 5). Hence provided the formation of the hard crust on the walls and base of the furrow can be avoided; for example, by mulching, there may still be merit in mechanised minimum tillage sowing on these wet soils.

Paradoxically, considering the poorer sunflower growth with mechanised zero tillage planting, no-tilled manual dibbling on wet soil was favourable for successful sunflower establishment, growth and yield. The apparent explanation is presently only based on observations, which suggest lesser soil smearing and seed-zone resistance in a manual dibble vertical round hole (2-3 cm) by a wooden stick than with mechanised zero tillage. Moreover, the vertical hole in manual dibbling may maintain the underlying soil macro-porosity, which possibly enhances oxygen and water supply for the emergence of seedling shoots and roots. In clay-textured soil, manual dibbling was apparently less successful if SWC is <30-33 % (w/w) when increased soil strength was associated with lower emergence, plant density and yield (Chapter 5).

In this present study, SWC, $EC_{1:5}$ and SP were measured at depths 0-7, 7-15, 15-30, 30-45 and 45-60 cm at different growth stages under different tillage systems. With the progress of the dry season, mechanised minimum tillage resulted in large vertical void cracks, which accelerated water loss from the soil profile through evaporation. Therefore, the upper soil at 0-7 cm dried fast, and the SWC dropped below the wilting point earlier than with full tillage. The soil water holding capacity is governed by total porosity and pore size distribution that can be influenced by tillage. The soil shrinkage and compaction with minimum tillage also increased the bulk density, which can reduce the soil porosity and pore size distribution and hence reduced the amount of plant available water held in the soil (Klute, 1982). By contrast, the higher soil disturbance ruptured pore connections in capillary pores and loosened the soil near the surface, which may reduce unsaturated water flow to the surface, and thereby reducing evaporative losses of deeply stored soil water (Unger and Cassel, 1991). Soil loosening with intensive soil disturbance tends to enhance the total soil porosity and pore volume, which results in a lower bulk density and higher soil water content (Peña-Sancho et al., 2017).

The response of soil electrical conductivity to soil disturbance needs to be understood in the salt-affected clay-textured soil. In this study, $EC_{1:5}$ was measured up to 60 cm soil depth throughout the season. The $EC_{1:5}$ was affected by tillage practices, soil depth, irrigation and rainfall associated with wetting and drying cycles. Soil disturbance by tillage can minimise the upward movement of salt in pore water to the soil surface by reducing the rate of soil evaporation (Bakker et al., 2010). The complete surface soil disturbance was associated with a more pulverized soil that breaks the soil capillary pores. The disturbed soils act as a mulch, which minimizes the soil evaporation and decreases the upward movement of salt to the soil surface (Bakker et al., 2010). By contrast, increasing soil drying and cracking after mechanised minimum soil disturbance accelerated soil water loss through evaporation, and increased salt accumulation in the top soil (0-7 cm). Moreover, in the clay-textured soil, after rainfall and irrigation, water movement through cracks can promote lateral displacement of salts because of the effect of the horizontal component of infiltration (Lozano-García et al., 2011).

In the dryland saline environment, decreasing soil water and increasing soil salinity significantly affects plant growth and development. Plant water uptake in the field is determined by the soil matric and solute potential (Rengasamy, 2010). Salinity affects plants due to both the osmotic effect (water deficit) and excessive amounts of salt transport to the cells (ion toxicity) (Munns et al., 2006). In minimum tillage treatment (Chapter 3), increasing salt concentration in the soil solutions and decreasing soil water content decreased osmotic potential, which restricted plant growth and yield (c.f. (Rengasamy, 2010)). Whereas, the higher SWC and lower salinity under intensive soil disturbance maintained a higher SP during the growing season, which was associated with higher sunflower yield. Soil water can be made unavailable to plants if the soil $EC_{1:5}$ is 1.0 dS m^{-1} combined with the gravimetric soil water content of 18 % for clay loam soil (Rengasamy, 2006). Plant response to salinity effect is usually measured by estimation of EC_e or $EC_{1:5}$ (Katerji et al., 2000; Maas and Hoffman, 1977).

However, in this current study, SP was better at explaining variation in sunflower yield to salt stress than $EC_{1:5}$ for early sown sunflower.

There are some limitations to the current study which require further investigation. Firstly, it lasted only two years, and no soil chemical analysis was carried out at the end of field experiments to examine the chemical composition in the soil after tillage and mulch treatments. Measurement of leaf water potential, soil matric potential (with tensiometers) and plant Na^+ and Cl^- uptake data would have been useful to distinguish between osmotic and ion toxicity effects of salinity on sunflower. The extent to which low oxygen limits subsoil root growth, and the response of root growth to increased oxygen supply around the vertical cracks needs to be examined. Effects of soil penetration resistance, soil porosity, the variation of soil moisture characteristics at different suction values, and soil consistency limits have been inferred in the present study, but direct measurements of these properties are required to draw firm conclusions about their effects on root and shoot growth of sunflower. Finally, it is not clear whether the yield responses reported here are driven primarily by improved crop canopy performance (higher photosynthesis and leaf area, lower plant water potential and ionic composition) of by improved root growth which enhanced canopy growth.

7.2 Implications of rice straw mulch use to alleviate soil constraints

Mulching with different materials has been demonstrated to increase soil water, reduce soil salinity, and increase yield and productivity (Abd El-Mageed et al., 2016; Balwinder et al., 2011; Peng et al., 2015). These findings were consistent across varied mulching types, application methods, loads of mulch, soil texture and climatic condition, and hence were of interest as a treatment in the present study. I examined the effects of rice straw mulch at 5 and

10 t ha^{-1} under strip tillage planting and zero tilled dibbling on sunflower yield. The increases in yield associated with mulches were attributed to increased soil water and decreased salinity in the upper soil profile (0-15 cm), reduced soil penetration resistance and cracking, and increased root growth in clay-textured saline soil (Chapter 4 and 6). In the study area, poor soil structure due to annual wet puddling for wet season rice establishment, lack of rainfall and high irrigation water and soil salinity in the dry season are constraints for rabi crop cultivation. Therefore, the ability to store soil residual moisture in the soil profile after the wet season is crucial for later use by crops. In Chapter 3, we found that practicing minimum tillage in this poorly structured soil accelerated soil surface dryness, soil compaction, and inhibited sunflower growth and yield. In the present study (Chapter 4 and 6), rice straw mulch mitigated these limitations by improving soil water storage and diminishing soil salinity, soil strength, and cracking with led to greater crop root growth, water productivity and yield. Throughout the study period, rice straw mulch (RS) increased average SWC by 3-17 % and reduced $EC_{1:5}$ by 8-16 % within 0-60 cm soil depth. The combination of greater SWC and lower soil salinity under straw mulch increased the SP, which is a plausible explanation for the higher sunflower yield (16-26 % greater than with no-mulch). In previous studies, improved plant growth and yield with straw mulch was attributed to either increased soil water or decreased soil salinity (Bezborodov et al., 2010; Gajri et al., 1994; Haque et al., 2018), but this present study highlighted the impact of mulch on soil water SP which is a function of both soil water and soil salinity. Straw mulch also decreased the soil penetration resistance by ~ 67 % at 0-7 cm and decreased crack length density and volume by 57-70 % and 84-91 %, respectively, relative to no-mulch. The lower soil strength and crack density under straw mulch were associated with greater dry root weight and total root length at 0-40 cm depth (Chapter 6).

Application of rice straw mulch on the soil surface decreases the top-soil temperature by shading from the sun and acts as a barrier for evaporative loss of water and upward movement of saline pore water to the surface (Arora et al., 2011). The beneficial effect of straw mulch on soil water, salinity, and crop growth can vary with soil texture, soil disturbance, seasonal rainfall, irrigation regimes, and thickness of the mulch layer. Arora et al. (2011) have pointed that the response of soybean yield to mulching was greater on sandy loam with partial irrigation than with full irrigation but did not differ between irrigation regimes on loamy sand. Using mulch for ten years increased maize yield (4-36 %) in loamy sand, but that mulch reduced yield (-11 to 18 %) in sandy loam during some years because of variation in distribution and amount of rainfall (Gajri et al., 1994).

The weight or thickness of mulch, together with the rate of evaporation, determines the rate of soil surface drying (Tolk et al., 1999). However, Steiner (1989) suggested that mulch thickness or volume per unit basis is more critical than mass per unit area for controlling evaporation. Straw mulch at the rate of 4-6 t ha^{-1} was beneficial to improve soil physical conditions, reduce evaporation and improve crop yield (Arora et al., 2011; Bhattacharya et al., 2019; Cook et al., 2006; Peng et al., 2015). Straw mulch at < 2 t ha^{-1} or less than 30 % coverage of total surface area had less potential for reducing evaporation and increasing soil water storage (Erenstein, 2002; Unger, 1978), while Mulumba and Lal (2008) stated that the threshold level of straw mulch rate was 8 t ha^{-1} for silty loam soil because beyond this level available water capacity was not increased. In our study, rice straw mulch at 5 or 10 t ha^{-1} had the same effect on soil physical properties, root growth, and yield. Mulch on the soil surface has not always increased yield because of other factors such as nutrient availability, irrigation frequency, evaporative potential, soil texture and incidence of weeds, pests, and diseases (Erenstein, 2002; Tolk et al., 1999). In our study (Chapter 5), there was no difference in yield between rice straw mulch at 5 t ha^{-1} and 1 t ha^{-1} in the first year. The probable reason may be the similarity in available water between these two mulch treatments in that season. Mulch will have a major impact on water storage if soil water depletion is severe as in 2017-18. On the other hand, the mulch effect can be unfavourable when the land condition is excessively wet due to poor drainage or waterlogging (Erenstein, 2002; Lal et al., 1990). Other studies that reported yield reduction with high residue application attributed to low N fertility and cold and rainy weather (Unger, 1986; Wicks et al., 1994)

The use of straw mulch on the soil surface has been shown to ameliorate compacted and cracked soils. In the present study, soil under mulch had a substantial lower penetration resistance (0.25-1.76 MPa) and crack volume (0.0007 - 0.003 m^3 m^{-2}) compared to no-mulch plots (soil resistance; 0.25 - 3.7 MPa and crack volume: 0.005 -0.02 m^3 m^{-2}) (Fig. 6.4 and 6.6). The lower soil penetration resistance and crack density with straw mulch were attributed to a higher soil water content, reduced bulk density and greater infiltration (e.g. (Fang et al., 2011; Jourgholami et al., 2018; Mulumba and Lal, 2008).

Increased soil strength with decreasing soil water can restrict root elongation, root density and depth of rooting even at soil water matric potentials as high as -0.1 MPa (Mullins et al., 1992; Whiteley and Dexter, 1982). In field conditions, the response of root distributions to mechanical impedance may vary due to fluctuation of soil water, the presence of macro-porosity, and aeration, which also directly affects crop growth due to a reduction of water and nutrients supply (Cannell and Finney, 1973). In Chapter 3, increased soil disturbance in a heavy clay soil increased the root density and total root length at 0-20 cm, which resulted in higher grain yield. In dry compacted soil, intensive tillage loosens the compacted layer. It decreases the soil penetration resistance, which accelerates root penetration deeper into the sub-soil, thus improving water and nutrients uptake and grain yield (Ide et al., 1984; Oussible and Crookston, 1987; So and Ringrose-Voase, 2000).

The adoption of mulch technology for crop management across the world has had mixed results because of the variable availability of mulch material, including crop residues. In many tropical and semi-tropical areas, crop residues have values as animal fodder, fuel, construction materials, and domestic purposes (Erenstein, 1999; Unger et al., 1991). The use of crop residues for other beneficial purposes will limit the amount of residues for use as mulch in the field. Residue burning for land clearing, weed/pest management, and fertility improvement also diminish the availability of mulch. The success of mulch technology for crop production is related to local biophysical, socio-economic status, and cost-benefit over yield. Therefore, a comprehensive cost-benefit analysis of field mulching relative to alternative uses of crop residue is needed to ascertain the likely acceptance of this technology in the Ganges coastal zone.

7.3 Alleviation of waterlogging and heat stress- early rabi crop establishment

After harvest of the wet season rice, the traditional tillage system was not suitable for the timely establishment of rabi crops due to excess soil water: mechanised zero tillage was also unsuitable for wet soils. Hence, no-till dibbling was used to enable early planting on wet soils. In our study, sunflower was dibbled on 23 and 30 November in the first year, and 25 November in the second year on extremely wet soil (gravimetric soil water content was ~ 50 %), but there was 95-98 % sunflower seedling emergence. The high SWC was not limiting for germination and emergence. Indeed, even with mechanised ZT and ST planting on wet soil, the initial emergence was faster than with full tillage (Chapter 3). These finding seem to be a variance with other studies that suggest excess soil water at the establishment stage was more harmful than at other stages (Loose et al., 2017; Yasumoto et al., 2011). Early establishment of sunflower (23 and 30 November and 10 December) on wet soil (gravimetric soil water content was ~ 46-50 %) in the first season produced the highest yield (~ 3.5 - 4 t ha^{-1}), which was attributed to greater average surface SWC, lower average salinity, and higher average SP during the growing season. By contrast, in the second year, sunflowers sown on 25 November were presumably affected by waterlogging due to rainfall (59 mm) at the seedling stage, which drastically reduced the yield to about 2 t ha^{-1}. Even this yield would not have been possible unless the plots had been drained immediately after the rainfall. A sunflower yield of 2 t ha^{-1} in the waterlogged plots indicated that surface drainage had been effective in removing the excess water in the root zone and minimizing the severe damage of crops. Despite the waterlogging, the yield from 25 November sowing was still higher than the late planting on 25 January (1.3 t ha^{-1}). In many areas, waterlogging due to higher than normal rainfall causes a reduction of grain yield (Grassini et al., 2007). Many studies have reported the short-term effect of waterlogging on sunflower growth and yield. Yasumoto et al. (2011) have found that waterlogging at the early development stage of sunflower severely reduced the plant height, stem length, leaf number and root dry weight, which eventually caused a lower yield. Crop response to waterlogging may differ from soil physical properties. Waterlogging stress can be greater in heavy clay textured soil with poor drainage, while the duration of waterlogging may last longer than in lighter soils (Ponnamperuma, 1984). In Chapter 6, another waterlogging event was observed at the flowering stage when 175 mm rainfall flooded the plots (~ 25 cm standing water on the ground for more than 24 hours). The immediate action to remove standing water by pumping and surface drainage alleviated the most severe effect of waterlogging and secured around 2.6 - 3.2 t ha^{-1} of yield. However, lodging and wilting of some plants across the field were observed. When dried compacted soils become saturated due to rain or more water supply, the soil has a diminished shear strength, which results in root lodging (Baker et al., 1998; Manzur et al., 2014). In waterlogging conditions, sunflower cultivars can mitigate the effects by generating many adventitious roots, which contribute to resistance to root lodging, prevent shoot injury, and supply oxygen to root tips, thereby enhancing plant recover and survival (Jackson, 1955; Rogers et al., 1984; Vartapetian and Jackson, 1997). In our study (Chapter 6), after waterlogging, we found a clear difference in the distribution of roots between mulch and no-mulch plots. Although there was a higher root dry weight with mulch plots, no-mulch plots produced more adventitious roots, which increased total root length at 0-20 cm depth. The plausible reason for this difference is the increase of plant anchorage strength generated by the growth of secondary roots from the stem that helped to compensate for the loss of soil strength after flooding (inundated soil).

In Chapters 3 and 4, we showed that sunflower yields were highly correlated with the SP of soil solutions. However, in the time of sowing experiment (Chapter 5), there was less relationship of SP to yield, especially in the second year due to the variation of seasonal rainfall. Apart from the effect SP on sunflower yield, the significance of temperature stress on sunflower yield was more prominent in the time of sowing experiments. Many authors have reported that sunflower sown after the optimum time had depressed growth and yield because of the adverse effect of high temperature at critical growth stages (De La Vega and Hall, 2002; Dp and Ja, 1994; Unger, 1980). In our study, early plantings on 23 and 30 November and 10 December in the first year, and 25 November and 14 December in the second year, had completed the vegetative and flowering phases before the end of February when the maximum temperature was below 30 ^{0}C, but sowing after 14 December exposed sunflower to > 30 ^{0}C at flowering and grain filling stages. The increased temperature in the later sown crops shortened the reproductive period (bud formation to flowering) by 5-6 days compared to early sowing. Moreover, the effects of high temperature induced earlier physiological maturity by 5-9 days in the first year and 15-20 days in the second year, respectively, which may be related to lower yield with the later dates of sowing. In many temperate and subtropical areas, high temperatures at the sunflower reproductive stage, particularly after late sowings, decrease seed numbers, grain unit weight, and grain quality (Chimenti et al., 2001; Rondanini et al., 2003). The most favourable temperature for sunflower cultivation is 25-28 ^{0}C (GRDC, 2017). Previous studies have highlighted that temperatures ≥ 28-30 ^{0}C during anthesis have been associated with lower oil yield (Harris et al., 1978), > 34-35 ^{0}C at early grain filling reduced grain size and yield (Rondanini et al., 2006), and > 40 ^{0}C at anthesis was related to head blast, lower leaf area and yield (Rawson et al., 1984). Across all sowing dates, an increasing minimum temperature was also associated with decreased sunflower yield. Decreased grain yield with increasing minimum temperature accounted for 79 and 69 % of the variation in crop yield in the first and second year, respectively. Across the two-year study, the optimum sowing window for sunflower cultivation in the coastal saline areas of Bangladesh was between 20 November and 15 December based on potential yield (3-4 t ha^{-1}); this provided an opportunity to maximise the use of soil water in the early season, while avoiding salinity and heat stress during the later part of the growing season. However, waterlogging from pre-monsoon rain is a significant risk that can depress establishment and early plant growth unless highly effective drainage has been installed.

7.4 Conclusions

Establishment of rabi crops by employing mechanised zero tillage or strip tillage in wet-clay soil in the salt-affected coastal zone of Bangladesh caused soil smearing planes beside and below the seed, which dried quickly, hardened and limited root growth and development. Subsequently, zero tillage and minimum soil disturbance with strip tillage increased soil dryness and salinity, bulk density and decreased the SP in soil surface layers, which were associated with a lower yield. By contrast, sunflower establishment by increased soil disturbance (BP, SPST and DP) had greater root elongation and density due to a lower bulk density. Moreover, increased soil disturbance had increased soil water availability and reduced soil salinity in the surface layers at 0-15 cm. The soil under this highest disturbance also had a greater SP. However, mechanised tillage delays sowing on wet clay soils.

Rice straw mulch at 5 t ha^{-1} in strip tillage planting increased in sunflower yield due to an increased SP of soil solutions associated with increased soil water content and reduced soil salinity at 0-15 cm depth. The benefits of straw mulch for yield were obtained with three, two or one irrigation events. In compacted and cracked soil, straw mulch cover on the soil surface was the best management option to improve soil physical and chemical constraints. Straw mulch reduced the soil penetration resistance by 67 % (1.22 MPa) relative to no-mulch plots (3.69 MPa) at 0-7 cm. In the case of crack volume, the reduction was 84-91 % with straw mulch relative to no-mulch. Using straw mulch, no-tilled dibbled sunflower had significantly enhanced root dry weight, total root length and root length density in surface soil to 20 cm depth. While there was higher total root length down the soil at 40-80 cm under no-mulch treatment. The improved soil quality and root biomass with straw mulch led to higher grain yield. However, increasing mulch levels from 5 t ha^{-1} to 10 t ha^{-1} caused no further decrease in soil resistance, cracking, or increase in sunflower growth and yield.

The no-till dibbled crop establishment method for sunflower on wet soil allowed early sowing. Early sowing affords the opportunity to use residual soil moisture up to the flowering stage while avoiding increasing salinity hazard and temperature stress at the flowering and grain filling stage, thus producing maximum yield. Based on better plant growth, development and potential yield (3-4 t ha^{-1}), the optimum sowing window for sunflower was between 20 November and 15 December, which was also associated with higher SWC, lower soil salinity, greater SP and lower temperatures at flowering. However, this early planting increases the risk of waterlogging stress and needs proper drainage to be successful. Overall, soil and crop management practices, including no-tilled dibbling and rice straw mulch facilitated early sowing and enhanced yield because of increased soil water availability in the upper root zone, particularly by improving the SP of soil solutions and alleviating soil physical constraints. On the other hand, sunflower establishment by mechanized tillage systems that increased soil disturbance was effective in enhancing soil conditions and crop growth and yield, but they necessarily delayed crop establishment.

Based on the above findings, the following priorities are proposed for future research to enhance cropping systems intensification in the Ganges coastal zone:

1. The positive effect of soil disturbance and straw mulch on crop yield were attributed to soil evaporation, but direct evidence of reduced evaporation is lacking. Moreover, there is an opportunity to determine how soil disturbance and mulch change the optimum irrigation requirements for sunflower on clay soils with a shallow groundwater table.
2. To improve the soil physical and chemical properties in the salt-affected Ganges delta, other mulching materials such as compost, cow manure, charcoal and green manure (*Sesbania bispinosa*) between the transition period of the rabi crop and the wet season rice can be tested.
3. A range of other promising rabi crop such as maize, barley, potato and wheat should be assessed to confirm the effects of mechanized minimum and reduced tillage, dibbling and mulching over a wider range of soils in the Ganges delta.
4. It is important to understand the role of oxygen supply to roots in understanding plant responses to soil disturbance, cracking, mulch, salinity, waterlogging etc.
5. Long term weather data can be analysed (rainfall, temperature, radiation and day length hour) to confirm the optimum sowing window for crop yield and soil water balance and identify the risks of crop failure with the early sowing.
6. APSIM and DSSAT models can be calibrated and validated to simulate the optimum date of crop sowing for yield, and to predict the risk of climate variability, climate change, spatial variability of soil types and salinity, suitable genotype, and management options for sustainable agricultural production in the salt-affected Ganges delta.

7. Salt and waterlogging-stress tolerant, short to medium growth duration and low irrigation requirement cultivars might be tested in the salt-affected Ganges delta as an adaptive management strategy to minimize the crop damage and yield loss.

7.5 References

Abd El-Mageed, T. A., Semida, W. M., and Abd El-Wahed, M. H. (2016). Effect of mulching on plant water status, soil salinity and yield of squash under summer-fall deficit irrigation in salt affected soil. *Agric. Water Manage.* **173**, 1-12.

Arora, V. K., Singh, C. B., Sidhu, A. S., and Thind, S. S. (2011). Irrigation, tillage and mulching effects on soybean yield and water productivity in relation to soil texture. *Agric. Water Manage.* **98**, 563-568.

Baker, C., Berry, P., Spink, J., Sylvester-Bradley, R., Griffin, J., Scott, R., and Clare, R. (1998). A method for the assessment of the risk of wheat lodging. *J. Theor. Biol.* **194**, 587-603.

Bakker, D. M., Hamilton, G. J., Hetherington, R., and Spann, C. (2010). Salinity dynamics and the potential for improvement of waterlogged and saline land in a Mediterranean climate using permanent raised beds. *Soil Tillage Res.* **110**, 8-24.

Balwinder, S., Eberbach, P. L., Humphreys, E., and Kukal, S. S. (2011). The effect of rice straw mulch on evapotranspiration, transpiration and soil evaporation of irrigated wheat in Punjab, India. *Agric. Water Manage.* **98**, 1847-1855.

Bezborodov, G. A., Shadmanov, D. K., Mirhashimov, R. T., Yuldashev, T., Qureshi, A. S., Noble, A. D., and Qadir, M. (2010). Mulching and water quality effects on soil salinity and sodicity dynamics and cotton productivity in Central Asia. *Agric. Ecosyst. Environ.* **138**, 95-102.

Bhattacharya, J., Saha, N. K., Mondal, M. K., Bhandari, H., and Humphreys, E. (2019). The feasibility of high yielding aus-aman-rabi cropping systems in the polders of the low salinity coastal zone of Bangladesh. *Field Crops Res.* **234**, 33-46.

Cannell, R., and Finney, J. (1973). Effects of direct drilling and reduced cultivation on soil conditions for root growth. *Outlook Agr.* **7**, 184-189.

Chimenti, C. A., Hall, A. J., and Sol López, M. (2001). Embryo-growth rate and duration in sunflower as affected by temperature. *Field Crops Res.* **69**, 81-88.

Cook, H. F., Valdes, G. S., and Lee, H. C. (2006). Mulch effects on rainfall interception, soil physical characteristics and temperature under Zea mays L. *Soil Tillage Res.* **91**, 227-235.

De La Vega, A. J., and Hall, A. J. (2002). Effects of planting date, genotype, and their interactions on sunflower yield: I. Determinants of oil-corrected grain yield. *Crop Sci.* **42**, 1191-1201.

Dp, H., and Ja, T. (1994). Effect of sowing time on growth, yield, and oil characteristics of irrigated sunflower in southern New South Wales. *Aust. J. Exp. Agr.* **34**, 255.

Erenstein, O. (2002). Crop residue mulching in tropical and semi-tropical countries: An evaluation of residue availability and other technological implications. *Soil Tillage Res.* **67**, 115-133.

Erenstein, O. C. (1999). "The economics of soil conservation in developing countries: The Case of Crop Residue Mulching. S.n."

Fang, S., Xie, B., Liu, D., and Liu, J. (2011). Effects of mulching materials on nitrogen mineralization, nitrogen availability and poplar growth on degraded agricultural soil. *New Forests* **41**, 147-162.

Gajri, P., Arora, V., and Chaudhary, M. (1994). Maize growth responses to deep tillage, straw mulching and farmyard manure in coarse textured soils of NW India. *Soil Use Manage.* **10**, 15-19.

Grassini, P., Indaco, G. V., Pereira, M. L., Hall, A. J., and Trápani, N. (2007). Responses to short-term waterlogging during grain filling in sunflower. *Field Crops Res.* **101**, 352-363.

GRDC (2017). Sunflower: Plant growth and physiology. *Grains Research and Development Corporation, Northern, Western Australia, Australia*.

Guérif, J., Richard, G., Dürr, C., Machet, J. M., Recous, S., and Roger-Estrade, J. (2001). A review of tillage effects on crop residue management, seedbed conditions and seedling establishment. *Soil Tillage Res.* **61**, 13-32.

Haque, M. A., Jahiruddin, M., and Clarke, D. (2018). Effect of plastic mulch on crop yield and land degradation in south coastal saline soils of Bangladesh. *Int. Soil Water Conserv. Res.* **6**, 317-324.

Harris, H. C., McWilliam, J., and Mason, W. (1978). Influence of temperature on oil content and composition of sunflower seed. *Aust. J. Agric. Res.* **29**, 1203-1212.

Ide, G., Hofman, G., Ossemerct, C., and Van Ruymbeke, M. (1984). Root-growth response of winter barley to subsoiling. *Soil Tillage Res.* **4**, 419-431.

Jackson, W. T. (1955). The role of adventitious roots in recovery of shoots following flooding of the original root systems. *Am. J. Bot.*, 816-819.

Jourgholami, M., Nasirian, A., and Labelle, E. (2018). Ecological restoration of compacted soil following the application of different leaf litter mulches on the skid trail over a five-year period. *Sustainability* **10**, 2148.

Katerji, N., Van Hoorn, J., Hamdy, A., and Mastrorilli, M. (2000). Salt tolerance classification of crops according to soil salinity and to water stress day index. *Agric. Water Manage.* **43**, 99-109.

Klute, A. (1982). Tillage effects on the hydraulic properties of soil: A review. In P. W. Unger D. M. Van Doren Jr. F. D. Whisler E. L. *Skidmore,Predicting tillage effects on soil physical properties and processes* (pp 29-43). ASA Special Publications.

Lal, R., Eckert, D., Fausey, N., and Edwards, W. (1990). Conservation tillage in sustainable agriculture. *Sustainable Agricultural Systems.*, 203-225.

Loose, L. H., Heldwein, A. B., Lucas, D. D., Hinnah, F. D., and Bortoluzzi, M. P. (2017). Sunflower emergence and initial growth in soil with water excess. *Eng. Agricola.* **37**, 644-655.

Lozano-García, B., Parras-Alcántara, L., and Muriel-Fernández, J. L. (2011). Soil tillage effects on monovalent cations (Na + and K +) in vertisols soil solution. *Catena* **84**, 61-69.

Maas, E. V., and Hoffman, G. J. (1977). Crop salt tolerance–current assessment. *J. Irrig. Drain. Div.* **103**, 115-134.

Manzur, M., Hall, A., and Chimenti, C. (2014). Root lodging tolerance in Helianthus annuus (L.): associations with morphological and mechanical attributes of roots. *Plant Soil* **381**, 71-83.

Minhas, P., Ramos, T. B., Ben-Gal, A., and Pereira, L. S. (2020). Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues. *Agric. Water Manage.* **227**, 105832.

Mondal, M. K., Paul, P., Humphreys, E., Tuong, T., Ritu, S., Rashid, M., Humphreys, E., Buisson, M., Pukinskis, I., and Phillips, M. (2015). Opportunities for cropping system intensification in the coastal zone of Bangladesh. In: Humphreys, E., Tuong, T.P., Buisson, Marie-Charlotte, Pukinskis, I., Phillips, M. (Eds.), Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015. Colombo. SriLanka: CGIAR Challenge Program on Water and Food (CPWF). pp. 449–476.

Mullins, C., Blackwell, P., and Tisdall, J. (1992). Strength development during drying of a cultivated, flood-irrigated hardsetting soil. I. Comparison with a structurally stable soil. *Soil Tillage Res.* **25**, 113-128.

Mulumba, L. N., and Lal, R. (2008). Mulching effects on selected soil physical properties. *Soil Tillage Res.* **98**, 106-111.

Munns, R., James, R. A., and Läuchli, A. (2006). Approaches to increasing the salt tolerance of wheat and other cereals. *J. Exp. Bot.* **57**, 1025-1043.

Oussible, M., and Crookston, R. K. (1987). Effect of Subsoiling a Compacted Clay Loam Soil on Growth, Yield, and Yield Components of Wheat 1. *Agron. J.* **79**, 882-886.

Peña-Sancho, C., López, M., Gracia, R., and Moret-Fernández, D. (2017). Effects of tillage on the soil water retention curve during a fallow period of a semiarid dryland. *Soil Res.* **55**, 114-123.

Peng, Z., Ting, W., Haixia, W., Min, W., Xiangping, M., Siwei, M., Rui, Z., Zhikuan, J., and Qingfang, H. (2015). Effects of straw mulch on soil water and winter wheat production in dryland farming. *Sci. Rep.* **5**, 10725.

Ponnamperuma, F. N. (1984). Effects of flooding on soils. *In:* Kozlowski, T. T. (ed.) *Flooding and plant growth.* San Diego: Academic Press.

Rawson, H., Dunstone, R., Long, M., and Begg, J. (1984). Canopy development, light interception and seed production in sunflower as influenced by temperature and radiation. *Funct. Plant Biol.* **11**, 255-265.

Rengasamy, P. (2006). World salinization with emphasis on Australia. *J. Exp. Bot.* **57**, 1017-1023.

Rengasamy, P. (2010). Soil processes affecting crop production in salt-affected soils. *Funct. Plant Biol.* **37**, 613-620.

Rogers, C., Unger, P., and Kreitner, G. (1984). Adventitious Rooting in 'Hopi' Sunflower: Function and Anatomy 1. *Agron. J.* **76**, 429-434.

Rondanini, D., Mantese, A., Savin, R., and Hall, A. J. (2006). Responses of sunflower yield and grain quality to alternating day/night high temperature regimes during grain filling:

effects of timing, duration and intensity of exposure to stress. *Field Crops Res.* **96**, 48-62.

Rondanini, D., Savin, R., and Hall, A. J. (2003). Dynamics of fruit growth and oil quality of sunflower (Helianthus annuus L.) exposed to brief intervals of high temperature during grain filling. *Field Crops Res.* **83**, 79-90.

So, H., and Ringrose-Voase, A. (2000). Management of clay soils for rainfed lowland rice-based cropping systems: an overview. *Soil Tillage Res.* **56**, 3-14.

Soane, B. D., Ball, B. C., Arvidsson, J., Basch, G., Moreno, F., and Roger-Estrade, J. (2012). No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil Tillage Res.* **118**, 66-87.

Steiner, J. (1989). Tillage and surface residue effects on evaporation from soils. *Soil Sci. Soc. Am. J.* **53**, 911-916.

Strudley, M. W., Green, T. R., and Ascough II, J. C. (2008). Tillage effects on soil hydraulic properties in space and time: State of the science. *Soil Tillage Res.* **99**, 4-48.

Tolk, J. A., Howell, T. A., and Evett, S. R. (1999). Effect of mulch, irrigation, and soil type on water use and yield of maize. *Soil Tillage Res.* **50**, 137-147.

Unger, P., Stewart, B., Parr, J., and Singh, R. (1991). Crop residue management and tillage methods for conserving soil and water in semi-arid regions. *Soil Tillage Res.* **20**, 219-240.

Unger, P. W. (1978). Straw-mulch Rate Effect on Soil Water Storage and Sorghum Yield 1. *Soil Sci. Soc. Am. J.* **42**, 486-491.

Unger, P. W. (1980). Planting Date Effects on Growth, Yield, and Oil of Irrigated Sunflower1. J. *Agron.* **72**, 914-916.

Unger, P. W. (1986). Wheat Residue Management Effects on Soil Water Storage and Corn Production 1. *Soil Sci. Soc. Am. J.* **50**, 764-770.

Unger, P. W., and Cassel, D. K. (1991). Tillage implement disturbance effects on soil properties related to soil and water conservation: a literature review. *Soil Tillage Res.* **19**, 363-382.

Vance, W. (2013). Overcoming soil water constraints to chickpea yield in rainfed environments of Western Australia and Bangladesh. PhD Thesis, Murdcoh University, WA, Australia.

Vartapetian, B. B., and Jackson, M. B. (1997). Plant adaptations to anaerobic stress. *Ann. Bot.* **79**, 3-20.

Whiteley, G., and Dexter, A. (1982). Root development and growth of oilseed, wheat and pea crops on tilled and non-tilled soil. *Soil Tillage Res.* **2**, 379-393.

Wicks, G. A., Crutchfield, D. A., and Burnside, O. C. (1994). Influence of wheat (Triticum aestivum) straw mulch and metolachlor on corn (Zea mays) growth and yield. *Weed Sci.* **42**, 141-147.

Yasumoto, S., Terakado, Y., Matsuzaki, M., and Okada, K. (2011). Effects of high water table and short-term flooding on growth, yield, and seed quality of sunflower. *Plant Prod. Sci.* **14**, 233-248.

8 Appendices

(Note: Root data was also collected in Chapter 3 and 5 which are attached below)

Section 8.1: Leaf chlorophyll content and stomatal conductance

Mulch had significant effects on chlorophyll content and stomatal conductance and there was a significant interaction between mulch and time on chlorophyll content but no interaction between mulch and time on stomatal conductance (Fig. 8.1). There was higher chlorophyll content with M2 and M3 treatments at the first two samplings on 18 Feb and 24 Feb (before flowering) than with M1 treatments, but afterward, there was no difference among mulch treatments (Fig. 8.1A). Throughout the sampling times, the average stomatal conductance was higher under M2 (712 mmol m^{-2} s^{-1}) and M3 (720 mmol m^{-2} s^{-1}) treatments than with M1 (656 mmol m^{-2} s^{-1}) treatment (Fig. 8.1B). Irrigation treatments did not affect chlorophyll content and stomatal conductance.

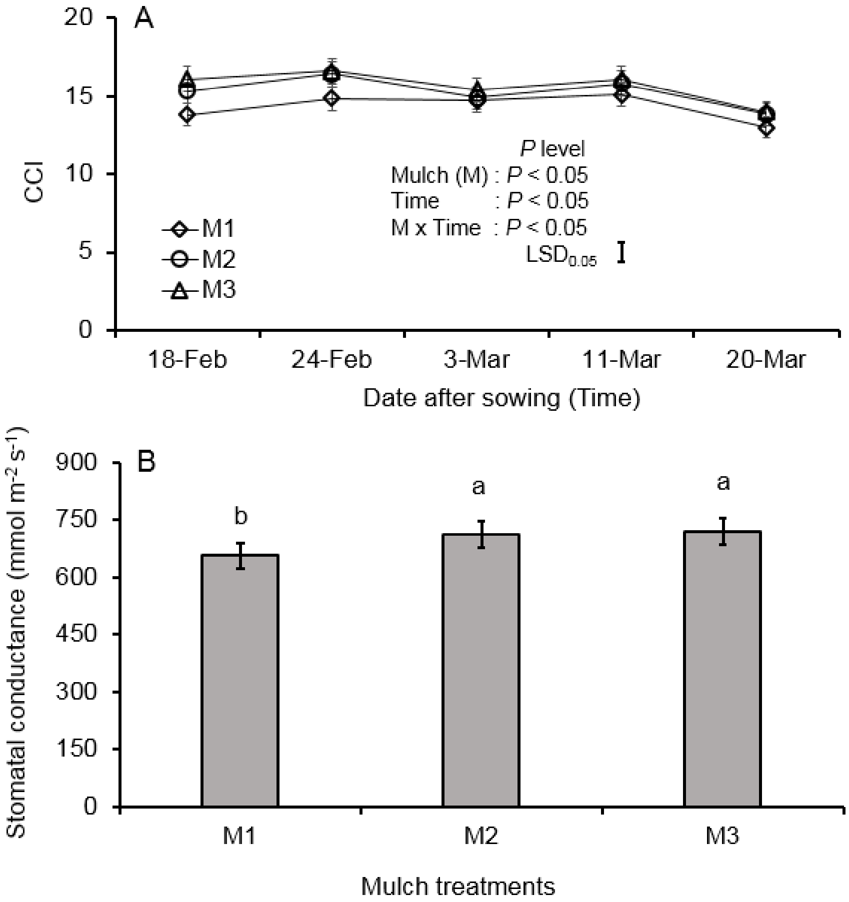

Fig. 8.1. Effect of mulch on: (A) chlorophyll content (CCI), (B) stomatal conductance. $LSD_{0.05}$ is the least significant difference of the interaction between mulch and time on CCI (A). Means with identical letters are not significantly different (B). M1 = no-mulch, M2 = rice straw ~ 5 t ha^{-1}, M3 = rice straw ~ 10 t ha^{-1}.

Section 8.2. Root measurements in different tillage systems and sowing dates

In the experiment of different tillage treatment (NST: narrow strip tillage, WST: wide strip tillage, BP: bed planting and SPST: single pass shallow tillage) (Chapter 3) and in the date of sowing experiment (five sowing dates: 25 Nov, 14 Dec, 25 Dec, 10 Jan and 25 Jan) (Chapter 5), root distribution was observed at flowering in the 2017-18 season. In both experiments, one plant was selected from each treatment replication. Shoots were excised, and sunflower root distribution was then observed to a depth of 80 cm. First two blocks were excavated from 20 cm along the row, 20 cm across the row and 10 cm deep. Below this depth, the blocks were sampled from the same areas, first to 20 cm and then in 20 cm deep increments up to 80 cm. Dry root weight (DRW), total root length (TRL), root length density (RLD) were measured in the procedure followed in the Chapter 6.

In 2018 season, root dry weight (RDW), total root length (TRL), root length density (RLD) and specific root length (SRL) were measured under different tillage systems (NST: narrow strip tillage, WST: wide strip tillage, BP: bed planting and SPST: single pass shallow tillage). Each factor of root distributions was significantly ($P < 0.05$) affected by depth, tillage and the interaction between depth and tillage. Dry root weight in the four tillage treatments decreased significantly with soil depth (Fig. 8.2A). At 0-10 cm, the BP had significantly higher DRW than with the NST, WST and SPST treatments, but below this depth there were no effects of tillage treatments on DRW. Total root length in the BP treatment was higher than in the NST, WST, and SPST at 0-10 cm and 10-20 cm depth (Fig. 8.2B). However, at 60-80 cm, TRL in the NST and WST was significantly greater than the BP and SPST treatments (Fig. 8.2B). The TRL was lower in 10-20 cm and 20-40 cm than at 40-60 and 60-80 cm. Root length density was significantly higher in BP than NST, WST and SPST at 0-10 cm and 10-20 cm depths (Fig. 8.2C). The RLD increased more at 40-60 and 60-80 cm than at 20-40 cm. At depth 60-80 cm, RLD in NST and WST increased significantly compared to other tillage types (Fig. 8.2C). Specific root length increased remarkably with increasing soil depth (Fig. 8.2D). At 0-10 cm depth, there was no effect of tillage on SRL. Below this depth, SPST produced the maximum SRL among tillage treatments. However, at depth 40-60 cm and 60-80 cm, NST significantly improved the SRL over BP and SPST (Fig. 8.2D). By contrast, SRL in BP was significantly lower than other tillage types at 60-80 cm.

In the date of sowing experiment (five sowing dates: 25 Nov, 14 Dec, 25 Dec, 10 Jan and 25 Jan) in 2017-18 season, sunflower DRW, TRL and SRL were measured under two mulching treatments to depth 80 cm (Fig. 8.3 - 8.5). The DRW, TRL and SRL were significantly affected by sowing dates, mulch, soil depth and interaction between sowing, depth and mulch. The second sowing on 14 Dec had maximum DRW, and first and last sowing had minimum DRW at 0-10 cm (Fig. 8.3). In all times of sowing, the RS had significantly greater DRW than RR treatment at depth 0-10 cm, but below this depth, there were no effects of mulch on DRW. The tilled soil on last sowing (25 Jan) and second sowing on 24 Dec produced higher TRL than other sowings at 0-10 cm depth (Fig. 8.4). The TRL was higher at 0-10 cm and then decreased the following depth at 10-20 and 20-40 cm (Fig. 8.4). However, TRL increased in the last two depths at 40-60 cm and 60-80 cm under RR treatment except the last sowing. The SRL significantly increased with the increment of soil depths in all times of sowing (Fig. 8.5). At depth 0-10 and 10-20 cm, there was no effect of sowing or mulch on SRL, but below this depth, first sowing (25 Nov) showed the highest SRL at depth 60-80 cm than the other four sowings which may be affected by waterlogging stress. Between two mulching treatments, there was higher SRL with RS treatment than with RR in the first and second sowing, but opposite results showed in the last sowing where RR had higher SRL than the RS treatment (Fig. 8.5).

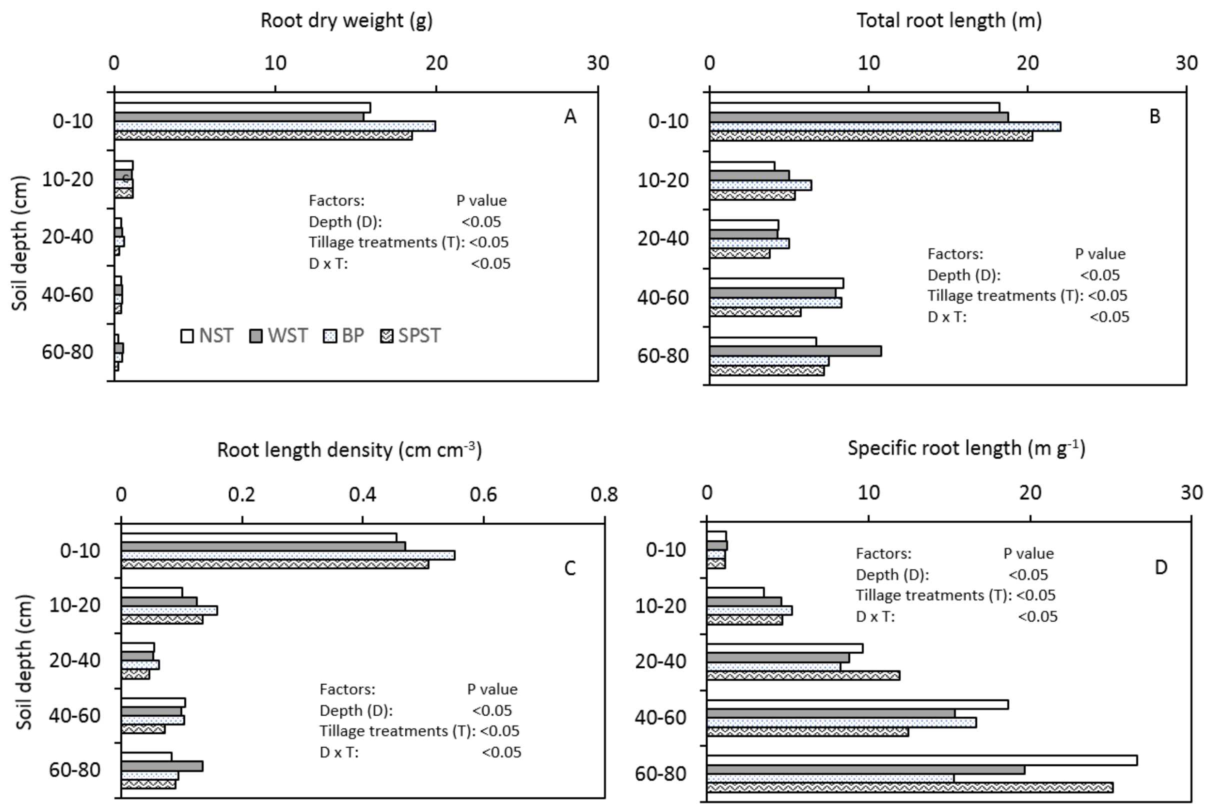

Fig. 8.2. Effects of tillage treatments on root parameters at different soil depths at flowering (80 DAS) in 2018: (A mean root dry weight (RDW), (B) total root length (TRL), (C) root length density (RLD), and (D) specific root length (SRL).

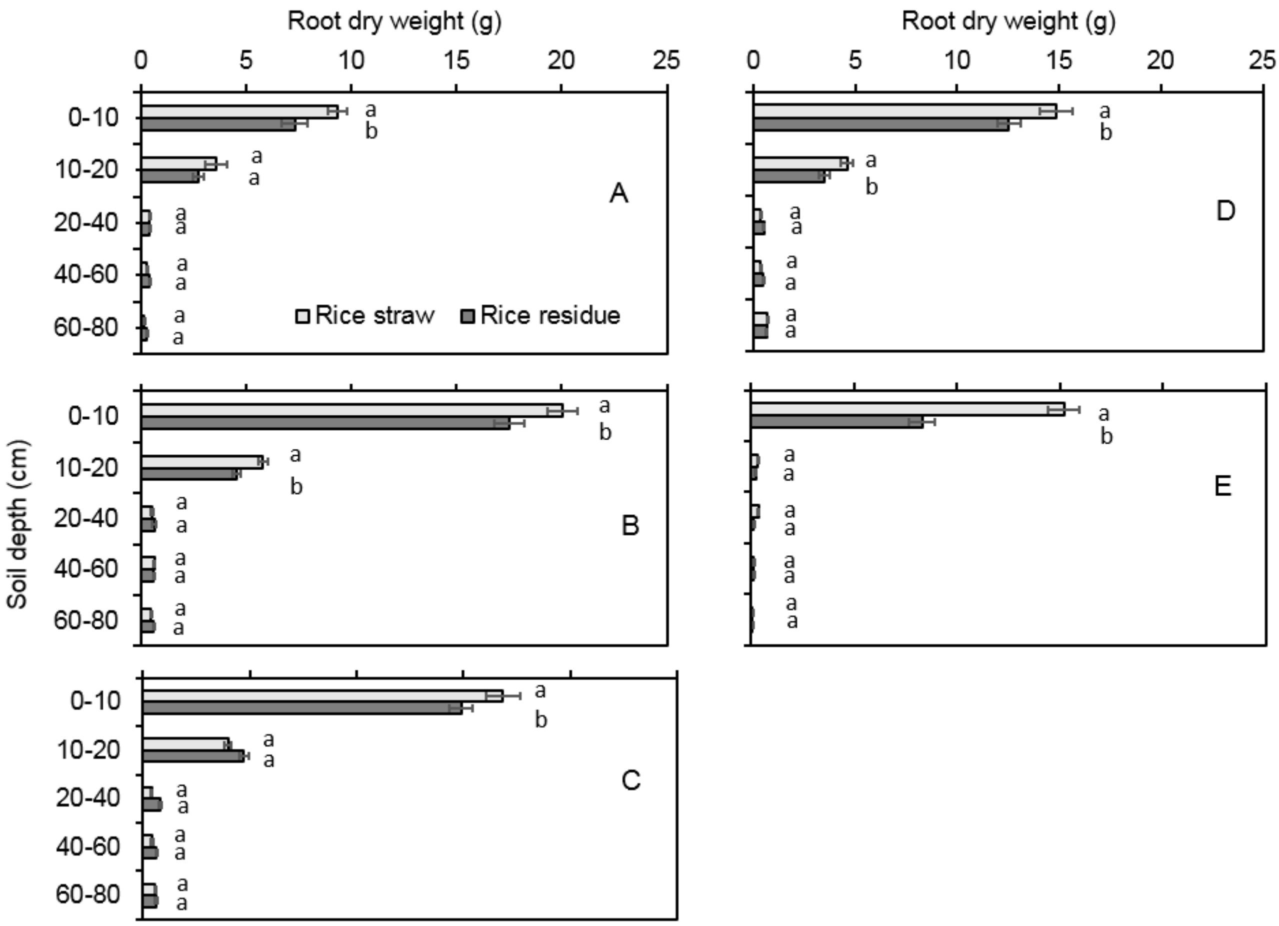

Fig. 8.3. Effects of sowing dates on root dry weight (RDW) at different soil depths at flowering (75 -85 DAS) under rice straw and rice residue treatments in 2017-18: (A) sowing 23 Nov, (B) sowing 14 Dec, (C) sowing 25 Dec, (D) sowing 10 Jan and (E) sowing 25 Jan in 2017-18. Vertical bars indicate standard error of the means. Same letters above the means are not significantly different at $P < 0.05$.

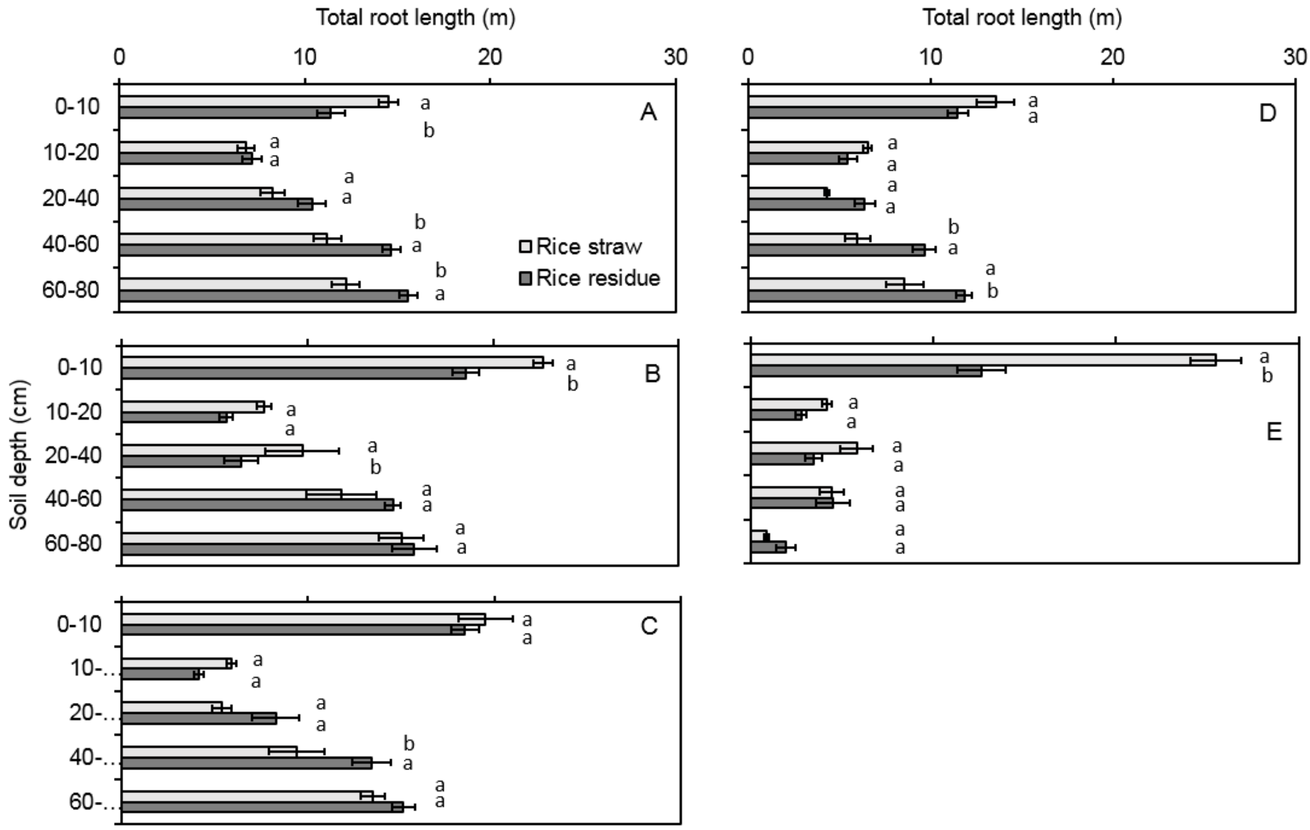

Fig. 8.4. Effects of sowing date on total root length (TRL) at different soil depths at flowering (75 - 85 DAS) under rice straw and rice residue treatments in 2017-18 season: (A) sowing 23 Nov, (B) sowing 14 Dec, (C) sowing 25 Dec, (D) sowing 10 Jan and (E) sowing 25 Jan in 2017-18. Horizontal bars indicate standard error of the means. Same letters above the means are not significantly different at $P < 0.05$.

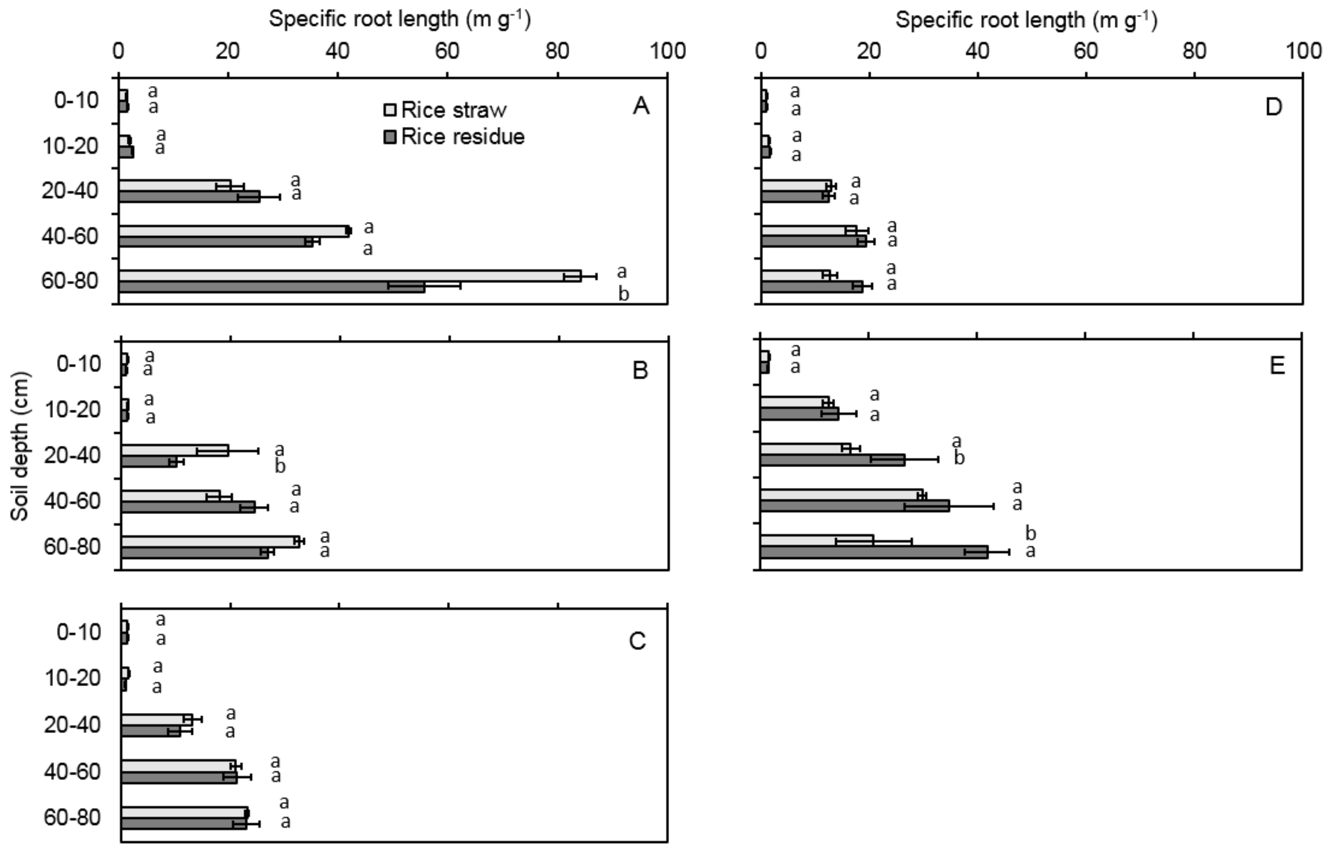

Fig. 8.5. Effects of sowing date on specific root length (SRL) at different soil depths at flowering (80 DAS) under rice straw and rice residue treatments in 2017-18 season: (A) sowing 23 Nov, (B) sowing 14 Dec, (C) sowing 25 Dec, (D) sowing 10 Jan and (E) sowing 25 Jan in 2017-18. Horizontal bars indicate standard error of the means. Same letters above the means are not significantly different at $P < 0.05$.