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Productivity Improvement Opportunities in the Coastal Polders to Address Food Security Challenges of Bangladesh

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Bangladesh has achieved self-sufficiency in rice using the green revolution technologies. But the 1.2 million ha land in the coastal polders have largely been deprived of these technological advancements despite huge efforts from the government, non-government and international organizations. Although there are tremendous opportunities to increase the productivity in the polders of the coastal zone through the adoption of improved cropping system technologies and practices, its wider adoption has been limited by the misperception that the river water is too saline. The results of our study showed that most rivers in the south-central coastal zone will remain non-saline until 2050 with a moderate climate change scenario A1B with 22 cm sea-level rise and a moderate precipitation change; while that in the southwest zone will remain suitable for crop production from July to mid-February (except Satkhira district). The farmer-participatory cropping trials showed the feasibility of intensifying and diversifying cropping having 2-3 times higher productivity than the current farmers' practice with improved drainage through systematic operation of sluice gates in the polders synchronizing with high and low tides that occur twice daily in the rivers of the coastal zone. Therefore, by adopting appropriate in-polder water management, Bangladesh can make a quantum leap in meeting future food security requirements and subsequently achieving the sustainable development goal within the time frame.

(***Key words:*** *Coastal zone, Food security, Polder, Sluice gate, System productivity, Tidal river water*)

The coastal zone of Bangladesh (147 upazilas in 19 districts), the southern part of the Ganges Delta, is characterized by extreme climatic and environmental challenges limiting agricultural productivity and influencing the livelihood of the communities (PDO-ICZMP, 2003a; Paul, 2009; Shamsuddoha and Chowdhury, 2007). This zone is broadly classified into interior coast (47,200 km^2) and exterior coast (23,900 km^2) based on its exposure to the sea and/or lower estuaries of the river systems (PDO-ICZMP, 2003b), and morphologically divided into southeast, south-central and southwest regions of Bangladesh (Islam, 2001; Maniruzzaman *et al*., 2015). The coastal zone occupies >30% of the country's cultivable land (SRDI, 2010; BBS, 2011ab), which comprises of low-lying lands with a dense network of rivers and canals and is strongly affected by cyclones, tidal surge, waterlogging and salinity intrusion (Islam 2004; Dasgupta *et al*., 2014; Haque *et al*., 2019). The rivers in this zone are tidal, and this effect extends about 150 km inland, with semi-diurnal water level fluctuations of up to 8 m (Chowdhury *et al*., 1997; IWM, 2014; Khan *et al*., 2015a). The water level in the rivers at high tide in the monsoon remains higher than the land elevation, resulting in flooding twice a day (Khan *et al*., 2015a; IRRI, 2017; Haque *et al*., 2019). The government has constructed 139 polders in the 1960s and 1970s encompassing about 1.2 M ha (42% of the coastal zone) to reduce the loss of life and enable agricultural production for the improved livelihood of the farming communities. Despite huge investment and continuous patronage by the government, non-government and international organizations, the cropping intensity and productivity in this region are much lower than in other parts of the country (MoA-FAO, 2013).

The general perception is that salinity is the main challenge for agricultural intensification and low productivity in the coastal zone of Bangladesh. In reality, most of the rivers in the south-central coastal

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zone (Barisal Division) remain non-saline almost throughout the year (Khan *et al*., 2015a). Almost similar salinity dynamics will remain until 2050 in most parts of the south-central coastal zone in the moderate climate change scenario A1B with a 22 cm mean sea level rise and a moderate precipitation change (Khan *et al*., 2015b). While, the river water in the medium saline coastal zone (part of the southwest region such as Khulna and Bagerhat districts) remains suitable for irrigation from July until early February (Mondal *et al*., 2006; Khan *et al*., 2015a). River water in some parts of the southwest region (Satkhira district) remains above 3 dS m^{-1} throughout the year and is considered unsuitable for crop agriculture, but it is a valuable resource for shrimp cultivation (Khan *et al*., 2015a). Like the water salinity, soil salinity showed a large temporal and spatial variation across the coastal zone depending on the rainfall pattern, the intensity of tidal flooding and the nature of the movement of saline groundwater (SRDI, 2010). In the Ganges delta, soil salinity varies from 1 to 17 dS m^{-1}. It remains the minimum from July to December, when high rainfall and tidal river water leached down and washed out salts accumulated on the soil surface. An increasing trend in soil salinity observed after the recession of rain reaching intermediate levels during the January-March period and maximum in April-May before the onset of monsoon in June (Burman *et al*., 2019).

Although Bangladesh as a whole has become self-sufficient in rice using the green revolution technologies, the coastal zone is deprived of these technological advancements and the communities are relatively food insecure (MoA-FAO, 2013; Tuong *et al*., 2014). The country faces enormous challenges to maintain food self-sufficiency for its growing population due to adverse climatic conditions and declining land-man ratio. There is little scope to further increase agricultural productivity, except in the underutilized lands in the polders of the coastal zone. Unlike the rest of Bangladesh, the farmers in the coastal zone have not widely adopted modern high yielding varieties (HYV) of rice because their shorter stature makes them unsuitable for the high water depths (20-70 cm) which often prevails in the polder ecosystem during the monsoon. The farmers in this zone usually cultivate traditional low yielding *aman* (wet season) rice (2.0-3.5 t ha^{-1}), sometimes followed by late sown low yielding *rabi* (dry season) crops (0.5-1.0 t ha^{-1}) and/or preceded by a pre-monsoon *aus* (2.5-3.5 t ha^{-1}) rice (Mondal *et al*., 2015a). The *rabi* crops are often damaged by the pre-monsoon rains and/or by cyclones at or near maturity. Moreover, most of the lands remain flooded or fully saturated until December that delays harvesting of *aman* rice. The late harvest of rice and waterlogged soil limits the cultivation of high yielding *rabi* crops which need to be established by early December for maximum yield. Due to these vulnerabilities, large areas of the coastal land (~810,000 ha) lie fallow during the dry season (Hasan *et al*., 2013). However, recent research has shown that the cropping intensity and productivity can be increased several-fold through improved water management (Bhattacharya *et al*., 2019; Mondal *et al*., 2015a, b and c; Ritu *et al*., 2015, Saha *et al*., 2015). This paper demonstrates the potential for more productive double (*aman-boro*/*rabi*) and triple (*aus-aman-boro*/*rabi*) cropping systems in medium and low salinity areas, respectively, of the coastal zone of Bangladesh.

MATERIALS AND METHODS

Study site

The study was conducted in the low and medium saline coastal zone of Bangladesh. The farmer-participatory demonstrations of different cropping patterns were implemented in a low salinity Polder 43/2F and Patuakhali Science and Technology University (PSTU) farm (outside polder) in the south-central and in a medium salinity Polder 30 located at the southwest region of Bangladesh (Fig. 1). The study sites were located adjacent to a canal connected to the surrounding river via a sluice gate in the polder embankment (a pipe sluice gate installed in the canal embankment at PSTU site) to facilitate drainage during the rainy season and to provide irrigation from canal water during the dry season. The soil type varied from silty clay to clay loam, slightly light soil texture was at the low saline sites. Further site details are provided in Table 1.

Cropping systems

Water in the rivers and canals in Polder 43/2F and PSTU farm remains non-saline throughout the year (Khan *et al*., 2015a; Mondal *et al*., 2015a; Saha *et al*., 2015), whereas scarcity of freshwater observed in the second half of the dry season in Polder 30 (Khan *et al*., 2015a; Mondal *et al*., 2010; Mondal *et al*., 2015b.

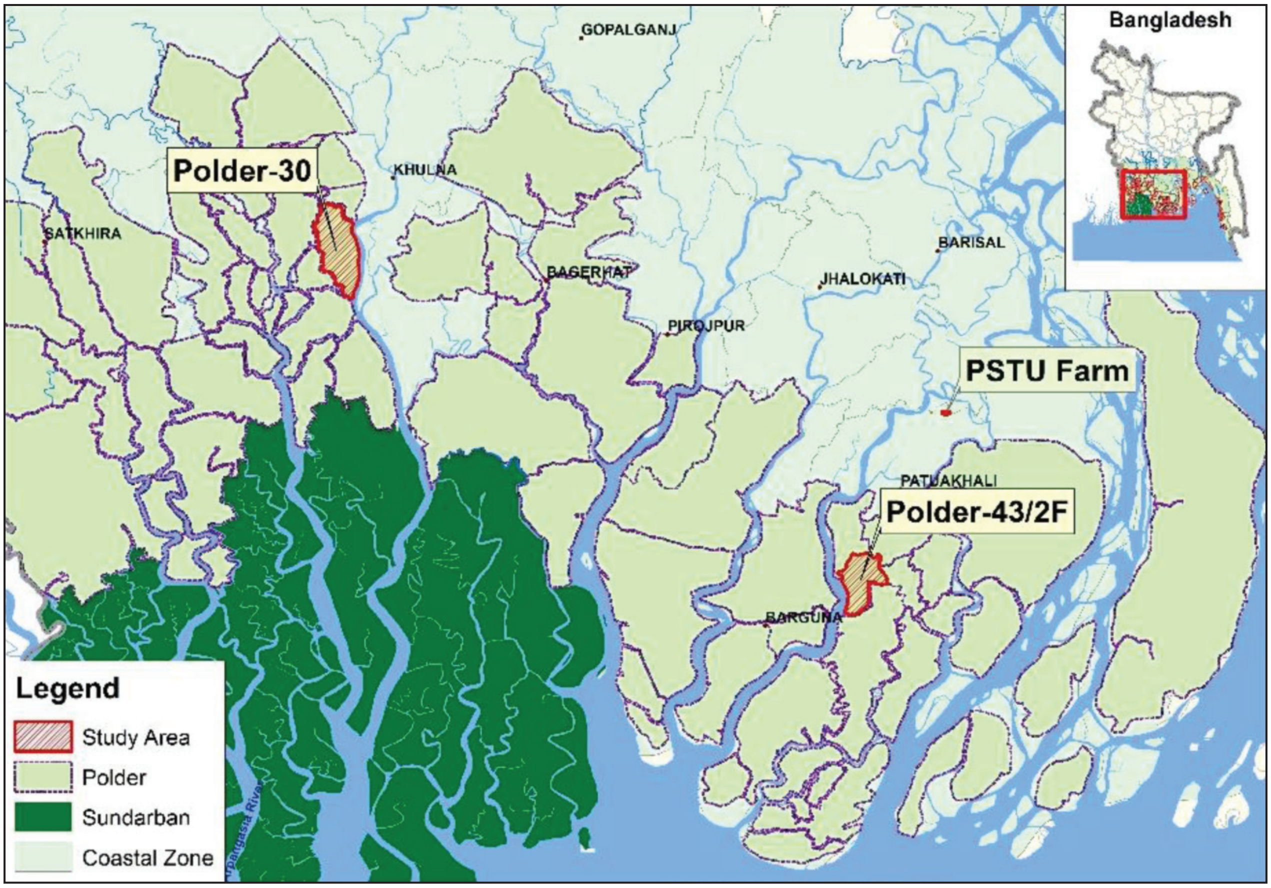

Fig. 1. Map of the coastal zone of Bangladesh showing the study sites.

Table 1. *Site details of the cropping intensification trials in the coastal zone*

Items	Salinity classification		
	Medium	Low	
Experimental site	Polder 30	Polder 43/2F	PSTU Farm
Village	Hatbati/Kismat Ful-tola	Bazarkhali	
Upazila	Batiaghata	Amtali	Dumki
District	Khulna	Barguna	Patuakhali
Latitude	22° 41′ 00″ N	22° 11′ 33″ N	22° 27′ 51″ N
Longitude	89° 30′ 00″ E	90° 15′ 41″ E	90° 22′ 56″ E
Height above sea level	1-3 m	1-3 m	1-3 m
River water salinity (EC, dSm^{-1})	0.2-24.0	0.2-2.4	0.1-0.8
Topsoil (0-15 cm) salinity (saturation extract EC, dSm^{-1})	2-16	2-8	2-8
Soil texture	Silty clay	Clay loam	Clay loam
Predominant cropping systems	*aman-sesame* *aman-mungbean*	*aman-grasspea* *aman-mungbean*	*aman-grasspea* *aman-mungbean*
Cropping systems evaluated	*aman-boro* *aman-rabi*	*aus-aman-boro* *aus-aman-rabi*	*aus-aman-boro* *aus-aman-rabi*

Utilizing these water resources, *aus-aman-boro* and *aus-aman-rabi* cropping systems were evaluated in the low saline zone from 2011 to 2014 and *aman-boro* were evaluated from 2005 to 2007 and *aman-rabi* from 2011 to 2016 in the medium saline coastal zone.

Variety selection

Modern, high yielding varieties (HYV) of rice and *rabi* crops were used in all the tested cropping patterns in the low and medium saline zone. Some important characteristics of the tested rice and *rabi* crops appropriate for their adoption in the coastal zone of Bangladesh are provided in Table 2.

For rice, short-duration varieties of *aus* rice; medium duration non-photoperiod sensitive, submergence/stagnant tolerant, and zinc enriched varieties of *aman*, and a medium duration *boro* rice variety were chosen to fit two to three crops per year. The grain type preference of the local community was also considered

Table 2. *Important characteristics of rice and rabi crops appropriate for the coastal zone*

Growing season	Crop	Variety	Field duration (d)	Mean yield (t/ha^{-1})	Other characteristics related to environmental suitability and social acceptability
Aus	HYV Rice	BRRI dhan42	100	3.5	• Stagnant flooding tolerant • Drought tolerant • Slender grain
	HYV Rice	BRRI dhan43	100	3.5	• Stagnant flooding tolerant • Drought tolerant • Grain type medium
	HYV Rice	BRRI dhan48	110	5.5	• Stagnant flooding tolerant • Suitable for lowland • Medium bold grain
	HYV Rice	BRRI dhan65	100	3.5	• Drought tolerant • Medium slender grain
Aman	HYV Rice	BRRI dhan 33	118	4.5	• Bold grain
	HYV Rice	BRRI dhan44	145	5.5	• Suitable for tidal ecosystem
	HYV Rice	BRRI dhan49	135	5.5	• Medium slender grain
	HYV Rice	BRRI dhan51	142	4.5	• Submergence tolerant
	HYV Rice	BRRI dhan52	140	5.0	• Submergence tolerant
	HYV Rice	BRRI dhan53	125	4.5	• Salinity tolerant • Medium slender grain
	HYV Rice	BRRI dhan54	135	4.5	• Stagnant flooding tolerant • Photoperiod sensitive
	HYV Rice	BRRI dhan62	100	4.5	• Zinc enriched
	HYV Rice	BRRI dhan72	125	6.0	• Zinc enriched
	HYV Rice	BINAdhan-7	120	5.0	• Slender grain
	HYV Rice	BINA dhan-12	130	5.0	• Submergence tolerant
Boro/Rabi	HYV Rice	BRRI dhan28	140	6.0	• Medium slender grain
	Hybrid Maize	Pacific 984	135	9.0	• Drought tolerant
	Hybrid Sunflower	Hysun 33	110	3.5	• Drought tolerant
	Hybrid Watermelon	Asian 2	90	50.0	• Sensitive to waterlogging
	Hybrid Chilli	Debgree	150	3.5	• Sensitive to waterlogging
	HYV Mungbean	BARI Mug 6	65	1.2	• Resistance to yellow mosaic virus
	HYV Sesame	BARI Til 4	100	1.2	• Sensitive to waterlogging

for demonstration of rice varieties in low and medium saline coastal zone (Table 2).

For *rabi* crops, hybrid and high yielding varieties of chilli, maize, mungbean, sesame, sunflower, and watermelon were evaluated in different cropping systems. As fresh water is available in the rivers and canals throughout the year at low saline sites, a range of high yielding and high value *rabi* crops was evaluated (Table 2). In contrast due to increasing trend in river water salinity with the progress of the dry season in medium saline coastal zone, performance of short duration *rabi* crops (mungbean and sesame) were evaluated utilizing residual soil water and rainfall, if any.

Crop management

Sowing and harvest date

The sowing date of *aman* rice was chosen to ensure that the crop could be harvested by the end of November so that the field could be drained during the first half of November. This drainage pattern will facilitate soil drying not only to facilitate harvesting *aman* rice; it will also facilitate the early establishment of *rabi* crops, and consequently the timely establishment of *aus* rice in the low saline zone. The sowing dates of *aman* rice varied from the first week of July to the first week of August depending on the growth duration of the varieties and cropping systems in the low and medium saline zone. The *aus* rice was sown in mid-April and the sowing dates ranged from late October to the end of December in *boro* season. *Aus* rice was harvested from 22 July to 20 August, *aman* from 12 November to 10 December and *boro* rice from 30 March to 13 May.

The *rabi* crops were sown within the recommended period (BARI, 2006). But the sowing dates varied among crops, cropping patterns and study sites depending on soil moisture after *aman* harvest and the optimum sowing time for each crop. The *rabi* crops in low saline coastal zone (Polder 43/2F and PSTU farm) were sown during 10 December-24 January, while it was done from 8 February to 16 March in medium saline zone (Polder 30). Harvest dates of *rabi* crops were influenced by variety, sowing date, temperature, and soil moisture. In low saline zone, it started from the first week April and completed within mid-May. But in medium saline zone, mungbean was harvested mostly in May (30 April-29 May) and sesame from 16 May to 12 June.

Cultural management

The lands were ploughed three times using a power tiller powered by a two-wheel tractor for both rice (wet tillage) and *rabi* (dry tillage) crops. The exception was land preparation for watermelon for which 60 cm x 60 cm x 60 cm pits were dug at 2 m x 2 m spacing. Final land leveling with a bamboo ladder drawn by the power tiller was done after basal application of fertilizer.

Rice was cultivated according to BRRI recommendations (BRRI, 2004; BRRI, 2010; BRRI, 2012; BRRI, 2016) and *rabi* crops as per BARI recommendation (BARI, 2006). Transplanting was done when the rice seedlings had four leaves, with two to three seedlings per hill, and a hill spacing of 20 cm x 20 cm. The *rabi* crops were sown in line, except the watermelon. Chilli, mungbean, sesame, maize and sunflower were sown in 2-4 cm deep furrows made using a hand furrower, and watermelon was sown in pits. One seed per hill was sown for maize and sunflower, and two seeds per pit for watermelon. Planting geometry was 75 cm x 25 cm for maize, 60 cm x 45 cm for sunflower, and 2 m x 2 m for watermelon. Chilli was sown at 50 cm row spacing, and mungbean and sesame at 30 cm spacing, and thinning was done two weeks after emergence to give 5 cm spacing between plants. Earthing up was done in maize and sunflower 50-60 d after sowing (DAS).

In rice, all fertilizers (P, K, S and Zn) except nitrogen(N) were broadcast just before the final land preparation and N was broadcast in two to three equal splits (depending on water depth on the paddy field) at mid-tillering, before panicle initiation and flowering. Excess water from the aus and aman fields was drained opening the sluice gates at low tides in the rivers before topdressing N fertilizer.

Fertilizer management in *rabi* crops influenced by water availability in the dry season. Since river water remains non-saline throughout the year in low saline coastal zone, one-third to one-half of the N and all the P, K, S, Zn, and B were broadcast just before final land preparation, except for watermelon fertilizer was applied to the pits 5 days before sowing. The rest of the N was top dressed thrice in chilli and watermelon, twice in maize, sesame, and sunflower, and once in mungbean. In the medium saline coastal zone, river water is saline in the dry season. For that half of the N and the full dose of P, K, S, Zn, and B were applied during final land preparation. The remaining N was top dressed once or twice depending on dry season rainfall.

The *aus* and *aman* crops were cultivated using rainfall and tidal river water, whereas the boro crop was fully irrigated by pumping water from the polder canals. The *rabi* crops were grown by utilizing residual soil water and rainfall, and supplemental irrigation from canal water in the low saline coastal zone only. All *rabi* crops in low saline coastal zone were irrigated two to four times by pumping water from the canal. The canal near PSTU farm was naturally fed by the river and in Polder 43/2F the canal was filled with river water by opening the sluice gate at high tide when needed. Irrigation method varied depending on the crop and stage of growth, topdressing of N fertilizer, and soil moisture, and included watering of small seedlings with a hand sprinkler, spraying with a hose pipe, and flood irrigation. In Polder 30, the *rabi* crops were grown mainly using residual soil moisture and rainfall due to scarcity of good quality irrigation water.

Weeding in rice and *rabi* crops was done manually synchronizing with the topdressing of urea, and during earthing up in maize and sunflower and thinning in other *rabi* crops. Disease and insect pest infestations were controlled well by spraying pesticides and insecticides as and when necessary.

Crop yield

The rice crop was harvested after physiological maturity when 80% of the grains had turned golden. The harvest date varied across the study sites and years depending on growing season, varietal characteristics, cropping patterns and soil dryness. Grain yield was determined by harvesting a 5 m x 2 m harvest area from the middle of the plot. Grain moisture content was determined at harvest and the yield was calculated at 14% moisture content.

While the harvest dates of *rabi* crops were influenced by variety, sowing date, temperature, and soil moisture. Most *rabi* crops were harvested when the leaves turned dry, brown and/or yellow. Sesame and mungbean were harvested when the pods were black and chilli when the fruit had turned reddish. Grain or fruit yield of the *rabi* crops was determined from a 5 m x 4 m harvest area in the middle of each plot, except watermelon for which the yield was assessed on a whole plot basis. The yield of maize, sunflower, sesame, and mungbean was converted to 12% moisture content and for chilli and watermelon, it was determined on a green weight basis immediately after harvest. Rice equivalent yield (REY) of the *rabi* crops was calculated taking farm gate price of rice and *rabi* crops using the formula:

REY (kg ha^{-1}) = *rabi* yield (kg ha^{-1}) x *rabi* price (Tk kg^{-1})/rice price (Tk kg^{-1})

The price of rice and *rabi* crops was collected by survey when the farmers sold in the local market. The average price of HYV rice was Tk. 16.25 per kg at low saline sites and Tk. 18.75 at medium saline site; while that of traditional rice was almost similar (~Tk 27.00 per kg) across the study sites. The prices of *rabi* crops were almost similar at both low and medium saline sites. The farm gate prices of chilli, grasspea, maize, mungbean, sesame, sunflower and watermelon was Tk. 25.00, 40.00, 16.25, 82.50, 50.00, 33.75 and 5.71 per kg, respectively were used to determine the REY of *rabi* crops.

Water salinity

The salinity of the canal water was measured daily using a portable EC meter in both low (from March 2012 to June 2014) and medium (February 2012 to December 2013) saline coastal zone.

RESULTS AND DISCUSSION

Canal water salinity

Salinity of the water in the canals in low saline coastal zone varied from 0.1 dS m^{-1} to 0.6 dS m^{-1}, reached a maximum of about 0.6 dS m^{-1} towards the end of each dry season (Fig. 2a), whereas it increased as the dry season progressed in medium saline zone (Fig. 2b). The salinity level in the medium saline coastal zone declined to about 0.2 dS m^{-1} during the rainy season. IRRI (2017), Mondal *et al*. (2016 and 2010) and Khan *et al*. (2015a) reported similar river water salinity in the low and medium saline coastal zone of Bangladesh. In low saline Polder 43/2F, river water was taken in through the sluice gate and stored in the polder canal networks. This water was used to irrigate dry season crops (boro rice and *rabi* crops); while water from the flowing canal (fed by the river) was pumped to irrigate the dry season crops at PSTU farm. In the medium saline zone, the canal inside the polder was filled with river water by opening the sluice gate at high tide until the first week of February in 2006, 2007 and 2012 and was stored for irrigation

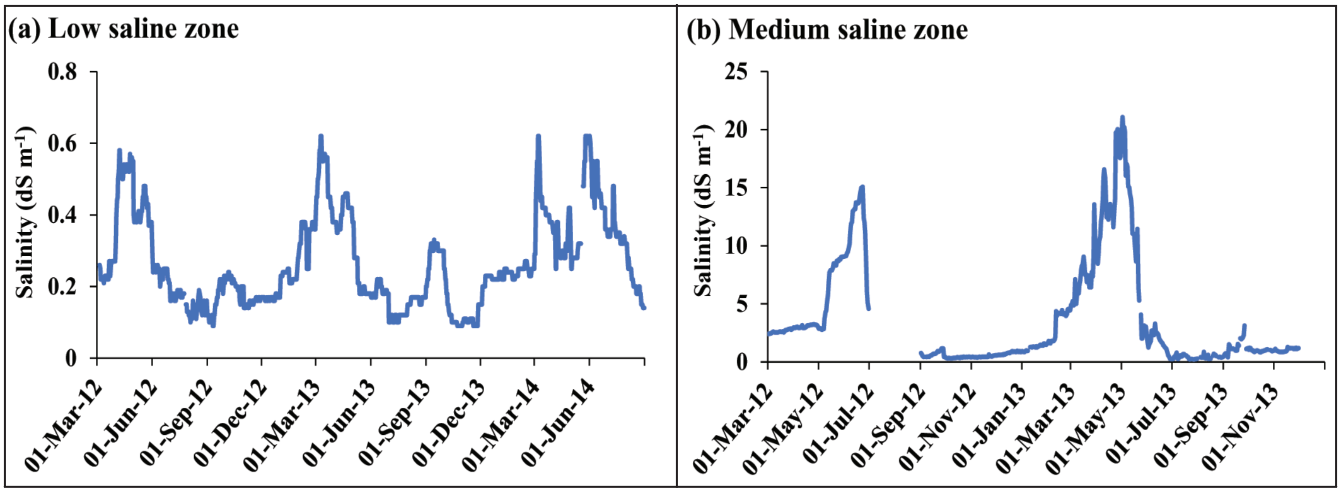

Fig. 2. *Canal water salinity in low (Polder 43/2F & PSTU) and medium saline (Polder 30) coastal zone.*

by closing the sluice gate. The water remained suitable for irrigation (<4 dS m^{-1}) until April and was used to irrigate boro rice (Mondal *et al*., 2010 and 2015b). But from 2013 to 2016, the sluice gate was kept partly open by the Water Management Organization (WMO) during the dry season to prevent siltation in the intake canal and the canal water became unsuitable for irrigation (IRRI, 2017; Mondal *et al*., 2015b) and salinity measurement was discontinued after 2013. Therefore, irrigation was not provided to *rabi* crops in the medium saline coastal zone and the crops were grown under rainfed conditions (by utilizing dry season rainfall and residual soil water).

Cropping system intensification in the coastal zone of Bangladesh has been limited by the misperception that the river water is too saline for irrigation. In reality, most of the rivers in the south-central coastal zone remain non-saline throughout the year, while the river water salinity in most parts of the southwest region (except Satkhira district) lies within the permissible limit for crop irrigation from July to until mid-February (Khan *et al*., 2015a; Mondal *et al*., 2010; Mondal *et al*., 2016). Our findings on water salinity in the canals in PSTU farm, Polder 43/2F and Polder 30 were consistent with the above findings.

There is also a misperception that HYV rice cannot be grown in the coastal zone due to water stagnation throughout the growing season of *aus* and *aman* rice. Our studies proved that the water environment can significantly be improved through the systematic operation of the sluice gates in the polders to drain out excess water at low tides that occurred twice daily in the coastal river systems. Possibilities of HYV rice cultivation in aman season through improved water management in the polders were also reported by Mondal *et al*. (2015c) and Sudhir-Yadav *et al*. (2019).

Performance of rice

A range of recommended HYV rice varieties (Table 2) was evaluated in *aus*, *aman*, and *boro* in low (Polder 43/2F and PSTU farm) and *aman* and *boro* seasons in medium (Polder 30) saline coastal zone. The mean yield of aus rice varied from 3.6 to 5.2 t ha^{-1}, *aman* ranged from 4.0 to 5.5 t ha^{-1} and *boro* rice varied from 2.0 to 7.0 t ha^{-1} depending mainly on the sowing time and varietal characteristics (Table 3, Figs. 3-4). Over the years (2011-2016), the average yield of all the HYVs tested in *aman* season was similar (4.4-5.0 t ha^{-1}), except for the short duration BRRI dhan33 and BRRI dhan62 (Fig. 3). Traditional rice is popularly cultivated by the farmers in the coastal zone (IRRI 2017; Mondal *et al*., 2015a). As the HYVs were grown in smaller area compared to the area coverage of traditional rice, bird damage due to its earliness was one of the reasons for such low yield.

Tidal river water and rainfall were sufficient to meet up the crop water requirement and pumping was not required to cultivate HYV rice in both *aus* and *aman* seasons. The growth duration of the tested aus varieties was about 100 days, observed slightly longer duration when the crop was submerged for a week after transplanting during a cyclonic storm in 2013 (Table 3). Therefore, the low saline coastal zone has the

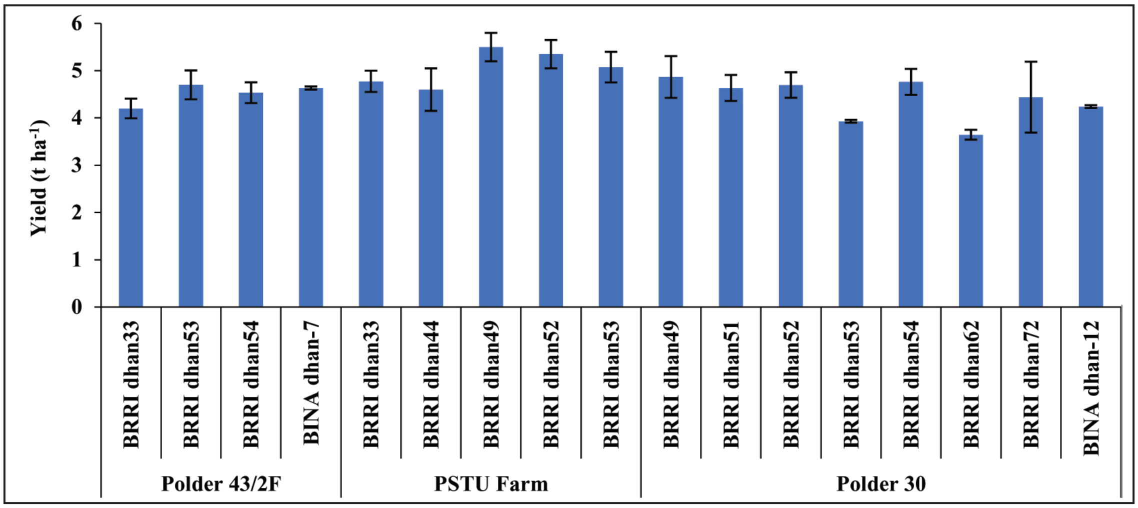

Fig. 3. *Yield of HYV aman rice in low (Polder 43/2F & PSTU) and medium (Polder 30) saline coastal zone (Vertical bars are standard errors)*

great potential to grow HYV rice in *aus* season. The crop was not submerged in *aman* season and the growth duration of aman rice varieties also varied depending mainly on the varietal characteristics (Table 2; BRRI, 2016).

Land elevation in the polders of the coastal zone was higher than water level elevation at high tides in the peripheral rivers in the dry season. For that, unlike in the wet season, the tidal water cannot flood agricultural lands in the dry season due to less water availability in the river systems. Therefore, pumping from the canal networks was required for the successful cultivation of boro rice. In the dry season, non-saline river water was taken in via sluice gates and stored in the canals in Polder 30 and Polder 43/2F; while that was directly pumped from the tidal river to canals at PSTU site to irrigate *boro* rice. The mean grain yield of *boro* rice in low saline coastal zone (Polder 43/2F and PSTU Farm) ranged from 4.4 to 7.9 t ha^{-1} and it varied from almost zero (early crop damaged due to cold stress at panicle initiation, Mondal *et al*., 2015b) to 6.3 t ha^{-1} in medium saline coastal zone (Polder 30) across sowing dates and years (Fig. 4). The growth duration of *boro* crop also varied widely (123-152 d in low saline and 135-166 d in a medium saline zone) across locations, sowing dates and years (Mondal *et al*., 2015b, Saha *et al*., 2015). A consistent trend in declining crop duration was observed with delayed sowing across the study sites, due to the warmer weather experienced by later

Table 3. *Growth duration and yield (mean ± SE) of aus crops in Polder 43/2F and PSTU farm.*

Year	BRRI dhan48	BRRI dhan42	BRRI dhan43	BRRI dhan65
Duration (d)				
2012	102	103	103	-
2013	117	108	108	108
2014	100	100	100	103
Mean	106	104	104	106
Grain yield (t ha^{-1})				
2012	4.6±0.0	5.1±0.2	5.2±0.2	-
2013	4.3±0.1	4.2±0.2	4.0±0.2	3.8±0.1
2014	4.1±0.1	3.6±0.0	3.6±0.1	3.6±0.1
Mean	4.3±0.2	4.3±0.4	4.3±0.4	3.7±0.1

sown crops (Mondal *et al*., 2015b). But in the low saline coastal zone, in most cases, little effect of sowing date on yield (>6 t ha^{-1}) was observed from mid-November to mid-December (Fig. 4a). In the medium saline zone, yields were always much lower than that in the low saline coastal zone for similar sowing dates (Fig.4 a and b). The maximum yield in the medium saline zone was observed when sowing was done during 7-15 November. Rice yield was drastically reduced when the crop was sown in the latter part of October due to cold injury at the panicle initiation stage (Mondal *et al*., 2015b).

The long-term data showed that both minimum and maximum temperature was lower in medium saline than low saline coastal zone from late December to mid-February (critical growth period for *boro* rice, when panicle initiation occurred), suggesting that the former zone is more risky for early planted *boro* rice than the later (Mondal *et al*., 2015b). Therefore, the main cause of lower yields in the medium saline zone maybe the combination of high salinity and adverse effects of low temperature at the panicle initiation stage of *boro* rice compared to low saline coastal zone. This study provides strong evidence of the feasibility of HYV *boro* rice cultivation in the low saline coastal zone of Bangladesh, where temperature and river water salinity remain within the permissible limits for HYV rice throughout the year. Yields of 6.0-7.5 t ha^{-1} could be achieved with sowing from mid-November to mid-December in the low saline zone, whereas *boro* yield of about 5.0 t ha^{-1} could be harvested with sowing in the second week of November in the medium saline coastal zone of Bangladesh (Fig. 4).

Performance of *rabi* crops

The performance of *rabi* crops varied across crop varieties and study sites (Table 4). Overall, yields of *rabi* crops were much higher in low saline than medium saline coastal zone under different management practices. Among the tested crops, maize and sunflower performed better in low saline (Polder 43/2F and PSTU) coastal zone. The yield of maize ranged from 7.5 to 9.5 t ha^{-1}, and sunflower from 2.9 to 3.8 t ha^{-1}. Yields of the mulched watermelon (42 and 63 t ha^{-1}) and chilli (2.3 and 3.6 t ha^{-1}) were also satisfactory compared to mungbean and sesame. The yield of mungbean and sesame was not satisfactory mainly due to poor germination.

In the medium saline (Polder 30) coastal zone, the yield of mungbean and sesame were generally poor (0.4-0.9 t ha^{-1}) due to poor germination, lack of irrigation and crop damage at the later growth stage by pre-monsoon rains (Table 4). In 2012-13, mungbean and sesame in the medium saline zone were destroyed by waterlogging owing to a cyclonic storm in the last week of May. Maize and sunflower were, therefore, evaluated during the dry seasons of 2013-14 and 2015-16 to evaluate their feasibility in the medium saline coastal zone under rainfed environment. But the crops were also affected by both waterlogging (due to high rainfall) and drought (due to lack or no rainfall) to different degrees over the study years. Despite environmental limitations (salinity, drought and excess rain), maize (5.7-6.7 t ha^{-1}) and sunflower (1.0-2.9 t ha^{-1}) produced a reasonable yield (Table 4) indicating the crops may be climate-resilient

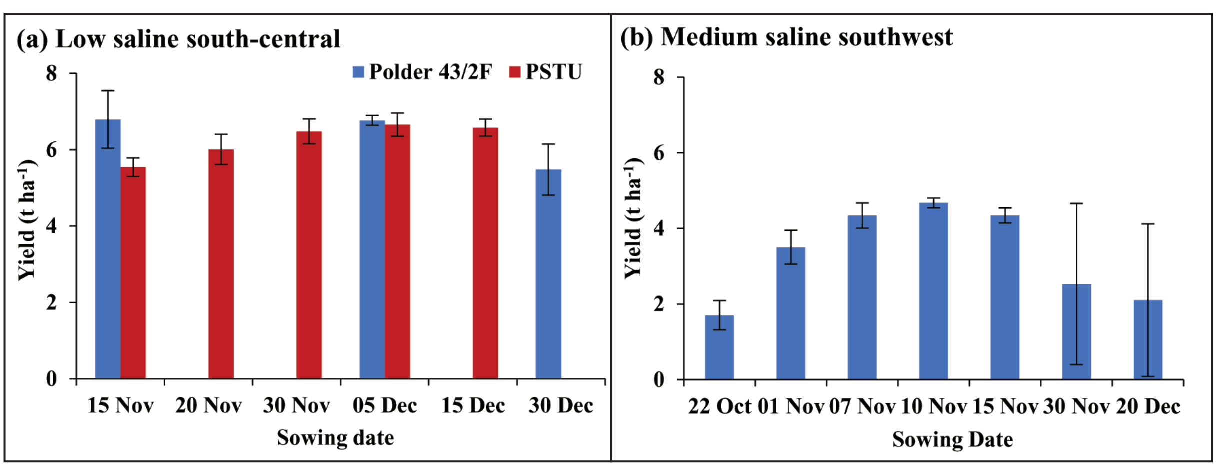

Fig. 4. *Effect of sowing date of BRRI dhan28 on grain yield in (a) low saline (Polder 43/2F & PSTU) and (b) medium (Polder 30) saline coastal zone in boro season (Vertical bars are standard errors)*

Table 4. *Yield (t ha^{-1}) of rabi crops in low (polder 43/2F and PSTU farm) and medium (polder 30) saline coastal zone*

Crop	Mulching	2011-12[a]		2012-13[b]		2013-14			2015-16	Mean yield
		Polder 43/2F	Polder 30	Polder 43/2F	PSTU Farm	Polder 43/2F	Polder 30	PSTU Farm	Polder 30	
Maize	Mulch	8.70		9.30	7.50	9.20	5.70	8.00		8.1±0.6
	No-Mulch	9.50		8.70	8.00	9.10	5.97	8.30	6.66	8.0±0.5
Sunflower	Mulch	3.60		3.60	3.20	3.80	2.86	3.50		3.4±0.1
	No-Mulch	3.70		3.80	2.90	3.70	2.63	3.10	1.03	3.0±0.4
Mungbean	Mulch	0.40		0.85		0.46				0.6±0.1
	No-Mulch	0.35	0.65	0.63		0.25	0.77		0.35	0.5±0.1
Sesame	Mulch			0.80		0.57				0.7±0.1
	No-Mulch		0.57	0.56		0.49	0.38			0.5±0.1
Watermelon	Mulch			63.00		42.00				52.5±11
	No-Mulch			33.00		12.00				22.5±11
Chilli	Mulch			3.62		2.30				3.0±0.7
	No-Mulch					2.00				2.0±0.0

[a]In polder 43/2F sesame crop damaged by 112 mm rainfall before harvest; [b]All crops in polder 30 damaged by about 500 mm rainfall in May 2013 due to cyclone Mohasen; chilli in polder 43/2F after the first harvest (yield of chilli combined for both mulched and non-mulched plots)

(than the farmers' cropping, mungbean and sesame) and suitable for the medium saline coastal zone of Bangladesh.

Total system productivity

Four major cropping patterns were evaluated in the low and medium saline coastal zone. The patterns were: (1) *Aus-aman-boro* and (2) *Aus-aman-rabi* in the low saline coastal zone; and (3) *Aman-boro*, (4) *Aman-rabi* in the medium saline coastal zone (Table 1).

Pattern 1: Aus-aman-boro

Total system yield (REY) of aus-aman-boro cropping pattern across the study sites, periods and three boro sowing dates ranged from 13.2 to 16.6 t ha^{-1} (Table 5; Mondal *et al*., 2015a). The mean REY of this pattern was more than 15 t ha^{-1} rice per year, which is 2-3 times higher than the present farmers' production level (Mondal *et al*. 2015b; Table 5).

Pattern 2: Aus-aman-rabi

The REY of *aus-aman-rabi* cropping pattern in low saline coastal zone varied from 8.5 to 30.7 t ha^{-1} over the study years with six *rabi* crops (Table 5; Mondal *et al*., 2015a). The inclusion of watermelon in a low saline zone resulted in much higher REY than in the *aus-aman-boro* system (Table 5), mainly due to its higher green yield compared to other crops. Similarly, the introduction of maize and sunflower produced comparable or slightly higher REY (16-19 t ha^{-1}) than the triple rice system (*aus-aman-boro*), due to the higher yield of maize and higher price of sunflower seed (Mondal *et al*., 2015a). But the system yield with mungbean, sesame, and chilli (10-13 t ha^{-1} yr^{-1}) was always considerably lower than that of the triple rice system (Table 5; Mondal *et al*., 2015b).

Pattern 3: Aman-boro

In the medium saline coastal zone, total system yield (REY) of the *aman-boro* cropping pattern ranged from 4.7 to 10.5 t ha^{-1} and was strongly affected by boro sowing date (Table 5; Mondal *et al*., 2015a and b), the mean REY was about 8 t ha^{-1}. The most consistent *aman-boro* system was with *boro* sown during 7-15 November yielded 8.8 to 10.2 t ha^{-1} (Mondal *et al*., 2010 and 2015b), which was at least double than farmers' practice (Table 5).

Pattern 4: Aman-rabi

The REY of aman-*rabi* pattern in medium saline coastal zone varied from 6.6 to 10.0 t ha^{-1} and systems with maize produced the highest yield (Table 5). Mondal *et al*. (2015a) reported that mungbean (5.9-8.9 t ha^{-1}) had higher system yield than with sesame (5.2-7.3

Table 5. *Annual system yield of different cropping patterns in the coastal zone.*

Location	Cropping Pattern			Total system rice equivalent yield (t ha^{-1})	
	Aus	*Aman*	*Boro/Rabi*	Improved practice	Farmers' practice (Mondal *et al*., 2015a)
Barisal	Rice	Rice	Rice	15.2	-
	Rice	Rice	Maize	17.8	-
	Rice	Rice	Sunflower	16.4	-
	Rice	Rice	Watermelon	21.7	-
	Rice	Rice	Mungbean	11.2	-
	Rice	Rice	Sesame	9.9	-
	Rice	Rice	Chilli	11.2	-
	Rice	Rice	Grasspea	-	6-9
	Fallow	Rice	Mungbean	-	5-7
Khulna	Fallow	Rice	Rice	8.0	-
	Fallow	Rice	Mungbean	8.8	-
	Fallow	Rice	Sesame	6.6	-
	Fallow	Rice	Maize	10.0	-
	Fallow	Rice	Sunflower	8.5	-
	Fallow	Rice	Sesame	-	4-5

t ha^{-1}). The REY of the best *aman-rabi* systems (rice-maize and rice-sunflower) was higher than that of the best *aman-boro* (rice-rice) and traditional *aman-rabi* (rice-mungbean and rice-sesame) systems (Table 5). The REY of the improved systems was almost double than of the farmers' practice in the medium saline coastal zone of Bangladesh.

Overall, the system productivity (REY) of all the tested cropping patterns in the low and medium saline coastal zone of Bangladesh was at least double than farmers' practice. The system yield with maize and sunflower was more stable over the study periods than with the other *rabi* crops (Table 5).

The farmer-participatory results presented above clearly demonstrate the feasibility of year-round cropping (*aus-aman*-boro and *aus-aman-rabi*) in the south-central coastal zone of Bangladesh. About 15 t ha^{-1} yr^{-1} rice can be harvested by adopting a triple rice system (*aus-aman-boro*) in comparison with current farmer production of 5-9 t ha^{-1} yr^{-1} (3-7 t ha^{-1} of rice, and 0-1 t ha^{-1} of *rabi* crops). Mondal *et al*. (2015a and b); Mondal *et al*. (2019) and Saha *et al*. (2015) reported similar productivity in the low and medium saline coastal zones. Moreover, the inclusion of maize and sunflower in the cropping pattern instead of *boro* is expected to produce total REY similar to or slightly higher than that of the triple rice system. Intensification and diversification to a wide range of *rabi* crops provide further more productive and climate-resilient cropping options than current farmers' practice (Mondal *et al*., 2019).

The results also demonstrate the feasibility of the adoption of high yielding *aman-boro* cropping systems in the medium saline southwest coastal zone where freshwater is limited in the dry season. In such areas, river water can be brought in through operating the sluice gates at high tide for water intake/irrigation directly from the river from November until early February. The final intake of river water should take place in early February, after which the sluice gates should be closed to store the water in canal networks in the polder ecosystem for rice irrigation. In this medium saline zone, early (7-15 November) sowing of *boro* was critical for consistently higher productivity and thus system yields of 9 to 10 t ha^{-1}, compared with current farmer production of 2-3 t ha^{-1} of *aman* rice and 0-1 t $ha^{-1}$of sesame or mungbean (Mondal *et al*., 2006; Mondal *et al*., 2010; Mondal *et al*., 2015; Ritu *et al*., 2015). The introduction of salt-tolerant HYVs in boro might increase the system productivity further. In addition, introduction of maize and sunflower in the improved and climate-resilient cropping systems (rice-maize and rice-sunflower) increased the yearly land productivity further. Bhattacharya *et al*. (2019), IRRI (2017), Mondal *et al*. (2019) and Sudhir-Yadav *et al*. (2019) reported similar results in the low and medium saline coastal zone of Bangladesh.

The successful production of traditional *rabi* crops (sesame and mungbean) in the medium saline southwest region currently depends very much on rainfall (Mondal *et al.,* 2015b). The dry season productivity varies greatly from year to year depending on the amount and frequency of rainfall - excess rain destroy the crop (no yield), lack or little rain hampers crop growth and development (30-50% of achievable yield) and moderate rainfall two to three times in the dry season act as supplemental irrigation that produce good yield (Mondal *et al*., 2019). Therefore, the early establishment of *rabi* crops by utilizing residual soil moisture would be beneficial for higher productivity of the *aman*-*rabi* cropping system. The key prerequisite to include high yielding and high-value *rabi* crops in *aman*-*rabi* pattern is early (by November) harvest of the *aman* rice, drain out water from the paddy field by mid-November that lead to early establishment and efficient use residual soil water for the growth and development of the crops (Mondal *et al*., 2015a, b and c; Mondal *et al*., 2016; Mondal *et al*., 2019; Sudhir-Yadav *et al*., 2019). Early drainage is essential for soil drying to create a favorable environment for *aman* harvest, and to facilitate the early establishment and safe harvest of *rabi* crops (Mondal et al., 2015a and c; Mondal et al. 2016). Although residual water in the soil profile retained after the monsoon is seen as a disadvantage for the successful cultivation of *rabi* crops in the coastal zone, our studies showed that this water could be a valuable resource for the medium saline southwest region, where water scarcity limits successful cultivation of *rabi* crops.

While tens of millions of dollars are invested in developing and maintenance of the polders, the coastal zone is still home to the poor, food-insecure and most vulnerable rural people (MoA-FAO, 2013). There have been tremendous improvements in cropping system technologies over the past 50 years. Bangladesh has achieved self-sufficiency in rice using the green revolution technologies. But the coastal zone is deprived of this technological advancement mainly due to the hydrology of the coastal zone, which is quite different from other parts of the country (Khan *et al.,* 2015a; Mondal *et al.,* 2016). In the coastal rivers, high and low tides occur twice daily with an amplitude difference of about 4 m, offering both irrigation and drainage by gravity. It is practically impossible for an individual farmer in the polder zone to manage huge tidal river water for adoption of year-round and improved cropping; while an individual in non-coastal zone can manage groundwater for household's food security without much difficulty. Using the Farmer Field School (FFS) model, the Department of Agricultural Extension (DAE) has successfully disseminated improved agricultural technologies in the non-coastal zone that helped the country to achieve food self-sufficiency. But there has been little change in production practices in 1.2 m ha lands in the coastal polders since its construction 50-60 years back, as the FFS model did not consider hydrology as the determinant in technology dissemination in the coastal zone of Bangladesh Mondal *et al*. (2016). IRRI (2017), Mondal *et al*. (2015c) and Mondal *et al*. (2016) showed that improved production systems can be adopted in the polder zone when the farmers are organized based on hydrological units (e.g., the catchment area of a sluice gate/regulator). Such an approach of organizing the community for technology dissemination was not considered in the FFS model. That's why despite huge efforts and investment from the government, non-government and international organizations; the productivity of the coastal zone remains much lower than other parts of Bangladesh.

It is possible to greatly increase the system productivity in low and medium salinity regions of the coastal zone, using improved rice and *rabi* crops and good water management - in particular, drainage during the monsoon to enable the cultivation of high yielding, early maturity aman rice varieties; terminal drainage in mid-November and periodic drainage after excessive rainfall in the dry season. In the south-central coastal zone, where freshwater was available almost throughout the year, triple rice system productivity of 13 to 17 t ha^{-1} yr^{-1} was achieved in the farmer's fields using appropriate rice varieties, time of sowing, and crop and water management practices. Similar or higher system productivity was also achieved by replacing the *boro* crop with early-sown maize, sunflower, and watermelon. In the moderately saline southwest coastal zone, 9 to 10 t ha^{-1} yr^{-1} of rice (or REY) were produced in an *aman*-boro and *aman*-*rabi* systems with the sowing of the *boro* crop in the second week of November and high yielding *rabi* crops in December/January.

Since cropping intensity and productivity in other parts of Bangladesh are already high, the under-utilized agricultural lands in the polders of the coastal zone may be the key region where significant gains in food production can be made through judicious management of water resources to address future challenges to the food security of Bangladesh and in achieving sustainable development goals within the time frame.

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