



## Yield and water productivity variation of *Boro* rice with irrigation strategies and transplanting dates under climate change – a case study in south-western Bangladesh

Tapos Kumar Acharjee<sup>1\*</sup>, Mohammad Abdul Mojid<sup>1</sup>, Kamonashish Haldar<sup>2</sup>

<sup>1</sup>Department of Irrigation and Water Management, Bangladesh Agricultural University, Bangladesh

<sup>2</sup>Environmental Technology, Wageningen University and Research, Netherlands

### ARTICLE INFO

#### Keywords:

AquaCrop  
Adaptation strategy  
Climate change  
Rice cultivation  
Water management

#### Article history

Submitted: 2022-01-15

Accepted: 2022-03-24

Available online: 2022-05-25

Published regularly: June 2022

\* Corresponding Author

Email address:

[tapos.bau@gmail.com](mailto:tapos.bau@gmail.com)

### ABSTRACT

Climate change has imposed major uncertainties on food and water security in Bangladesh. Understanding the recent changes in potential yield and water productivity of major crops is essential to formulate effective adaptation strategies under climate change conditions. This study assessed the yield and water productivity variation of dry season *Boro* rice with different irrigation regimes and transplanting dates over long-term (1985–2017) in a south-western district (Khulna) of Bangladesh using AquaCrop model. The evaluation of yield and water productivity was done for five transplanting dates (1<sup>st</sup> & 15<sup>th</sup> of December and January and 1<sup>st</sup> of February) and four irrigation strategies (fixed short- and long-interval irrigations, and measured irrigation with ‘low stress, low dose’ and ‘high stress, high dose’). Transplanting rice seedlings on 1<sup>st</sup> December results in 17% yield increase compared to transplanting on 1<sup>st</sup> January. There are significant ( $p \leq 0.05$ ) increasing trends of attainable biomass, grain yield and water productivity of *Boro* rice. The measured irrigation practices are superior to the traditional fixed irrigation practices. The ‘low stress, low dose’ irrigation strategy increases irrigation-water productivity and provides an opportunity to exploit the possible benefits of climate change. Adjustment of the irrigation strategy can reduce water usage without reducing the potential yield of *Boro* rice with an eventual increase in irrigation-water productivity, while adjustment of the transplanting date can increase potential yield with additional water usage. These findings would help develop suitable agricultural adaptation strategies for irrigated rice cultivation under climate change.

**How to Cite:** Acharjee, T.K., Mojid, M.A., Haldar, K. (2022). Yield and water productivity variation of *Boro* rice with irrigation strategies and transplanting dates under climate change – a case study in south-western Bangladesh. *Sains Tanah Journal of Soil Science and Agroclimatology*, 19(1): 60-72. <https://dx.doi.org/10.20961/stjssa.v19i1.58560>

### 1. INTRODUCTION

The effect of climate change on crop yield depends on the magnitude of changes in the climatic variables and the crop’s sensitivity to those variables. The climatic variables, particularly the temperature, solar radiation, and atmospheric CO<sub>2</sub> concentration, critically influence the production of rice (Nyang’au et al., 2014). Higher temperature can reduce rice production by reducing spikelet fertility, whereas an increase of CO<sub>2</sub> concentration can increase rice production (Dharmarathna et al., 2012). The effect of increased CO<sub>2</sub> concentration is different on different crops; C3 crops, such as rice, respond to CO<sub>2</sub> more vigorously than C4 crops and their yield increases, on average, by 41% for a doubling of CO<sub>2</sub> concentration (Cure & Acock, 1986). Kontgis et al. (2019) observed a decline in rice yield without CO<sub>2</sub> fertilization but slight increase in yield with CO<sub>2</sub> fertilization in Vietnam. Crop yield may also differ with

planting dates. Planting date fixes the time of occurrence of different growth stages of the crop. Rice is highly susceptible to high temperature at flowering stage (Jagadish et al., 2008). Global warming also alters the growth duration of crops; the warming climate has shortened the rice growth period in China over the past three decades (Zhang et al., 2013). Climate change has already adversely affected India’s rice production (Auffhammer et al., 2012). Changes in rainfall exert a more significant influence on rainfed rice yield than changes in temperature (Boonwichai et al., 2018). The influences of temperature on crop production were reported more pronounced compared to that of rainfall in Bangladesh (Sarker et al., 2012). However, climate change is expected to cause low flows, droughts, and significant changes in river salinity in the south-west coastal area of Bangladesh during the dry season. Due to temporal and spatial variation in

climate variables, the impacts of climate change on crop yield will differ for different locations, seasons, crops, cultivars and also for recent and future periods. Therefore, it is crucial to understand the changes in yield and water productivity of crops during the past decades to deal with future impacts of climate change.

The impacts of climate change have imposed major uncertainties into food security and water resources management in Bangladesh. Climate variability has a significant effect on water demand and yield of rice and the effect varies among the three rice-growing seasons of Bangladesh, namely Kharif-I, Kharif-II and Rabi (Sarker et al., 2012). In North-western parts of the country, the temperature is already approaching critical levels from March to June (Wright, 2014). Karim et al. (2012) predicted 33% reduction in rice yields during 2081 to 2100 in Bangladesh. However, prediction also reveals an increase in food grain production due to an increase in atmospheric CO<sub>2</sub> fertilization under increasing temperature (Karim et al., 1999). Although the predicted increases in CO<sub>2</sub> concentration and incoming solar radiation are found to augment rice yield to some extent, their effects are insignificant compared to the adverse effects of temperature in 2050 and 2070 (Basak et al., 2010).

Freshwater resources being particularly vulnerable to climate change (Mackay, 2008) have become limited in Bangladesh's drought-prone North-West and saline-prone South-West regions where more than 1.8 million people do not have access to an improved water source. Irrigation accounts for the largest off-stream water usage in Bangladesh; about 88% of total water withdrawal in 2008 was used for agriculture, 79% of which came from groundwater source (FAO, 2012). Several studies (Ahmad et al., 2014; Mojid et al., 2021; Mojid et al., 2019; Salem et al., 2017) identified long-term unsustainable water withdrawal and demonstrated significant declining trends in groundwater. Scarcity of irrigation water is hindering crop cultivation in the

coastal saline-prone region, which comprises 30% of the country's total cultivable land. Soil-moisture stress due to lack of freshwater is expected to be more intense during the dry season that might force the farmers to reduce the acreage for *Boro* rice. Consequently, water use in rice production systems must be reduced and water productivity increased to cope with declining water availability (Belder et al., 2004). Therefore, it is essential to reduce the usage of freshwater for irrigation without causing any decline in food grain production, and that is to be done under the likely impact of climate change.

Adaptation under climate change will be more challenging for developing countries than the developed ones due to limitations in adaptive capacity. Therefore, the effectiveness of low-cost adaptation strategies should be justified. The adoption of efficient surface irrigation is very important for salinity-prone regions to cope with the impact of climate change (Haj-Amor & Acharjee, 2020). Adjustment of planting date could also be a potential option to reduce the irrigation demand of rice (Mainuddin et al., 2020). In Vietnam, the rice yield increases to potential levels during summer when transplanting date is altered and additional irrigation is applied (Shrestha, 2014). The alternation of cropping seasons promoted the positive effects of doubling CO<sub>2</sub> in Northern Japan (Horie et al., 1996). Several studies (Acharjee, Halsema, et al., 2017; Acharjee, Ludwig, et al., 2017; Basak et al., 2010; Dasgupta et al., 2015, 2018; Karim et al., 2012; Karim et al., 1990; Mojid et al., 2015; Rabbani et al., 2013; Shahid, 2011) have addressed the effects of climate change on water requirement, yield and water productivity of rice in Bangladesh. However, the influences of agronomic managements like irrigation management and adjustment of transplanting date on yield and water productivity of *Boro* rice have not received adequate attention yet. So, this study evaluated the yield and water productivity variation of *Boro* rice with five planting dates and four irrigation strategies.

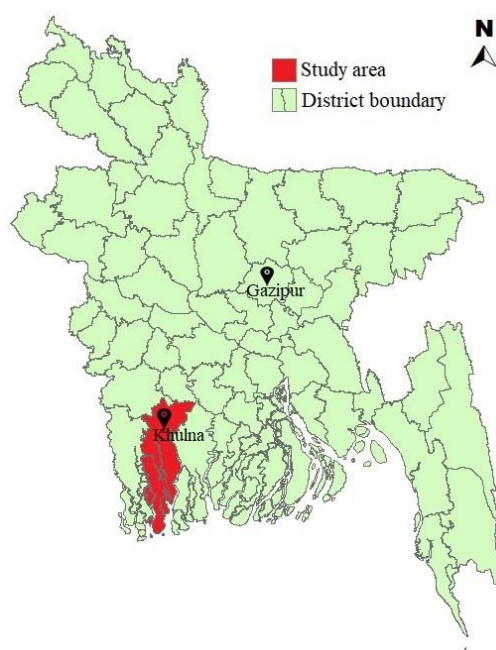


Figure 1. The location of the study area (Khulna) in Bangladesh map

## 2. METHODOLOGY

### 2.1. Study area

The south-western region of Bangladesh is a 'salinity risk' hotspot of the country. The present study focused on Khulna District (Fig. 1) that extends from 22° 42' to 23° 00' N latitude and 88° 14' to 89° 45' E longitude and has a gentle slope and an elevation of 9 m above mean sea level. The area is characterized with a tropical Savanna climate (a dry winter and a rainy summer). Soil pH ranges from 6.4 to 7.9 and organic matter from 0.54% to 2.42%. The annual average temperature is 26.3 °C and the monthly mean temperature varies between 12.4°C in January and 34.3°C in May. The annual average rainfall is 1,809.4 mm, 87% of which occurs from May to October. Rice-based cropping patterns dominate most of the area, with high yielding *Boro* rice covering 31,253 ha and yielding 122,432 metric tons rice grain during 2016–17 (BBS, 2020). Most of the present *Boro* rice cultivars are drought and salinity sensitive.

### 2.2. Data collection

The daily climate data on maximum and minimum temperatures, relative humidity, wind speed, sunshine duration and rainfall for Khulna weather station were collected from Bangladesh Meteorological Department (BMD) for the period from 1984 to 2017. Data on soil textures were collected from the Soil Resources Development Institute (SRDI) of Bangladesh. Daily reference crop evapotranspiration ( $ET_o$ ) was estimated from the climate data by using Penman-Monteith method as expressed by Allen et al. (1998),

$$ET_o = \frac{0.408\Delta(R_n - G) + \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + 2(1 + 0.34u_2)} \quad [1]$$

For details of the variables and coefficients of the Penman-Monteith model, the readers are referred to Allen et al. (1998).

### 2.3. FAO-AquaCrop 6.0 model

FAO-AquaCrop model describes how crops and waterways interact in the soil-crop-atmosphere system. This model was developed by FAO with a view to balance simplicity, robustness, and accuracy. AquaCrop model uses a relatively small number of explicit parameters and the estimation procedure is grounded on basic and complex biophysical processes to guarantee an accurate simulation. It requires inputs on local climate data, crop characteristics and management practices to run the simulation (Raes et al., 2009). The model reliably simulates attainable crop biomass and harvestable yield in response to available water (Steduto et al., 2009) by utilizing normalized biomass-water productivity and adjusted harvest index (HI). The biomass-water productivity expresses above-ground dry matter produced per unit land area per unit of water transpired, and normalized biomass-water productivity takes into account the adjustments for atmospheric CO<sub>2</sub>, climate, synthesized products and soil fertility. The adjusted HI takes into account the total effect of both water and temperature stresses.

### 2.4. AquaCrop model parameterization and calibration

AquaCrop model needs three main input files: climate, crop and soil files. The climate input file for the model was

prepared by using the climate data. The crop file was parameterized for *Boro* rice (BRRI Dhan28, a popular HYV *Boro* rice variety cultivated widely in Bangladesh) utilizing the observed data of Mondal et al. (2015) and Saha and Mondal (2015) for 2012–13 crop period for a central district (Gazipur) of Bangladesh (Fig. 1). The Growing-Degree-Days (GDD) approach was adopted in AquaCrop model; GDD determines crop development and phenology (Miller et al., 2001). The GDD values were calibrated in the model using data of 2012–13 crop period to better simulate the duration of different growth stages of the selected rice variety. The calibrated GDD from transplanting to recovered transplant, maximum rooting depth, initiation of senescence, flowering and maturity are 78, 648, 1214, 1127 and 1783°C, respectively. GDD is 202°C during flowering stage and 1869°C during entire crop period. The base temperature is 8°C and upper temperature is 30°C. The soil input file was parameterized for deep uniform 'silty clay' soil profile. Default values of atmospheric CO<sub>2</sub> concentration for the period from 1902 to 2099 (MaunaLoa.CO2) were also included in the climate input file.

### 2.5. Estimation of yield and water productivity

The normalized biomass-water productivity was estimated by taking into account the influence of atmospheric CO<sub>2</sub> concentration and climate variables, and harvest index (HI) by taking into account both water and temperature stresses (both heat and cold stress) for calculating biomass and grain yield of rice. Note that the effects of soil salinity, weed infestation and soil fertility stress had not been considered in estimating yield since our purpose is to identify the impact of climate change only on the potential yield of rice. The details of estimating crop attributes by AquaCrop model can be found in Steduto et al. (2009) and Raes et al. (2009).

Water productivity is the amount of water required to produce yield; the amount of water can have different measures, such as net irrigation water requirement of the crop, irrigation water requirement plus effective rainfall, and actual crop evapotranspiration (ET). In this study, ET-water productivity and irrigation-water productivity of *Boro* rice were estimated for the period from 1985 to 2017. AquaCrop model simulated ET-water productivity from crop yield and total reference crop evapotranspiration,  $ET_o$ , and irrigation-water productivity from model outputs of potential yield and irrigation amount. The two water productivity indices are expressed as:

$$ET\text{-water productivity} = \frac{\text{Potential grain yield}}{\text{Total } ET_o \text{ during the growing period}} \quad [2]$$

$$Irrigation\text{-water productivity} = \frac{\text{Potential grain yield}}{\text{Net irrigation}} \quad [3]$$

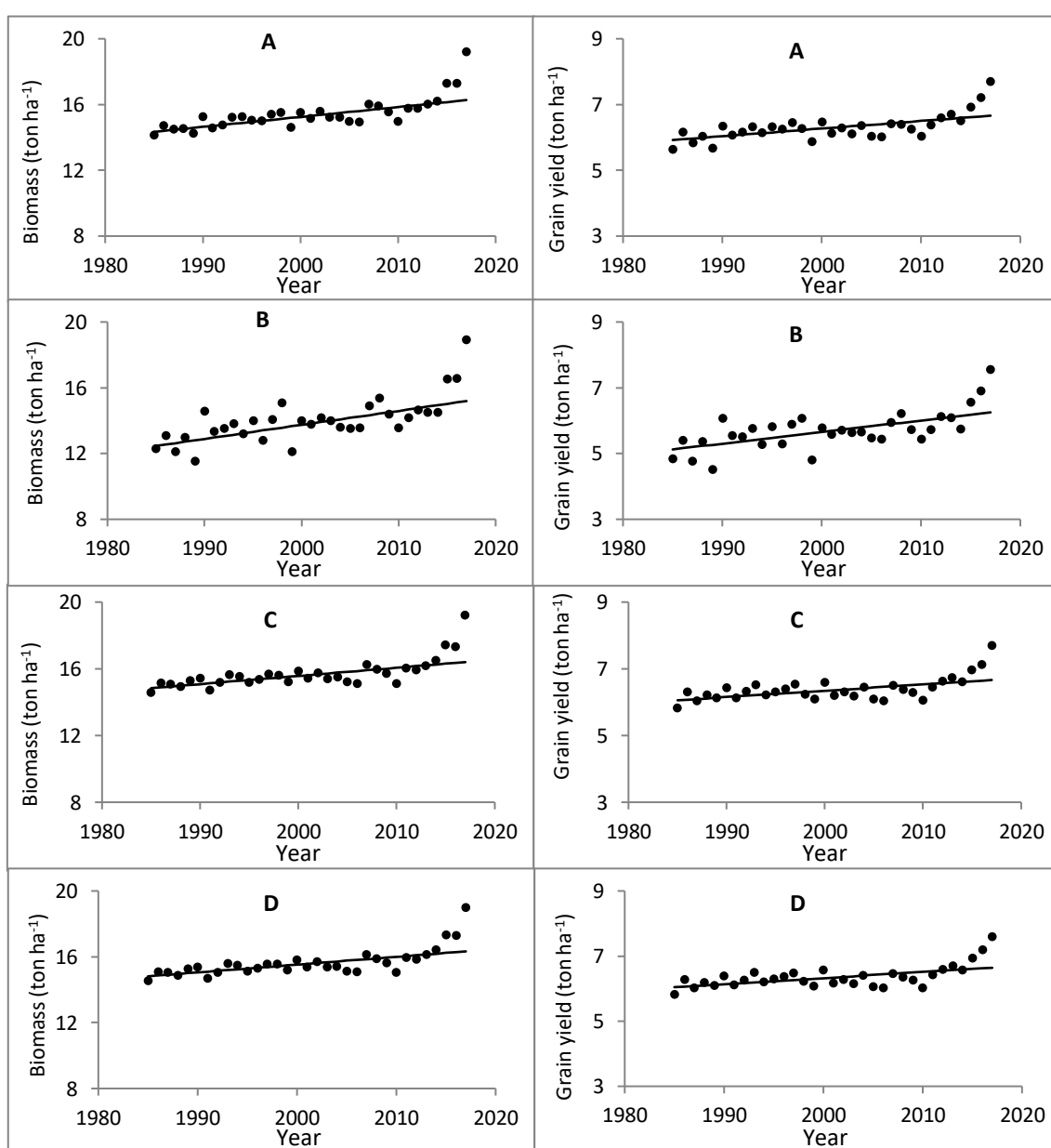
The biomass, grain yield and growth period of *Boro* rice; total  $ET_o$  and available rainfall (R) during the growth period of rice; applied (net) irrigation and infiltration amount, and ET-water productivity were estimated by using the AquaCrop model. Rainfall deficit was estimated from  $ET_o$  and R as ( $ET_o - R$ ) during the growth period. Irrigation-water productivity was calculated from potential grain yield and net irrigation amount (Eq.3).

**Table 1.** Four different irrigation strategies for simulating yield and water productivity of *Boro* rice

Irrigation strategies	Time criteria	Irrigation interval/timing	Application amount
Fixed short-interval irrigation (Strategy A)	Before 19 <sup>th</sup> DAT* 20 <sup>th</sup> to 99 <sup>th</sup> DAT After 100 <sup>th</sup> DAT	At 12 <sup>th</sup> day 8 days interval 12 days interval	100 mm
Fixed long-interval irrigation (Strategy B)	Before 19 <sup>th</sup> DAT 20 <sup>th</sup> to 99 <sup>th</sup> DAT After 100 <sup>th</sup> DAT	At 16 <sup>th</sup> day 12 days interval 16 days interval	100 mm
Measured irrigation with 'low stress, low dose' (Strategy C)	Before 19 <sup>th</sup> DAT 20 <sup>th</sup> to 99 <sup>th</sup> DAT After 100 <sup>th</sup> DAT	50% depletion of RAW** 20% depletion of RAW 50% depletion of RAW	Back to field capacity (FC)
Measured irrigation with 'high stress, high dose' (Strategy D)	Before 19 <sup>th</sup> DAT 20 <sup>th</sup> to 99 <sup>th</sup> DAT After 100 <sup>th</sup> DAT	60% depletion of RAW 30% depletion of RAW 60% depletion of RAW	Back to FC plus 10 mm additional water

Remarks: \*DAT = Days after transplanting

\*\*RAW = Readily available water

**Figure 2.** Trends of changes in biomass production and grain yield of *Boro* rice during 1985–2017 in Khulna with irrigation under fixed short-interval irrigation (A), fixed long-interval irrigation (B), measured irrigation with 'low stress, low dose' strategy (C) and measured irrigation with 'high stress, high dose' strategy (D).

Four irrigation input files were prepared to specify four different irrigation strategies considering different time and depth criteria (Table 1). Fixed short-interval irrigation is the most common irrigation practice in Bangladesh except in some locations that suffer from drought or salinity problems. On the other hand, fixed long-interval irrigation is a usual practice in areas with less water availability or metered-pricing-practice irrigation schemes in which the volume of supplied water is metered in real time and water price is estimated from its volume. Measured irrigation has been a less practiced method in Bangladesh during the past decades. However, adoption of Alternate Wetting and Drying (AWD) method for rice irrigation in recent years has introduced a form of measured irrigation.

The effects of different irrigation strategies were evaluated by estimating yield, water requirement and productivity parameters of *Boro* rice for a normal transplanting date (1 January). The effects of adjustment of transplanting date were quantified by estimating these crop attributes for very early (1 December), early (15 December), late (15 January) and very late (1 February) transplanting dates under fixed-interval irrigation application.

## 2.6. Trend analysis of potential yield and water productivity

The trends of the predicted yield, water requirement and water productivity of *Boro* rice were estimated by using non-parametric Mann-Kendall test. The slopes of these rice attributes were estimated using non-parametric Sen's method (Sen, 1968), which being insensitive to outliers provides robust estimates of the slopes. The method is robust compared to typical other methods for estimating slope of regression lines (Sen, 1968). Sen's slope is given by the median slope that is estimated as a change in value per change in time and expressed by

$$\text{Sen's slope} = \text{Median} \left( \frac{x_j - x_i}{j - i}; i < j \right) \quad [4]$$

where  $x_i$  and  $x_j$  are time series elements with  $i < j$ .

## 3. RESULTS

### 3.1. Trend of potential rice yield

Both potential biomass and grain yields of *Boro* rice show increasing trends during 1985 to 2017 in the study area

(Khulna District) for the four irrigation strategies (Fig. 2). However, the average biomass production is higher with the measured irrigation strategies (15.73 ton ha<sup>-1</sup> for 'low stress, low dose' and 15.67 ton ha<sup>-1</sup> for 'high stress, high dose' strategy) than with the fixed irrigation strategies (15.42 ton ha<sup>-1</sup> for short-interval irrigation and 14.06 ton ha<sup>-1</sup> for long-interval irrigation) (Table 2). The measured irrigation with 'low stress, low dose' strategy produces the highest grain yield, while the fixed long-interval strategy produces the lowest grain yield. The average grain yield during 1985–2017 period revealed higher production under the measured irrigation strategies (1.59% more for 'low stress, low dose' and 1.27% more for 'high stress, high dose') compared to the fixed short-interval irrigation application. The fixed long-interval irrigation application results in 8.82% less biomass and 9.37% less grain yield compared to fixed short-interval irrigation application. Both the biomass and grain yields show more variations during recent decades under the fixed long-interval irrigation strategy compared to the other irrigation strategies. The Mann-Kendall test reveals significant ( $p \leq 0.05$ ) increasing trends of the biomass and grain yields under the four irrigation strategies. These results are in agreement with those of Chowdhury and Khan (2015), who reported increasing trend in the yield of *Boro* rice during the recent decades. Therefore, the recent changes in climate variables did not impose any direct detrimental impact on biomass and grain production of *Boro* rice; rather, promising increasing trends of these rice attributes were predicted under the changing climate.

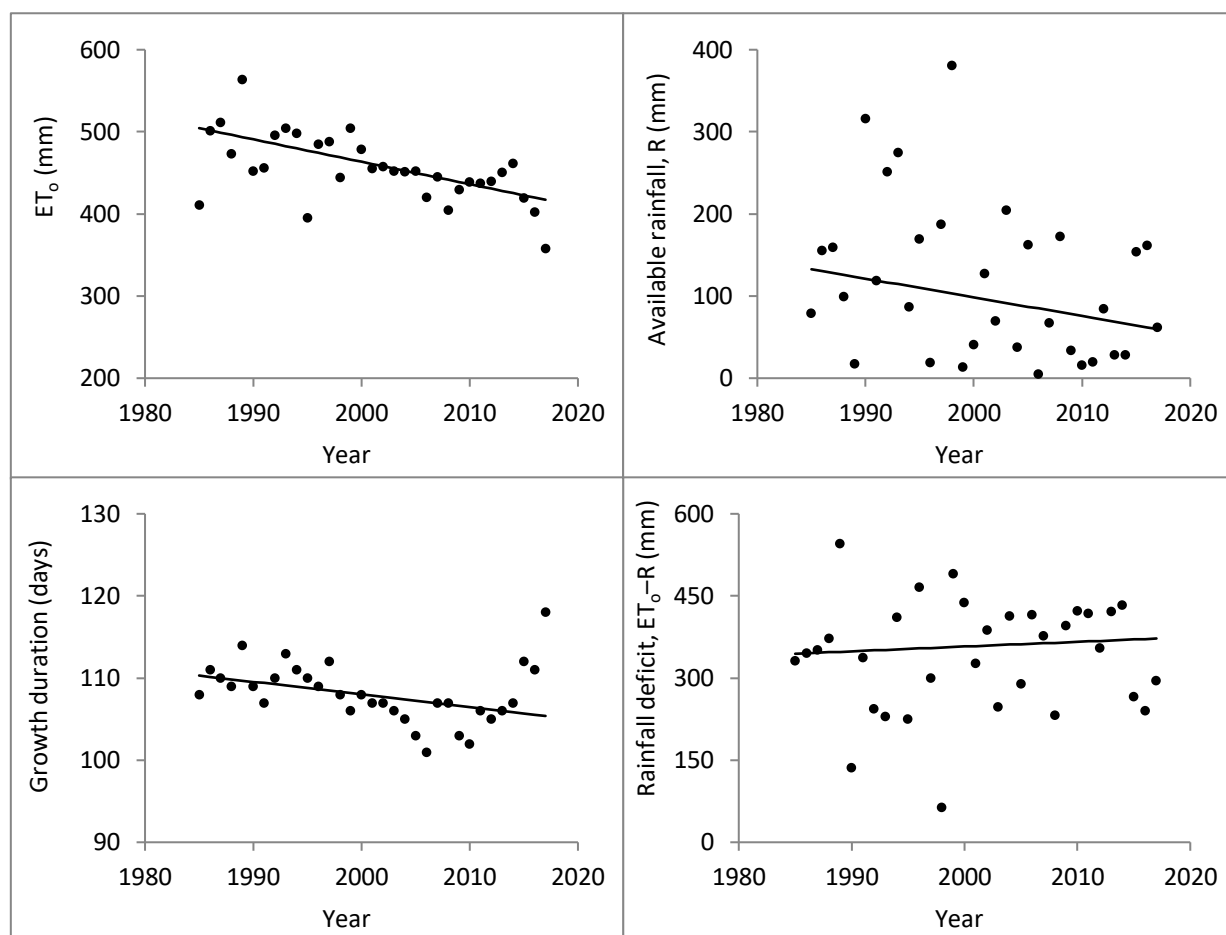
### 3.2. Trend of reference crop evapotranspiration and irrigation amount

Fig. 3 illustrates declining trends of reference crop evapotranspiration,  $ET_o$ , available rainfall,  $R$ , and crop-growth duration, and increasing trends of rainfall deficit, ( $ET_o - R$ ), during *Boro* rice cultivation. The  $ET_o$  and  $R$  show a significant ( $p \leq 0.05$ ) declining trend during the growth period of rice, the rate of decline being 2.73 mm year<sup>-1</sup> and 2.28 mm year<sup>-1</sup>, respectively. The decline in  $ET_o$  and  $R$  during the crop period was mainly due to significant declining trend of growth duration (0.15 days year<sup>-1</sup>) of *Boro* rice.

**Table 2.** Statistics of biomass and grain yield of *Boro* rice during 1985 to 2017 in Khulna following the fixed short-interval irrigation (A), fixed long-interval irrigation (B), measured irrigation with 'low stress, low dose' strategy (C) and measured irrigation with 'high stress, high dose' strategy (D).

Statistics	Biomass for irrigation strategy:				Grain yield for irrigation strategy:			
	A	B	C	D	A	B	C	D
Mean biomass/grain yield (ton ha <sup>-1</sup> )	15.42	14.06	15.73	15.67	6.30	5.71	6.40	6.38
Standard deviation (ton ha <sup>-1</sup> )	0.99	1.41	0.89	0.86	0.41	0.59	0.36	0.35
Mann-Kendall test value with significance level	5.25***	4.42***	4.82***	4.71***	4.00***	3.77***	3.27**	3.21**
Sen's slope estimate (ton ha <sup>-1</sup> year <sup>-1</sup> )	0.061	0.085	0.049	0.047	0.023	0.035	0.019	0.019
Average change (%) compared to case A	0.00	-8.82	2.01	1.62	0.00	-9.37	1.59	1.27

Remarks: \*\* and \*\*\* signs indicate significant at 0.01 and 0.001 level of significance, respectively.



**Figure 3.** Trends of changes in reference crop evapotranspiration ( $ET_0$ ), available rainfall, growth duration, and rainfall deficit during *Boro* rice cultivation from 1985 to 2017 in Khulna (same for all irrigation strategies).

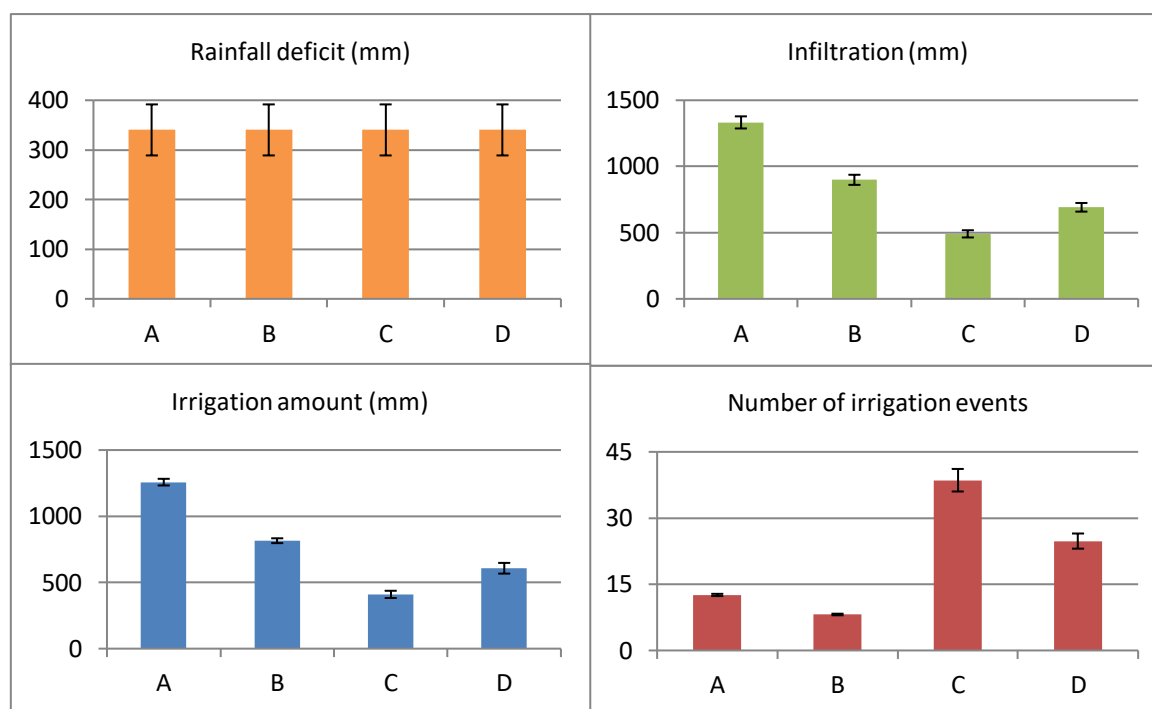
The reduction in growth duration is a direct effect of increasing temperature during the recent past decades as reported by (Acharjee, Halsema, et al., 2017) for the North-West region of Bangladesh. The rate of decline was smaller for R than for  $ET_0$  with a resulting increase in rainfall deficit by  $0.87 \text{ mm year}^{-1}$ . This result indicates continuously increasing climatic water requirement of *Boro* rice in the study area. Although rainfall deficit remains invariable for the four irrigation strategies, the amount of infiltration varies depending on soil-water balance associated with the water application strategies. Water loss through infiltration is higher under fixed short-interval irrigation application compared to measured 'low stress, low dose' irrigation application. So, the amount of irrigation varies accordingly for different irrigation strategies as illustrated in Fig. 4. For the measured application of irrigation, infiltration loss is 63% less for 'low stress, low dose' and 48% less for 'high stress, high dose' strategy compared to fixed short-interval irrigation application. Infiltration loss is 33% lower under fixed long-interval irrigation application than fixed short-interval irrigation application. Consequently, the fixed long-interval irrigation application requires 35% less water than fixed short-interval irrigation application. For the measured irrigation application, the amount of irrigation is 67% less for 'low stress, low dose' and 52% less for 'high stress, high dose' strategy compared to fixed short-interval irrigation application. Therefore, the measured application of irrigation would save a significant amount of water without affecting the yield of *Boro* rice. This

result is in agreement with that of Chapagain and Yamaji (2010), who reported 28% saving of water with AWD irrigation practice without any reduction in grain yield of rice.

Although water requirement is less for the measured application of water, the number of irrigation events is almost three times higher for 'low stress, low dose' and two times higher for 'high stress, high dose' irrigation strategy compared to the fixed short-interval application of water. For the fixed long-interval irrigation application, the number of irrigation events is only 0.6 times of that for the fixed short-interval application of water.

### 3.3. Trend of crop-water productivity

Both ET-water productivity (Eq.2) and irrigation-water productivity (Eq.3) of *Boro* rice show increasing trend for the fixed application of irrigation with both the short- and long-interval, and measured application of irrigation with both the 'low stress, low dose' and 'high stress, high dose' strategies (Fig. 5). However, the increasing trends of water productivities are of different patterns for different irrigation management practices. Although ET-water productivity varies minimally with the irrigation strategies, irrigation-water productivity varies greatly between the fixed interval and measured irrigation strategies. This is because ET of rice remains mostly unchanged among the irrigation strategies, but water loss is much higher under the fixed-interval irrigation application compared to the measured irrigation application.



**Figure 4.** Average (bars) and standard deviation (error bars) of rainfall deficit, infiltration amount, irrigation amount and number of irrigation events for *Boro* rice cultivation during 1985–2017 in Khulna under fixed short-interval irrigation (A), fixed long-interval irrigation (B), measured irrigation with ‘*low stress, low dose*’ strategy (C) and measured irrigation with ‘*high stress, high dose*’ strategy (D).

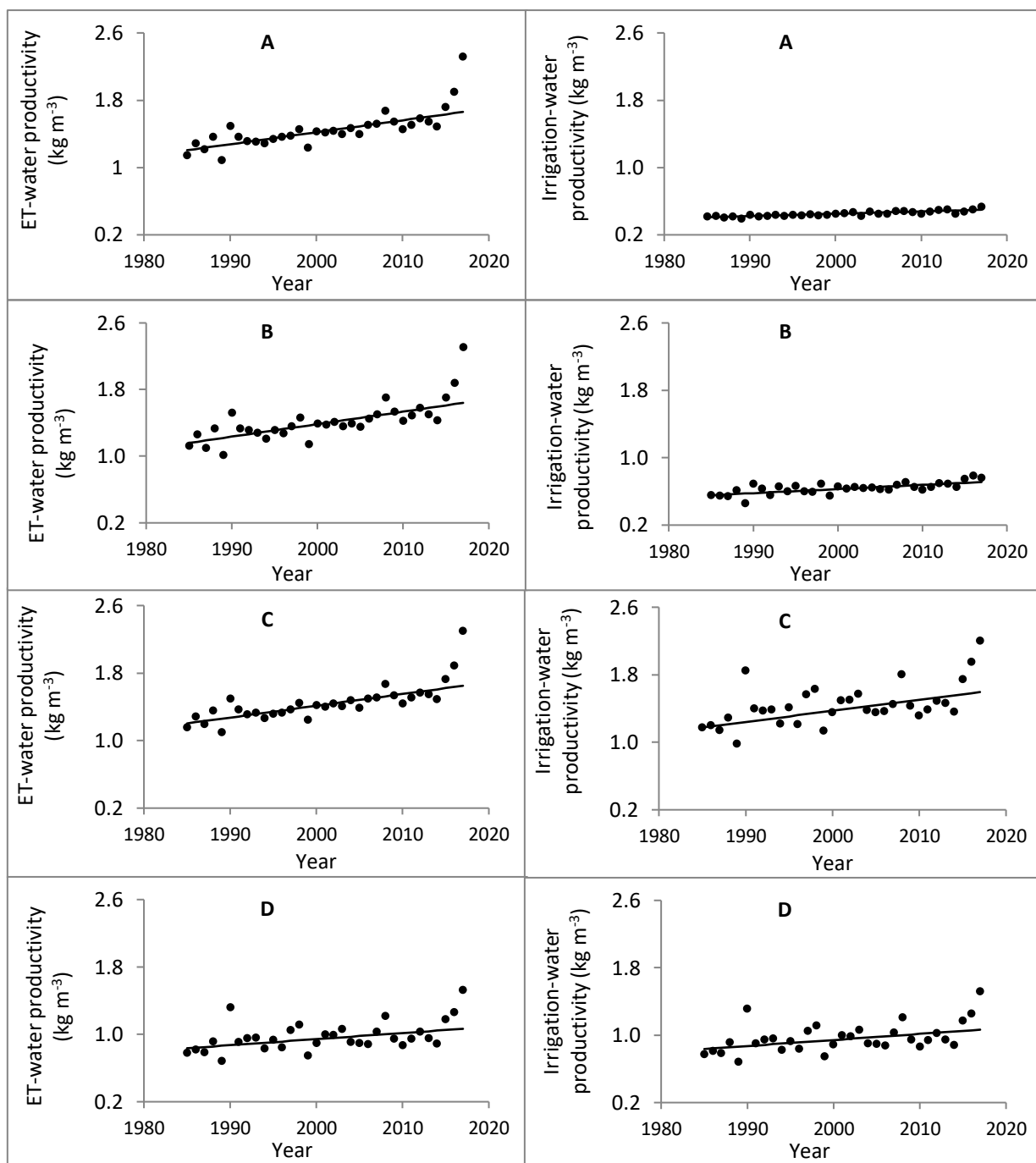
**Table 3.** Statistics of ET-water productivity and irrigation-water productivity of *Boro* rice during 1985 to 2017 in Khulna following the fixed short-interval irrigation (A), fixed long-interval irrigation (B), measured irrigation with ‘*low stress, low dose*’ strategy (C) and measured irrigation with ‘*high stress, high dose*’ strategy (D).

Statistics	ET-water productivity for irrigation strategy:				Irrigation-water productivity for irrigation strategy:			
	A	B	C	D	A	B	C	D
Mean water productivity (kg m <sup>-3</sup> )	1.46	1.42	1.45	1.46	0.45	0.64	1.45	0.97
Standard deviation (kg m <sup>-3</sup> )	0.22	0.24	0.22	0.22	0.03	0.07	0.25	0.17
Mann-Kendall test value with significance level	5.72***	5.19***	5.67***	5.60***	5.78***	4.11***	3.08**	2.74**
Sen’s slope estimate (kg m <sup>-3</sup> year <sup>-1</sup> )	0.014	0.015	0.014	0.014	0.003	0.005	0.013	0.007
Average change (%) compared to case A	0.00	-2.74	-0.68	0.00	0.00	42.22	222.22	115.56

Remarks: \*\* and \*\*\* signs indicate significant at 0.01 and 0.001 level of significance, respectively.

Both the fixed short-interval irrigation application and the measured irrigation application with ‘*high stress, high dose*’ strategies provide the highest average ET-water productivity (1.46 kg m<sup>-3</sup>) (Table 3). However, this water productivity for the fixed long-interval irrigation application and the measured irrigation application with ‘*low stress, low dose*’ strategy (1.42 and 1.45 kg m<sup>-3</sup>, respectively) does not differ significantly from the highest water productivity. The measured irrigation application with ‘*low stress, low dose*’ strategy provides the highest average irrigation-water productivity (1.45 kg m<sup>-3</sup>), which is statistically similar to the average ET-water productivity under the same irrigation strategy. Both the fixed short- and long-interval irrigation applications provide much lower irrigation-water productivity (0.45 and 0.64 kg m<sup>-3</sup>, respectively) compared to the

measured irrigation application with ‘*low stress, low dose*’ strategy. This water productivity under measured irrigation application with ‘*high stress, high dose*’ strategy is also lower than that under the measured irrigation application with ‘*low stress, low dose*’ strategy, but higher than that under the fixed short- and long-interval irrigation application. The Mann-Kendall test result reveals significant increasing trends of water productivity for all four irrigation strategies (Table 2). The average increase in irrigation-water productivity is 222% higher for the measured irrigation application with ‘*low stress, low dose*’ strategy than for the fixed short-interval irrigation application. This result is in alignment with that of Pirmoradian et al. (2004) who reported 60% increase in water-use efficiency with intermittent flooding compared to continuous flooding for rice cultivation in Iran.



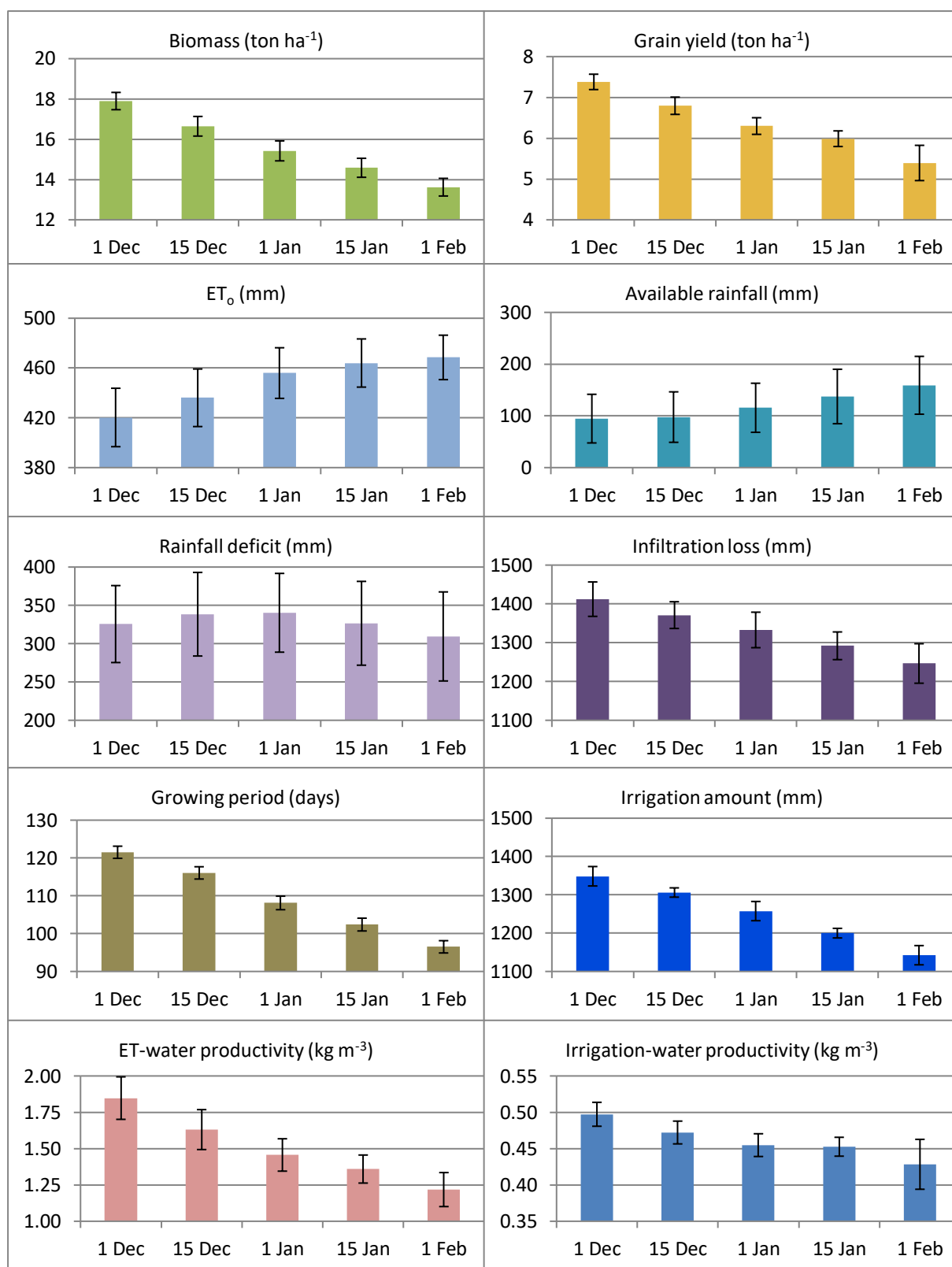
**Figure 5.** Trends of changes in ET-water productivity and irrigation-water productivity of *Boro* rice during 1985–2017 in Khulna under fixed short-interval irrigation (A), fixed long-interval irrigation (B), measured irrigation with 'low stress, low dose' strategy (C), and measured irrigation with 'high stress, high dose' strategy (D).

### 3.4. Yield and water productivity of rice under different transplanting dates

Fig. 6 illustrates a comparison of average (bars) and standard deviation (error bars) of the simulated potential yield, water requirement and water-productivity components of *Boro* rice among very early (1 December), early (15 December), normal-time (1 January), late (15 January) and very late (1 February) transplanting dates. The average biomass and grain yields are higher for early transplanting dates but lower for late transplanting dates compared to normal transplanting date. Total reference crop evapotranspiration and available rainfall during the rice-

growing period are lower for early transplanting but higher for late transplanting compared to normal planting date. The higher available rainfall is obtained mainly due to more number of rainy days usually with large amount of rainfall under late transplanting dates compared to early transplanting. Rainfall deficit is the largest for normal transplanting date but lower for late transplanting due to higher available rainfall and for early transplanting due to lower reference crop evapotranspiration compared to normal transplanting date. From a climatic water-demand perspective, the late transplanting of *Boro* rice would be the best choice and the early planting would be a better one compared to the normal transplanting date.





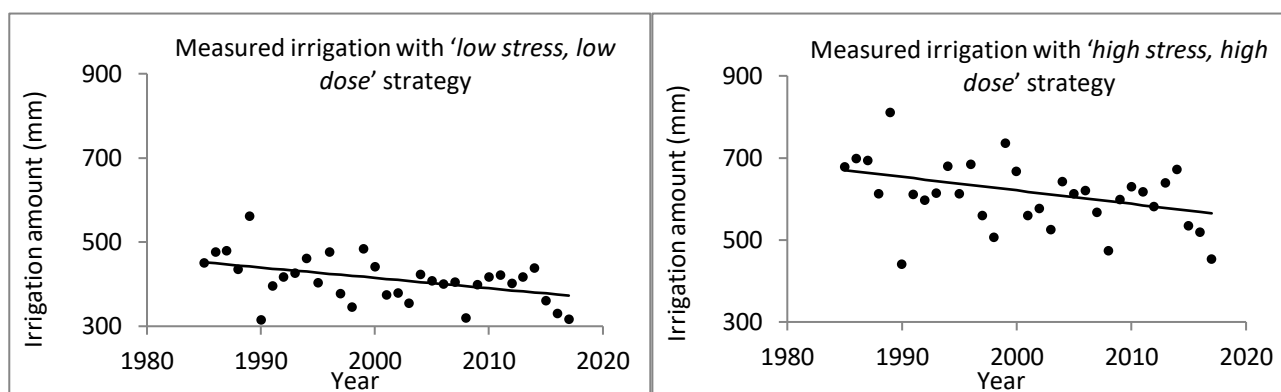
**Figure 6.** Biomass, grain yield, reference crop evapotranspiration (ET<sub>o</sub>), available rainfall during growing period, rainfall deficit, infiltration loss, duration of growing period, irrigation amount, ET-water productivity and irrigation-water productivity of *Boro* rice during 1985–2017 in Khulna for different transplanting dates (1 Dec: very early; 15 Dec: early; 1 Jan: Normal; 15 Jan: late; 1 Feb: very late transplanting) under fixed short interval irrigation.

For the commonly-practiced fixed-interval irrigation application, infiltration loss of water from the crop field is significant; it is higher for early transplanting and lower for late transplanting compared to normal transplanting time. Consequently, the amount of irrigation requirement is also

higher for early transplanting but lower for late transplanting compared to the normal transplanting time. So, from a water-requirement perspective, the late transplanting would be a better choice than the early and normal-time transplanting.

**Table 4.** Average change (%) in different study parameters of *Boro* rice during 1985 to 2017 in Khulna for early and late transplanting dates (1 Dec: very early; 15 Dec: early; 15 Jan: late; 1 Feb: very late transplanting) compared to normal transplanting date (1 Jan) under fixed short-interval irrigation.

Parameters	Change in parameters (%) for:			
	Early transplanting dates		Late transplanting dates	
	1 Dec	15 Dec	15 Jan	1 Feb
Biomass	16.0	7.9	-5.4	-11.7
Grain yield	17.2	7.9	-4.9	-14.4
Reference crop evapotranspiration, $ET_0$	-7.8	-4.4	1.8	2.8
Available rainfall during growing period, R	-18.1	-15.6	18.8	37.6
Rainfall deficit, $ET_0 - R$	-4.3	-0.5	-4.0	-9.1
Infiltration loss	6.0	2.9	-3.1	-6.5
Irrigation amount for fixed-interval application	7.2	3.9	-4.6	-9.2
Growing period	12.4	7.3	-5.3	-10.7
ET-water productivity	26.9	12.0	-6.7	-16.4
Irrigation-water productivity	9.3	3.8	-0.5	-5.8



**Figure 7.** Applied irrigation amount for *Boro* rice cultivation under measured irrigation strategies during 1985–2017 in Khulna.

Despite the increasing irrigation requirement under early transplanting, the higher yield of rice provides higher ET-water productivity and irrigation-water productivity compared to the normal-time and late transplanting. Therefore, both from the grain yield and water productivity perspectives, the early transplanting of *Boro* rice would be a better choice for the study area.

Very early transplanting (1 December) of *Boro* rice would increase biomass and grain yields by 16.0% and 17.2%, respectively, while very late transplanting (1 February) would reduce biomass and grain yields by 11.7% and 14.4%, respectively compared to the normal-time transplanting (Table 4). Under very early transplanting, the reference crop evapotranspiration, available rainfall and rainfall deficit decrease by 7.8%, 18.1% and 4.3%, respectively compared to normal-time transplanting of *Boro* rice. However, the infiltration loss and the amount of irrigation requirement with the usual fixed-interval irrigation application increase by 6.0% and 7.2%, respectively under early transplanting compared to the normal-time transplanting. In spite of this additional water requirement, the ET-water productivity and irrigation water productivity increase by 26.9% and 9.3%, respectively under very early transplanting compared to normal-time transplanting. Both the grain yield and water productivity decrease as the transplanting date shifts forward.

#### 4. DISCUSSION

The increase in biomass and grain yields, as estimated in this study, is likely to be due to the positive impacts of changing climate variables, including minimum temperature, humidity and atmospheric  $CO_2$  concentration, which increased consistently from 345 ppm in 1984 to 406 ppm in 2017 ( $1.88 \text{ ppm year}^{-1}$ ). Zhang et al. (2021) find out that rice yield would remain stable or increase slightly because some positive effects of increased precipitation and  $CO_2$  concentration offset the negative effects of increased temperature on rice. Several studies (Allen et al., 1998; Cure & Acock, 1986) demonstrated the increase in yield of C3 plants like rice due to increased level of  $CO_2$  concentration. The increase in rice yield with increasing  $CO_2$  has also been predicted for several regions of China (Yao et al., 2007). Although a temperature rise would significantly reduce rice production, a doubling of atmospheric  $CO_2$  concentration in association with the rise in temperature would result in 20% increase in rice production (Karim et al., 1999). Therefore, the increase in temperature during the recent decades has not exceeded the threshold that could subjugate the positive effect of increased  $CO_2$  on rice yield. On the basis of increasing trends of biomass and grain yields, the most effective irrigation method is the 'fixed short-interval irrigation application (Strategy A, Table 1)' since the rice crop can

exploit the benefit of increased CO<sub>2</sub> concentration more efficiently under the situation of more water availability; the benefit of increased CO<sub>2</sub> concentration decreases under water stress condition. However, in accordance with the highest biomass and grain yields, the most effective irrigation method is the 'measured irrigation with 'low stress, low dose' strategy (C, Table 1)'. Therefore, the sequence of superior irrigation strategy would be *Strategy C > Strategy D > Strategy A > Strategy B* considering the yield attributes of *Boro* rice. On the other hand, the sequence of strategy in order of their superiority would be *Strategy C > Strategy D > Strategy B > Strategy A* considering irrigation-demand management.

The more precise the irrigation application, the more is the number of irrigation events and more challenging the management of a large number of irrigation events becomes. Adjustment of the irrigation system following precise irrigation techniques is required to implement the measured irrigation application described in this study. Making irrigation system automatic will further increase the precision of water application. The applied irrigation amount under the fixed-interval irrigation application does not depict the actual water demand by the crop, but the water that is applied under the fixed criteria. So, the long-term estimate of the applied water under the fixed-interval irrigation does not show any significant variation over time since the number of irrigation remains almost same over the years except only minimal possibility of variation due to change in growth duration of the crop. Under the measured irrigation application, there are changing trends in irrigation demand of *Boro* rice under some water-stress conditions (Fig. 7). Similar declining trends of irrigation requirement of *Boro* rice was also reported both for the past decades (Acharjee, Halsema, et al., 2017) and future period (Acharjee, Ludwig, et al., 2017) under climate change scenarios in the North-West region of Bangladesh. Therefore, with the measured irrigation strategies, *Boro* rice cultivation will likely exploit the benefit of reduced water demand by the crop. The large increase in irrigation-water productivity under measured irrigation with 'low stress, low dose' strategy occurs mainly due to a large reduction in water usage compared to fixed irrigation methods while grain yield remains almost unchanged. We, therefore, endorse that adjustment of irrigation strategy is an effective way to reduce water usage without reducing the yield although this strategy is not very effective to increase the yield of *Boro* rice.

*Boro* rice passes through more number of days with lower temperature under early transplanting and with higher temperature under late transplanting compared to normal-time transplanting. The low yield of *Boro* rice for late transplanting is associated with the negative effects of unfavourable (high) temperature and possible heat-stress (Acharjee et al., 2019). The temperature variation during growth periods for the two transplanting dates also causes variation in growth duration of the crop. The early transplanting of rice requires a higher amount of irrigation due to higher infiltration loss of water and the late transplanting requires lower amount of irrigation due to lower infiltration loss compared to the normal-time transplanting. Therefore, the sequence of superiority of the

transplanting time would be *1 December > 15 December > 1 January > 15 January > 1 February* as per yield attributes. But the sequence would be just the reverse of that for the yield attributes on the basis of irrigation-demand management. Therefore, the adjustment of transplanting date, although effective in improving biomass and grain yields of *Boro* rice with some additional increase in water demand, is not very effective to increase water productivity.

Since the AquaCrop model simulates attainable crop biomass and harvestable yield, these crop attributes will not be similar to those under real field conditions due to multiple stresses like salinity, nutrient deficiency, and weed and pest infestation. Although the biomass and grain yields may not be as large in real field conditions as estimated in this study, the trends of their variation in response to changes in climatic condition will be similar under normal conditions.

## 5. CONCLUSION

Irrigation strategy with measured application of irrigation water significantly reduces water loss compared to irrigation strategy with fixed-interval application of water and consequently has a potential to save large amount of water without affecting the yield. Compared to latter transplanting of rice seedlings within feasible transplanting period early transplanting always provides higher potential yield and water productivity of *Boro* rice. However, irrigation water demand of the crop will increase, to some extent, under early transplanting. Hence, the adjustment of the irrigation strategy can increase irrigation-water productivity of rice, while adjustment of the transplanting date can increase potential yield of rice with additional water usage.

## Declaration of Competing Interest

The authors declare no competing financial or personal interests that may appear and influence the work reported in this paper.

## References

- Acharjee, T. K., Halsema, G. v., Ludwig, F., & Hellegers, P. (2017). Declining trends of water requirements of dry season *Boro* rice in the north-west Bangladesh. *Agricultural Water Management*, *180*, 148-159. <https://doi.org/10.1016/j.agwat.2016.11.014>
- Acharjee, T. K., Ludwig, F., van Halsema, G., Hellegers, P., & Supit, I. (2017). Future changes in water requirements of *Boro* rice in the face of climate change in North-West Bangladesh. *Agricultural Water Management*, *194*, 172-183. <https://doi.org/10.1016/j.agwat.2017.09.008>
- Acharjee, T. K., van Halsema, G., Ludwig, F., Hellegers, P., & Supit, I. (2019). Shifting planting date of *Boro* rice as a climate change adaptation strategy to reduce water use. *Agricultural Systems*, *168*, 131-143. <https://doi.org/10.1016/j.agsy.2018.11.006>
- Ahmad, M.-u. D., Kirby, M., Islam, M. S., Hossain, M. J., & Islam, M. M. (2014). Groundwater Use for Irrigation and its Productivity: Status and Opportunities for Crop Intensification for Food Security in Bangladesh. *Water*

- Resources Management*, 28(5), 1415-1429. <https://doi.org/10.1007/s11269-014-0560-z>
- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, 300(9), D05109. <http://www.fao.org/3/x0490e/x0490e00.htm>
- Auffhammer, M., Ramanathan, V., & Vincent, J. R. (2012). Climate change, the monsoon, and rice yield in India. *Climatic Change*, 111(2), 411-424. <https://doi.org/10.1007/s10584-011-0208-4>
- Basak, J. K., Ali, M. A., Islam, M. N., & Rashid, M. A. (2010). Assessment of the effect of climate change on boro rice production in Bangladesh using DSSAT model. *Journal of Civil Engineering (IEB)*, 38(2), 95-108. [http://mail.jce-ieb.org/doc\\_file/3802001.pdf](http://mail.jce-ieb.org/doc_file/3802001.pdf)
- BBS. (2020). *Yearbook of Agricultural Statistics-2019 (31st Series)*. Bangladesh Bureau of Statistics (BBS), Statistics and Informatics Division(SID), Ministry of Planning, Government of the People's Republic of Bangladesh. [https://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/1b1eb817\\_9325\\_4354\\_a756\\_3d18412203e2/2020-05-18-03-38-d3332b38e92c1adb7900d1bb94290177.pdf](https://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/1b1eb817_9325_4354_a756_3d18412203e2/2020-05-18-03-38-d3332b38e92c1adb7900d1bb94290177.pdf)
- Belder, P., Bouman, B. A. M., Cabangon, R., Guoan, L., Quilang, E. J. P., Yuanhua, L., Spiertz, J. H. J., & Tuong, T. P. (2004). Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. *Agricultural Water Management*, 65(3), 193-210. <https://doi.org/10.1016/j.agwat.2003.09.002>
- Boonwichai, S., Shrestha, S., Babel, M. S., Weesakul, S., & Datta, A. (2018). Climate change impacts on irrigation water requirement, crop water productivity and rice yield in the Songkhram River Basin, Thailand. *Journal of Cleaner Production*, 198, 1157-1164. <https://doi.org/10.1016/j.jclepro.2018.07.146>
- Chapagain, T., & Yamaji, E. (2010). The effects of irrigation method, age of seedling and spacing on crop performance, productivity and water-wise rice production in Japan. *Paddy and Water Environment*, 8(1), 81-90. <https://doi.org/10.1007/s10333-009-0187-5>
- Chowdhury, I. U. A., & Khan, M. A. E. (2015). The impact of climate change on rice yield in Bangladesh: a time series analysis. *Russian Journal of Agricultural and Socio-Economic Sciences*, 40(4), 12-28. <https://doi.org/10.18551/rjoas.2015-04.02>
- Cure, J. D., & Acock, B. (1986). Crop responses to carbon dioxide doubling: a literature survey. *Agricultural and Forest Meteorology*, 38(1), 127-145. [https://doi.org/10.1016/0168-1923\(86\)90054-7](https://doi.org/10.1016/0168-1923(86)90054-7)
- Dasgupta, S., Hossain, M. M., Huq, M., & Wheeler, D. (2015). Climate change and soil salinity: The case of coastal Bangladesh. *Ambio*, 44(8), 815-826. <https://doi.org/10.1007/s13280-015-0681-5>
- Dasgupta, S., Hossain, M. M., Huq, M., & Wheeler, D. (2018). Climate Change, Salinization and High-Yield Rice Production in Coastal Bangladesh. *Agricultural and Resource Economics Review*, 47(1), 66-89. <https://doi.org/10.1017/age.2017.14>
- Dharmarathna, W. R. S. S., Weerakoon, S. B., Rathnayake, U. R., & Herath, S. (2012). Variation of irrigated rice yield under the climate change scenarios. SAITM Research Symposium on Engineering Advancements (SAITM – RSEA 2012), Malabe, Sri Lanka.
- FAO. (2012). *Irrigation in Southern and Eastern Asia in figures. AQUASTAT Survey-2011* (K. Frenken, Ed.). Food and Agriculture Organization of The United Nations. [http://www.ipcinfo.org/fileadmin/user\\_upload/faowater/docs/WR\\_37\\_web.pdf](http://www.ipcinfo.org/fileadmin/user_upload/faowater/docs/WR_37_web.pdf)
- Haj-Amor, Z., & Acharjee, T. K. (2020). Effect of irrigation efficiency enhancement on water demand of date palms in a Tunisian oasis under climate change. *Journal of Water and Climate Change*, 12(5), 1437-1453. <https://doi.org/10.2166/wcc.2020.099>
- Horie, T., Matsui, T., Nakagawa, H., & Omasa, K. (1996). Effects of Elevated CO<sub>2</sub> and Global Climate Change on Rice Yield in Japan. In K. Omasa, K. Kai, H. Taoda, Z. Uchijima, & M. Yoshino (Eds.), *Climate Change and Plants in East Asia* (pp. 39-56). Springer Japan. [https://doi.org/10.1007/978-4-431-66899-2\\_4](https://doi.org/10.1007/978-4-431-66899-2_4)
- Jagadish, S. V. K., Craufurd, P. Q., & Wheeler, T. R. (2008). Phenotyping Parents of Mapping Populations of Rice for Heat Tolerance during Anthesis. *Crop Science*, 48(3), 1140-1146. <https://doi.org/10.2135/cropsci2007.10.0559>
- Karim, M. R., Ishikawa, M., Ikeda, M., & Islam, M. T. (2012). Climate change model predicts 33 % rice yield decrease in 2100 in Bangladesh. *Agronomy for Sustainable Development*, 32(4), 821-830. <https://doi.org/10.1007/s13593-012-0096-7>
- Karim, Z., Hussain, S., & Ahmed, M. (1990). *Salinity Problems and Crop Intensification in the Coastal Regions of Bangladesh* (Vol. 3). Soil and Irrigation Division, Bangladesh Agricultural Research Council.
- Karim, Z., Hussain, S. G., & Ahmed, A. U. (1999). Climate Change Vulnerability of Crop Agriculture. In S. Huq, Z. Karim, M. Asaduzzaman, & F. Mahtab (Eds.), *Vulnerability and Adaptation to Climate Change for Bangladesh* (pp. 39-54). Springer Netherlands. [https://doi.org/10.1007/978-94-015-9325-0\\_4](https://doi.org/10.1007/978-94-015-9325-0_4)
- Kontgis, C., Schneider, A., Ozdogan, M., Kucharik, C., Tri, V. P. D., Duc, N. H., & Schatz, J. (2019). Climate change impacts on rice productivity in the Mekong River Delta. *Applied Geography*, 102, 71-83. <https://doi.org/10.1016/j.apgeog.2018.12.004>
- Mackay, A. (2008). Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Journal of Environmental Quality*, 37(6), 2407-2407. <https://doi.org/10.2134/jeq2008.0015br>
- Mainuddin, M., Maniruzzaman, M., Alam, M. M., Mojid, M. A., Schmidt, E. J., Islam, M. T., & Scobie, M. (2020). Water usage and productivity of Boro rice at the field level and their impacts on the sustainable groundwater irrigation in the North-West Bangladesh.

- Agricultural Water Management*, 240, 106294. <https://doi.org/10.1016/j.agwat.2020.106294>
- Miller, P., Lanier, W., & Brandt, S. (2001). Using growing degree days to predict plant stages. *Ag/Extension Communications Coordinator, Communications Services, Montana State University-Bozeman, Bozeman, MO, 59717(406), 994-2721*. <https://store.msuextension.org/publications/AgandNaturalResources/MT200103AG.pdf>
- Mojid, M. A., Aktar, S., & Mainuddin, M. (2021). Rainfall-induced recharge-dynamics of heavily exploited aquifers – A case study in the North-West region of Bangladesh. *Groundwater for Sustainable Development*, 15, 100665. <https://doi.org/10.1016/j.gsd.2021.100665>
- Mojid, M. A., Parvez, M. F., Mainuddin, M., & Hodgson, G. (2019). Water Table Trend—A Sustainability Status of Groundwater Development in North-West Bangladesh. *Water*, 11(6), 1182. <https://www.mdpi.com/2073-4441/11/6/1182>
- Mojid, M. A., Rannu, R. P., & Karim, N. N. (2015). Climate change impacts on reference crop evapotranspiration in North-West hydrological region of Bangladesh. *International Journal of Climatology*, 35(13), 4041-4046. <https://doi.org/10.1002/joc.4260>
- Mondal, M. S., Saleh, A. F. M., Razzaque Akanda, M. A., Biswas, S. K., Md. Moslehuddin, A. Z., Zaman, S., Lazar, A. N., & Clarke, D. (2015). Simulating yield response of rice to salinity stress with the AquaCrop model [10.1039/C5EM00095E]. *Environmental Science: Processes & Impacts*, 17(6), 1118-1126. <https://doi.org/10.1039/C5EM00095E>
- Nyang'au, W. O., Mati, B. M., Kalamwa, K., Wanjogu, R. K., & Kiplagat, L. K. (2014). Estimating Rice Yield under Changing Weather Conditions in Kenya Using CERES Rice Model. *International Journal of Agronomy*, 2014, 849496. <https://doi.org/10.1155/2014/849496>
- Pirmoradian, N., Sepaskhah, A. R., & Maftoun, M. (2004). Effects of Water-Saving Irrigation and Nitrogen Fertilization on Yield and Yield Components of Rice (*Oryza sativa* L.). *Plant Production Science*, 7(3), 337-346. <https://doi.org/10.1626/pps.7.337>
- Rabbani, G., Rahman, A., & Mainuddin, K. (2013). Salinity-induced loss and damage to farming households in coastal Bangladesh. *International Journal of Global Warming*, 5(4), 400-415. <https://doi.org/10.1504/ijgw.2013.057284>
- Raes, D., Steduto, P., Hsiao, T. C., & Fereres, E. (2009). AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description. *Agronomy Journal*, 101(3), 438-447. <https://doi.org/10.2134/agronj2008.0140s>
- Saha, D., & Mondal, M. S. (2015). Simulation of Boro Rice Yield in South-west Coastal Bangladesh Using the AquaCrop Model. 5th International Conference on Water & Flood Management (ICWFM-2015), Tokyo, Japan.
- Salem, G. S. A., Kazama, S., Shahid, S., & Dey, N. C. (2017). Impact of temperature changes on groundwater levels and irrigation costs in a groundwater-dependent agricultural region in Northwest Bangladesh. *Hydrological Research Letters*, 11(1), 85-91. <https://doi.org/10.3178/hrl.11.85>
- Sarker, M. A. R., Alam, K., & Gow, J. (2012). Exploring the relationship between climate change and rice yield in Bangladesh: An analysis of time series data. *Agricultural Systems*, 112, 11-16. <https://doi.org/10.1016/j.agsy.2012.06.004>
- Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, 63(324), 1379-1389. <https://doi.org/10.1080/01621459.1968.10480934>
- Shahid, S. (2011). Impact of climate change on irrigation water demand of dry season Boro rice in northwest Bangladesh. *Climatic Change*, 105(3), 433-453. <https://doi.org/10.1007/s10584-010-9895-5>
- Shrestha, S. (2014). Adaptation Strategies for Rice Cultivation Under Climate Change in Central Vietnam. In S. Shrestha (Ed.), *Climate Change Impacts and Adaptation in Water Resources and Water Use Sectors: Case studies from Southeast Asia* (pp. 93-119). Springer International Publishing. [https://doi.org/10.1007/978-3-319-09746-6\\_6](https://doi.org/10.1007/978-3-319-09746-6_6)
- Steduto, P., Hsiao, T. C., Raes, D., & Fereres, E. (2009). AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agronomy Journal*, 101(3), 426-437. <https://doi.org/10.2134/agronj2008.0139s>
- Wright, H. (2014). What does the IPCC say about Bangladesh? – ICCCAD Briefing. In *The International Centre for Climate Change and Development Policy Briefs*. IPCC Working Group II. <https://iccad.net/wp-content/uploads/2015/01/IPCC-Briefing-for-Bangladesh.pdf>
- Yao, F., Xu, Y., Lin, E., Yokozawa, M., & Zhang, J. (2007). Assessing the impacts of climate change on rice yields in the main rice areas of China. *Climatic Change*, 80(3), 395-409. <https://doi.org/10.1007/s10584-006-9122-6>
- Zhang, T., Huang, Y., & Yang, X. (2013). Climate warming over the past three decades has shortened rice growth duration in China and cultivar shifts have further accelerated the process for late rice. *Global Change Biology*, 19(2), 563-570. <https://doi.org/10.1111/gcb.12057>
- Zhang, Y., Niu, H., & Yu, Q. (2021). Impacts of climate change and increasing carbon dioxide levels on yield changes of major crops in suitable planting areas in China by the 2050s. *Ecological Indicators*, 125, 107588. <https://doi.org/10.1016/j.ecolind.2021.107588>