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# The role of soil water availability in potential rainfed rice productivity in Bangladesh: applications of the CERES-Rice mode

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# The role of soil water availability in potential rainfed rice productivity in Bangladesh: applications of the CERES-Rice model

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**Abstract**

Soil water stress and its impact on the monsoon season potential rainfed rice productivity in Bangladesh is investigated. A crop growth simulation model, CERES-Rice, is applied to 16 locations representative of the major rice growing regions of Bangladesh to determine the impact of soil water stress on the regional scale potential yield for four transplanting dates: 1 June, 1 July, 15 July, and 15 August. A quantified estimate of potential yield loss for four regions and for Bangladesh as a whole is calculated for water stress during flowering and maturing stages. For example, in Bangladesh, average potential yield for 1 June transplanting date, under low water stress during both flowering and maturing stages, is 7218 kg ha$^{-1}$. On the other hand, high water stress during maturing, flowering, and both flowering and maturing stages, results in yield reduction of 37%, 46%, and 73%, respectively. Model applications show that for a 15 July transplanting date, average potential yield under low water stress during both flowering and maturing stages is 6077 kg ha$^{-1}$. However, the loss of potential yields are 39%, 57%, and 70% for this transplanting date, due to high water stress during

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maturing, flowering, and both flowering and maturing stages, respectively. For a 15 August transplanting, average potential yield is 4217 kg $ha^{-1}$ and loss is 32%, 38%, and 38% for high water stress during maturing, flowering, and both flowering and maturing stages, respectively. The results of this study can be further utilized for future agricultural planning in Bangladesh and other parts of monsoonal Asia.

**Keywords:** Bangladesh, The CERES-Rice model, Soil water stress, Yield

## Introduction

Agriculture and related activities dominate daily lives of millions of Bangladeshi citizens. In Bangladesh, like many other Asian countries, stability of the socioeconomic condition is largely dependent on a prosperous agricultural sector. Bangladesh's agriculture sector contributes 35% of the national Gross Domestic Product (GDP) and employs 66% of the total employed labor force (Food and Agricultural Organization, 2002). Within the crop sector of agriculture, 71% of gross output of all crops is contributed by rice (Food and Agricultural Organization, 2002), the staple food in Bangladesh. Furthermore, rainfed '*aman*' rice, among a number of other varieties of seasonal rice, constitutes more than 50% of the total rice production in Bangladesh (Bangladesh Bureau of Statistics, 1989). Rainfed rice production is largely dependent on the supply of water during rainy monsoon season, with the timing and amount of rainfall playing a critical role. An early arrival of the monsoon and excessive rainfall can cause flooding, which is harmful to young rice seedlings. On the other hand, a late arrival usually leads to severe water stress. Ample rainfall during growing season is also essential for attaining optimum yield. Often variability of rainfall during the monsoon season results in severe flooding and loss of crops. To overcome the loss of crops during flooding, farmers occasionally re-plant rice seedlings in an attempt to avoid food shortages.

Farmers in Bangladesh harvest *aman* rice after the departure of the monsoon. Since agriculture is subsistence in nature, in many cases, Bangladeshi farmers grow three crops a year. Year-round farming, however, often does not allow land to be available to farmers with sufficient time for its preparation for *'aman'* rice transplanting. Thus, from a practical standpoint, July is the earliest available period when farmers in Bangladesh can transplant rice, although the exact date of transplanting varies from region to region. Generally, late transplanting of the *'aman'* rice results in yield loss due to soil water stress during flowering and maturing of crops. However, farmers often are forced to transplant rice on dates later than desirable because of early season water stress or flooding or to re-transplant late due to crop damages. This optimum management can reduce some of the yield loss by providing ample water during transplanting period, by supplying required amount of fertilizer and pesticide, and by transplanting early.

Despite a general understanding that end-of-the season water stress reduces yield, a quantitative regional scale systematic *potential* yield assessment has not been completed for a series of transplanting dates and under end-of-the growing season water stressed conditions in Bangladesh. This paper focuses on the summer monsoon in Bangladesh and calculates regional scale potential rainfed *aman* (in this case the most common variety, the BR11) rice yield and its relationship to soil water stress. A crop growth simulation model, CERES-Rice (Ritchie, Alocilja, Singh, & Uehara, 1987; Tsuji, Uhera, & Balas, 1994), is applied to 16 locations distributed over the major rice growing regions of Bangladesh (Fig. 1). These locations represent various precipitation regimes and soil characteristics of the country. To calculate potential yield, optimum management is provided. Thus, the CERES model applications assume saturated soil condition (due to puddling) at the time of transplanting and optimum supply of fertilizers. These are the two critically limiting factors for obtaining potential yield. To reflect local practice and the status of *'aman'* as rainfed rice, it is assumed that the rice plant is dependent on naturally occurring rainfall after transplanting.

The CERES-Rice model is applied to four transplanting dates to determine potential yield for these dates. Moreover, various levels of soil water stresses during flowering and maturing stages and their impacts on regional scale potential yield are also determined. Application of the model helps to understand the relationship between the soil water availability during monsoon and potential productivity. Transplanting dates are representative of prevailing timing of transplanting in response to land availability, favorable and unfavorable hydroclimatic conditions. Weather data from the monsoons of 1975 through 1987 are used for this study, although this time series is representative of inter-annual variations of monsoons over a much longer period. For example, the monsoon season precipitation anomaly, for 1975 through 1987, ranged from –20% to +40% below and above normal, respectively (Matsumoto,

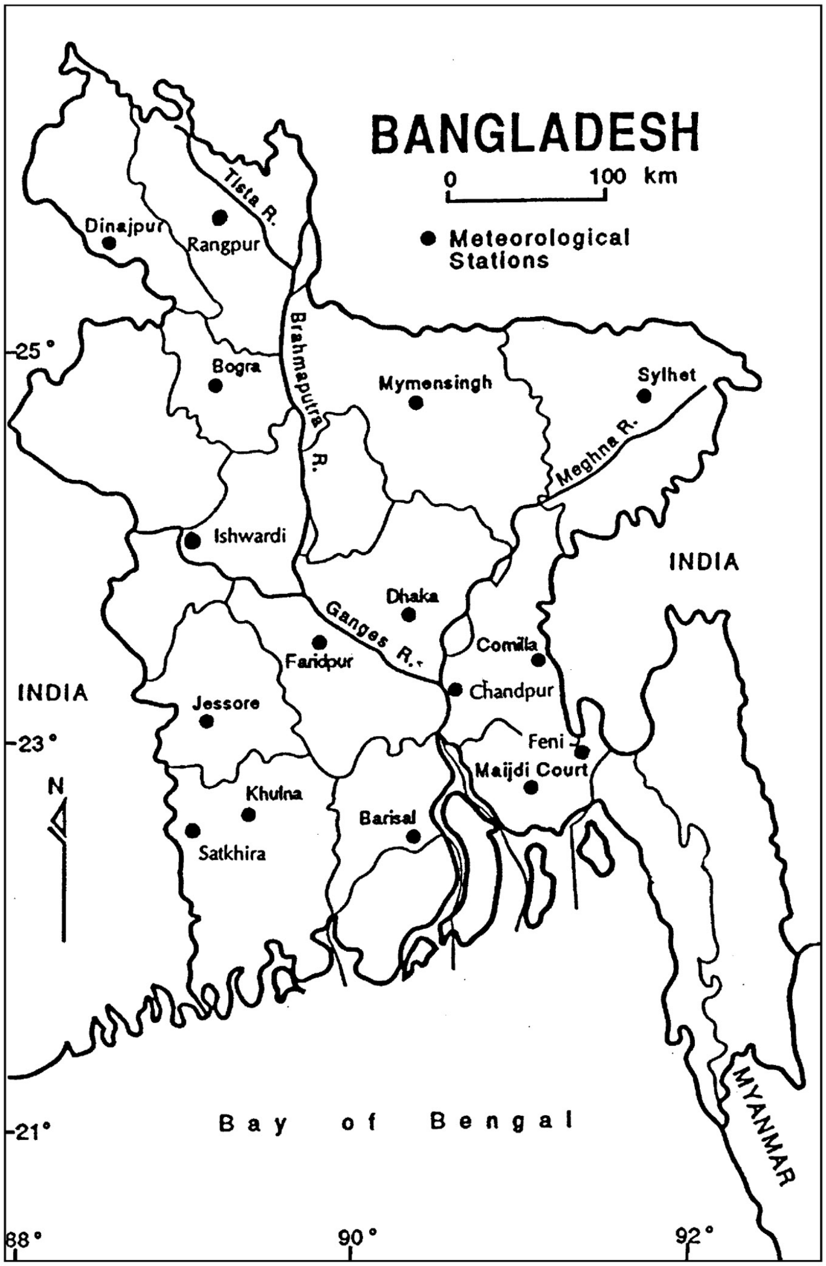


**Fig. 1.** Location of model application sites.

1992). Thus, the time series is well represented by inter-annual monsoonal variations and resultant droughts and flooding. Since climate cycle repeats itself, the results of this study with the data set used here will be applicable to future hydroclimatic conditions.

With sufficient infra-structural and governmental capital support, it is possible for Bangladeshi farmers to provide optimum management. In that case, it is possible for them to ensure sufficient supply of water for puddling during transplanting period. The response of regional scale potential yield to a condition when supply of moisture is abundant during transplanting and water stress at the end-of-the season is unknown and is not quantified. The impacts of water stress during flowering and or maturing stages on regional scale potential yield in Bangladesh and similar societies are also unknown. This study will quantify potential yield and thus address these issues.

Our results will have a number of implications. First, it will provide a baseline for future work in rice crop–climate relationships in Bangladesh and other parts of monsoonal Asia. Mahmood and Hayes (1995) and Mahmood (1997, 1998a,b) investigated impacts of climate change on winter season irrigated rice productivity, its irrigation requirements, and potential cropping pattern changes in Bangladesh. Recently, Mahmood, Meo, Legates, and Morrissey (2003) completed a study on vulnerability of rainfed monsoon season rice productivity in Bangladesh. However, the impacts of water stress on regional scale potential yield of monsoon season rainfed rice under optimum management have not been investigated and quantified. Second, most of the studies on climate impacts on agriculture and its resource base focus on developed nations under mid-latitudinal climatic conditions. There is a lack of literature on climate impacts in tropical regime where societies are more vulnerable to abnormal conditions. The present study will fulfill some of these voids in the scientific literature. Third, the results of this study can be utilized for future agricultural decision making, crop loss management, and agricultural disaster management in Bangladesh and other similar societies. Fourth, Bangladesh stands at the cross roads of vulnerable socio-economic and natural environment. It is a small and overcrowded developing nation with a size of 147, 000 $km^2$ and 128 million population (Government of Bangladesh, 2002). Natural disasters and '*aman*' crop losses due to monsoonal variability are frequent. Thus, maintaining a crop productivity to feed its population and averting socioeconomic disaster is an utmost concern of Bangladesh. In addition, this study will provide a benchmark for future climate change research for Bangladesh and similar vulnerable regions.

## The hydroclimatological context of rice farming in Bangladesh

The political boundary of Bangladesh covers nearly two-third of the Bengal delta, the largest delta in the world, as three great rivers—the Ganges, the Brahmaputra, and the Meghna—open to the Bay of Bengal. Surface water during the summer monsoon (June–October) in Bangladesh is abundant, owing to hundreds of rivers and channels of the Ganges–Brahmaputra–Meghna watershed that distribute the water. Overflowing rivers during monsoon seasons help farming lands replenish their fertility. Due to the subsistence nature of agriculture, Bangladeshi farmers try to use the land as many times as possible during a cropping year. Thus, the rice cropping pattern in Bangladesh is dominated by three rice crops—the *aus*, the *aman*, and the *boro*. The spring (March–May), the summer monsoon (June–October), and the dry winter (November–February), are growing seasons of the *aus*, the *aman*, and the *boro* rice, respectively (Table 1).

The onset of the monsoon in Bangladesh occurs during June and is marked by heavy showers that continue until the end of the season in October with July usually being the wettest month. Thus, Bangladesh receives 74–84% of its annual rainfall during the monsoon months (Islam, 1987). Mean monthly rainfall for four representative locations (Fig. 2a–d) are based on the long-term estimates provided by the Food and Agricultural Organization (FAO, 1987) of the United Nations. These figures show that, for all four stations, monthly total rainfall increases gradually during the Spring and reaches to its maximum during the monsoon season. Note that rainfall decreases as the monsoon season progresses and that monthly total rainfall decreases significantly after the departure of

**Table 1.** Mean climatic features of Bangladesh during the three rice crop growing seasons

| Rice growing seasons | $T_{max}$ (°C) | $T_{min}$ (°C) | Solar radiation MJ ($m^{-2}$ $day^{-1}$) | Precipitation (mm) |
|---|---|---|---|---|
| *Aus* (March–August) | 34–31 | 16–26 | 14–23 | 1200–3100 |
| *Aman* (July–November) | 34–28 | 26–16 | 14–19 | 1250–3000 |
| *Boro* (December–May) | 24–34 | 10–26 | 14–23 | 250–550 |

$T_{max}$ = mean maximum air temperature; $T_{min}$ = mean minimum air temperature. Range of values for $T_{max}$, $T_{min}$ and solar radiation represent respective increase and decrease as rice growing season progresses. Precipitation shows seasonal total (mm) with regional variation.

the monsoon. Of all the locations considered, Sylhet and Jessore record the highest and the lowest seasonal total rainfall during the monsoon, respectively. Local orography results in such higher rainfall in Sylhet. In addition, June or July is the wettest month of the monsoon season for all locations. The northeastern and the southeastern Bangladesh receive much higher rainfall than the other parts of the country.

Withdrawal of the monsoon from Bangladesh is marked by a sharp decrease of rainfall in October (Fig. 2a–d). The monsoon trough starts to shift progressively to a southerly direction with the march of the thermal equator to the south. An important feature of the withdrawal of the monsoon in Bangladesh is the development of depressions and severe cyclonic storms and associated storm surges and downpours during October. These storms often result in a loss of the *aman* rice crop, which is ready to be harvested, due to high winds. These severe weather conditions cause lodging of the mature crop due to high wind and flooding of the crop field due to intense rainfall during cyclonic storms. A late withdrawal of the monsoon forces Bangladeshi farmers to practice late sowing and resultant late transplanting of the *boro* rice because of higher depth of water in the rice fields. Thus, a late sowing and transplanting results in a shorter growing season and lower yield.

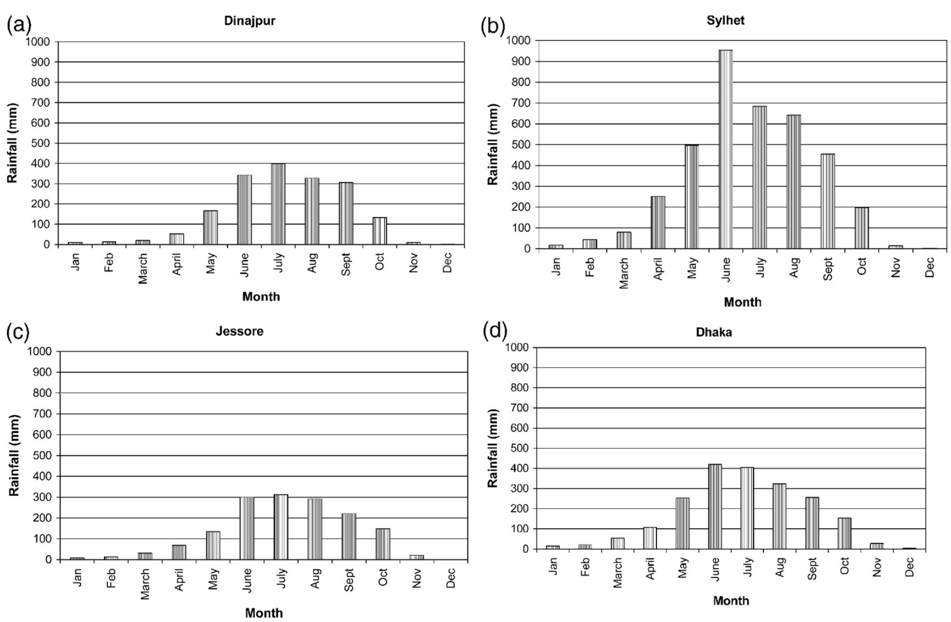


**Fig. 2.** Mean monthly rainfall for four representative locations: (a) Dinajpur; (b) Sylhet; (c) Jessore; and (d) Dhaka.

## The CERES-Rice model

The CERES-Rice is an advanced physiologically based rice crop growth simulation model. It has widely been applied to understand the relationship between rice plant and its environment (Bachelet & Gay, 1993; Rosenzweig & Parry, 1994; Mahmood et al., 2003). A number of regional studies have used this model successfully to estimate the impacts of climate change on rice productivity (cf., Baer, Meyer, & Erskine, 1994; Escano & Buendia, 1994; Tongyai, 1994; Barry & Geng, 1995; Jin, Ge, Chen, & Fang, 1995; Seino, 1995; Singh & Padilla, 1995). Note that the CERES-Rice model is variety-specific (e.g., the BR11 *aman*) and thus is able to simulate rice plant response to various environmental conditions and to predict rice productivity more accurately.

Furthermore, the CERES-Rice model assumes that cultivar, soil water conditions, and crop management are the key controlling factors of rice productivity (Bachelet & Gay, 1993). The model requires daily precipitation, daily maximum and minimum air temperature, and daily solar radiation data for simulation (Table 2). In addition, input data on soil characteristics (to calculate evapotranspiration and components of the water balance) and management practices, including cultivar, planting date, plant density, and nitrogen fertilization, also are required (Ritchie et al., 1987; Tsuji et al., 1994; Hoogenboom et al., 1995; Hunte & Boote, 1998). When detailed input data are not available, a more simplified input data can be provided instead and obtain reasonable simulation results. In the past, key aspects and assumptions of the CERES-Rice model have been presented in detail (cf., Ritchie et al., 1987; Ritchie, Singh, Godwin, & Bowen, 1998; Singh, 1992; Singh & Padilla, 1995; Godwin & Singh, 1998; Ritchie, 1998). Thus, the following discussion provides a summarized outline of the relevant parts of the model, including the plant growth and water balance components. A description of the nitrogen sub-model is not included here because the present study assumes an optimum supply of fertilizer, as recommended by the Bangladesh Rice Research Institute (BRRI, 1995).

Phasic and morphological development constitutes the growth of rice plant in the CERES-Rice model. Changes in growth stages are represented by phasic development, which is also related to significant changes in the biomass-partitioning pattern. In the model, the major growth stages are juvenile, floral induction, heading, flowering, grain

**Table 2.** Input data requirements for the CERES-Rice model (based on Ritchie et al., 1987; Tsuji et al., 1994)

| |
|---|
| *Weather data* |
| Daily maximum and minimum air temperature |
| Daily precipitation |
| Daily solar radiation |
| *Pedological-hydrological data* |
| Soil classification Texture |
| Number of layers in soil profile |
| Slope |
| Permeability |
| Drainage |
| Soil layer depth |
| Soil horizon |
| Clay, silt, and sand content |
| Bulk density |
| Saturated hydraulic conductivity for each soil layer |
| Total nitrogen for each layer |
| pH of the soil in water for each layer |
| Root quantity for each layer |
| *Agronomic* |
| Transplanting date |
| Row spacing |
| Number of plants per hill |
| Number of plants per square meter |
| Age of seedling |
| Base temperature to estimate phenological stages |
| Floodwater depth |
| Fertilizer application dates, amounts |
| Planting depth |

filling, maturing, and harvesting. Accumulation of growing degree-days (GDD) determines completion of these growth stages.

Growth stage determines allocation of biomass into the root and influences the density of roots and their efficiency in supplying nutrients to shoots. The CERES-Rice model assumes that the allocation of biomass to the roots decreases as the growing season progresses and as the rice plant becomes mature. Water or nitrogen stress results in greater partition to roots during all of the growth stages except during grain-filling stage. Through the entire growing season, the CERES-Rice model maintains a constant proportionality between root mass and length. The product of rice grain numbers, individual kernel grain weight, and the number of plants per unit area determine end-of-season rice yield. The CERES-Rice model calculates infiltration, runoff, drainage and evapotranspiration to assess soil water balance. Runoff is determined by using a modified Soil Conservation Service Curve Number Technique. The difference between daily precipitation and runoff provides estimate of infiltration. The model uses the Priestly–Taylor method (Priestly & Taylor, 1972) to estimate potential evapotranspiration ($ET_p$).

The CERES-Rice model calculates a water stress deficit factor ($SW_{DEF}$), which is the ratio of potential root water uptake to potential transpiration. $SW_{DEF}$ ranges from 0.0 to 1.0 representing the absence of water stress to extreme water stress, respectively. Yield is estimated by integrating conditions measured with a daily temporal resolution over the duration of the growing season. Moreover, rice plant physiological processes and the phasic growth of the rice plant and soil water balance can be simulated at a daily temporal resolution. This allows for a better understanding of the responses of rice plants to various hydroclimatic conditions and crop management practices.

## Data

### *Meteorological data*

Daily maximum and minimum air temperature, daily rainfall, and daily cloud cover for 1975 through 1987 was acquired from the Bangladesh Meteorological Department (BMD). This time period recorded significant variations in the monsoonal rainfall (cf., Krishnamurti, Bedi, & Subramaniam, 1989; Matsumoto, 1992; Shukla, 1987). As in many other countries, the quality of daily solar radiation data for Bangladesh is extremely poor and missing observations are widespread. For this study, a modified version of Black's (1956) method to estimate solar radiation, $R_s$, from the daily cloud cover data was used

$$R_s = R_{so}0.66667(0.803 - 0.00340C - 0.0000458C^2) + 0.33333R_{so} \quad (1)$$

where $R_{so}$ is radiation at the top of the earth's atmosphere and $C$ is cloud cover (in percent). The constants 0.66667 and 0.33333 are direct and diffuse beam radiation during summer monsoon months, respectively (from Stanhill, 1966). It is suggested that the ratio of diffuse beam and total radiation ranges from 0.3 to 0.5 and this proportion remains remarkably constant (Stanhill, 1966). For Bangladesh, this proportion should be closer to 0.3 due to its tropical location. As a result, 0.66667 and 0.33333 were adopted for direct and diffuse beam radiation, respectively.

### *Soils, agronomic, and management data*

Soils, agronomic, and management data were obtained from Hussain (1995) and the Bangladesh Agricultural Research Council (Table 3). Planting dates relative to the temporal distribution of monsoonal rainfall can significantly affect the final rice yield by limiting the availability of soil moisture. The rainfall distribution may also restrict the solar radiation interception by plants and the need for dry weather during maturing and harvesting stages required for optimum yield. The BRRI recommends that farmers should transplant rainfed *aman* rice no later than 15 August (BRRI, 1995). Transplanting in August may help to cope with yield loss due to abnormal hydroclimatic conditions (e.g., early season flooding or extremely dry conditions) and may allow for a partial mitigation of food deficits. Subsistence character of agriculture in Bangladesh made this type of late transplanting activities and harvesting essential components of farming activities. Four planting dates were selected for this study, reflecting actual practice, to determine impacts of water stress on regional scale potential yield (Table 3).

**Table 3.** Agronomic and management parameter input data for the study (Hussain, 1997)

| *Agronomic and management parameter* | *Input data* |
|---|---|
| Transplanting date | 06/01, 07/01, 07/15, 08/15 |
| Row spacing | 20 cm |
| Number of plants per hill | 6 |
| Number of plants at emergence | 44 $m^{-2}$ |
| Transplanting age | 30 days |
| Base temperature to estimate phenological phases | 9°C |
| Floodwater depth | 15 cm |
| Planting depth | 6 cm |
| Planting method | Transplanted |
| Fertilizer (N) application | |
| Fifteen days after transplanting Application amount: | 25 kg $ha^{-1}$ |
| Twenty-five days after transplanting Application amount: | 30 kg $ha^{-1}$ |
| Fifty days after transplanting Application amount: | 25 kg $ha^{-1}$ |

During a growing season, rainfed rice transplanting is a continuous process in any farming community and there is no single specific date for this activity; Bangladesh is no exception. In short, transplanting dates are a composite product of current hydroclimatic condition and input availability to an individual farmer. In this study, the selected four transplanting dates are a result of BRRI recommendation, prevailing hydroclimatic conditions, and past yield responses. These dates are representative of time-segments when farmers usually transplant rice seedlings in Bangladesh. For example, 1 June, 15 July, and 15 August represent transplanting as the monsoon season begins, widespread mid-monsoon transplanting, and late season transplanting, respectively.

### *Baseline yield estimated by the CERES-Rice model*

Li-Ling (1987) and Jintrawet (1991) have successfully validated the CERES-Rice model. Model performance also has been evaluated by Timsina, Singh, Badarudddin, and Meisner (1998) during its application to a rice–wheat sequence in Bangladesh. The CERES-Rice model was applied to Joydebpur (24.00°N and 90.43°E), Bangladesh from 1975 through 1987 to evaluate its performance for the present study. Joydebpur is located at a close proximity to Dhaka. Availability of observed yield data from experiment sites at Joydebpur was primary reason for selecting this site. Analyses of simulated and observed yields and harvest index demonstrate close agreements in most cases (Mahmood et al., 2003).

Model simulations were conducted for 16 locations and for four transplanting dates including 1 June, 1 July, 15 July, and 15 August. Baseline yields were determined by computing the average for each station and each transplanting date. The model application sites represent four regions and are aggregated based on proximity of their location and similarity in hydroclimatic conditions (Manalo, 1976). Thus, Chandpur, Comilla, Feni, Maijdi Court, and Sylhet represent the eastern region; Barisal, Dhaka, Faridpur, and Mymensingh represent the central region; Jessore, Khulna, and Satkhira represent the southwestern region; and Bogra, Dinajpur, Ishwardi, and Rangpur represent the northwestern region. For presentation here, four representative locations of these four regions were selected: Chandpur, Dhaka, Jessore, and Dinajpur to represent the eastern, central, southwestern, and northwestern regions, respectively. For a 1 June transplanting date, Chandpur, Dhaka, Jessore, and Dinajpur report yields of 7220, 7564, 6344, 7021 kg $ha^{-1}$, respectively. For all locations, yield also decreases with the progression of transplanting date. For example, compared to 1 June transplanting date, Dhaka's yield reduction is 11%, 29%, and 73% for 1 July, 15 July, and 15 August, respectively (Fig. 3). Overall, each region exhibits a similar pattern of yield reduction with the progression of transplanting date (Fig. 4). Thus, model applications in Bangladesh show that, on average, potential yield for a 1 June transplanting date is 6907 kg $ha^{-1}$. It is also found that, compared to a 1 June transplanting date, Bangladesh would experience 27%, 48%, and 75% potential yield reduction for 1 July, 15 July, and 15 August transplantings, respectively.

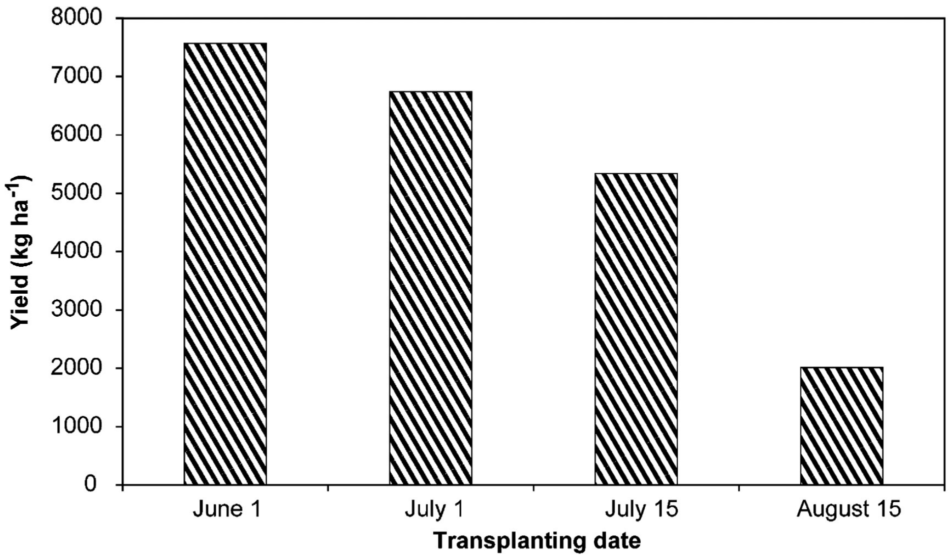


**Fig. 3.** Transplanting date and potential yield reduction in Dhaka, Bangladesh.

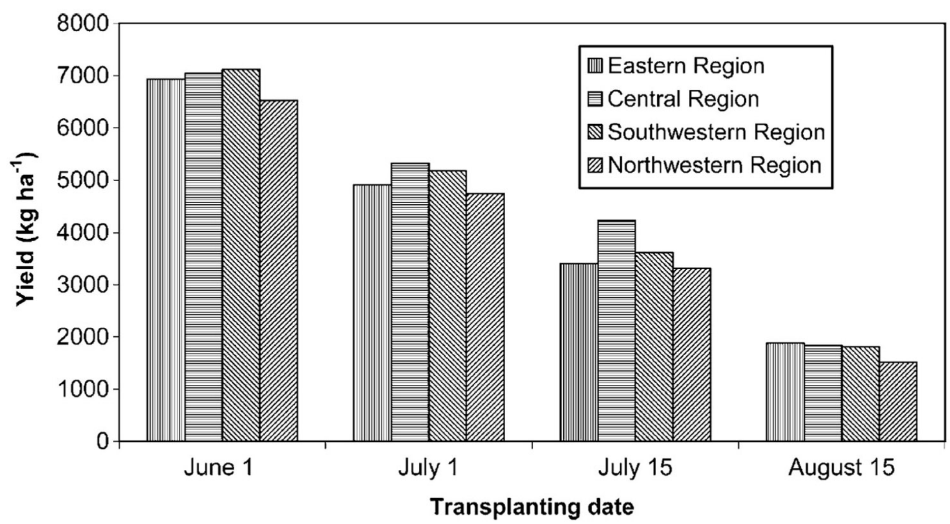


**Fig. 4.** Transplanting date and regional potential yield reduction in Bangladesh.

## Transplanting date, soil water stress, and yield in Bangladesh

Late transplanting causes moisture stress during the flowering and maturing stage, which results in lower yield. Note that rice plant productivity and yield are most sensitive to water stress during the flowering and maturing stages (De Datta, 1981; Yoshida, 1981). As discussed above, a soil water deficit factor, $SW_{DEF}$, that ranges from 0.0 to 1.0 is used in the CERES-Rice model to determine the relationship between water availability and yield. Fig. 5a–b shows declining yields due to increasing water stress during flowering and maturing stage in Dhaka and hence

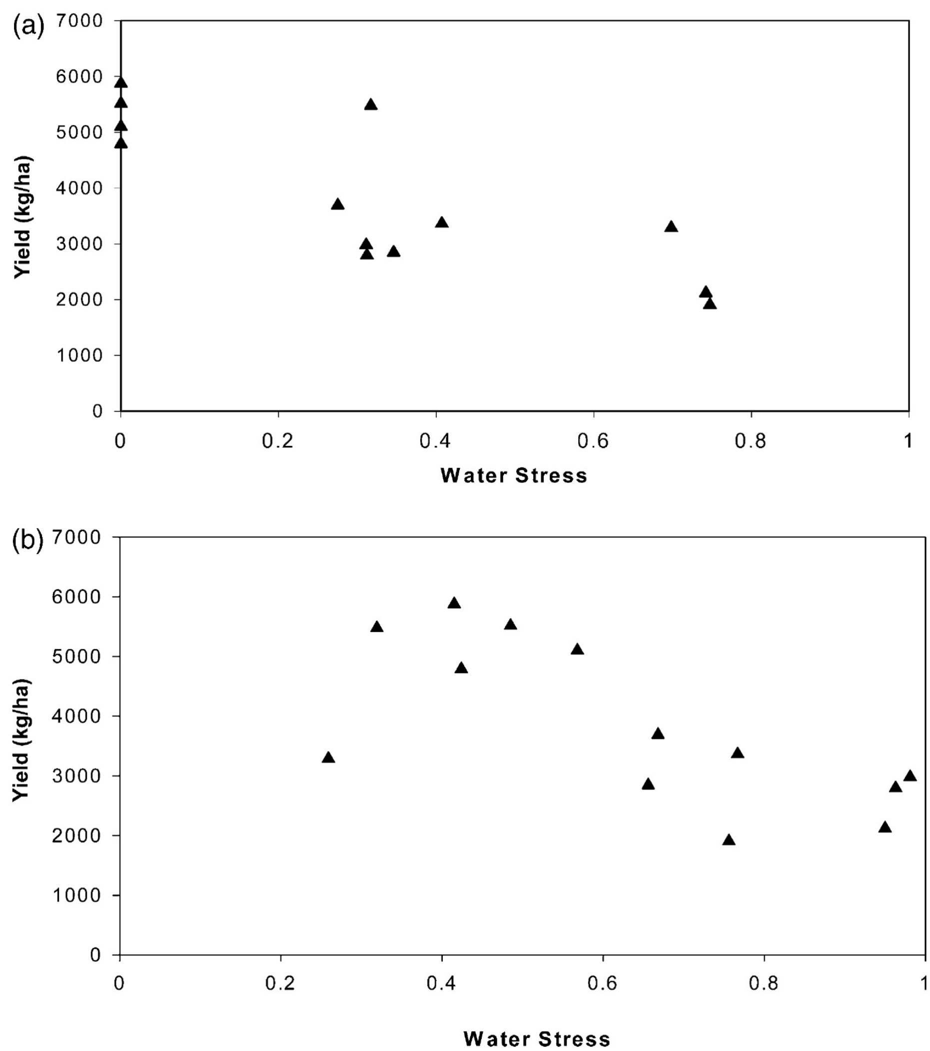


**Fig. 5.** Water stress and declining potential yield in Dhaka: (a) water stress during flowering stage; and (b) water stress during maturing stage.

corroborate the findings from the field experiments (cf., Jearakongman et al., 1995; Lilley & Fukai, 1994; Thangaraj, O'Tool, & Datta, 1990; Yambao & Ingram, 1988; Gupta & Agarwal, 1989). As farmers move the transplanting date to the later part of the monsoon, the possibility of water stress during the flowering and the maturing stage increases. However, if farmers in Bangladesh transplant BR11 *aman* on 1 June, the occurrence of water stress during flowering and maturing stage is minimal (Fig. 6a–b). For a 1 July transplanting date, however, rice plants mostly experience low levels of water stress during the maturing stage. Although

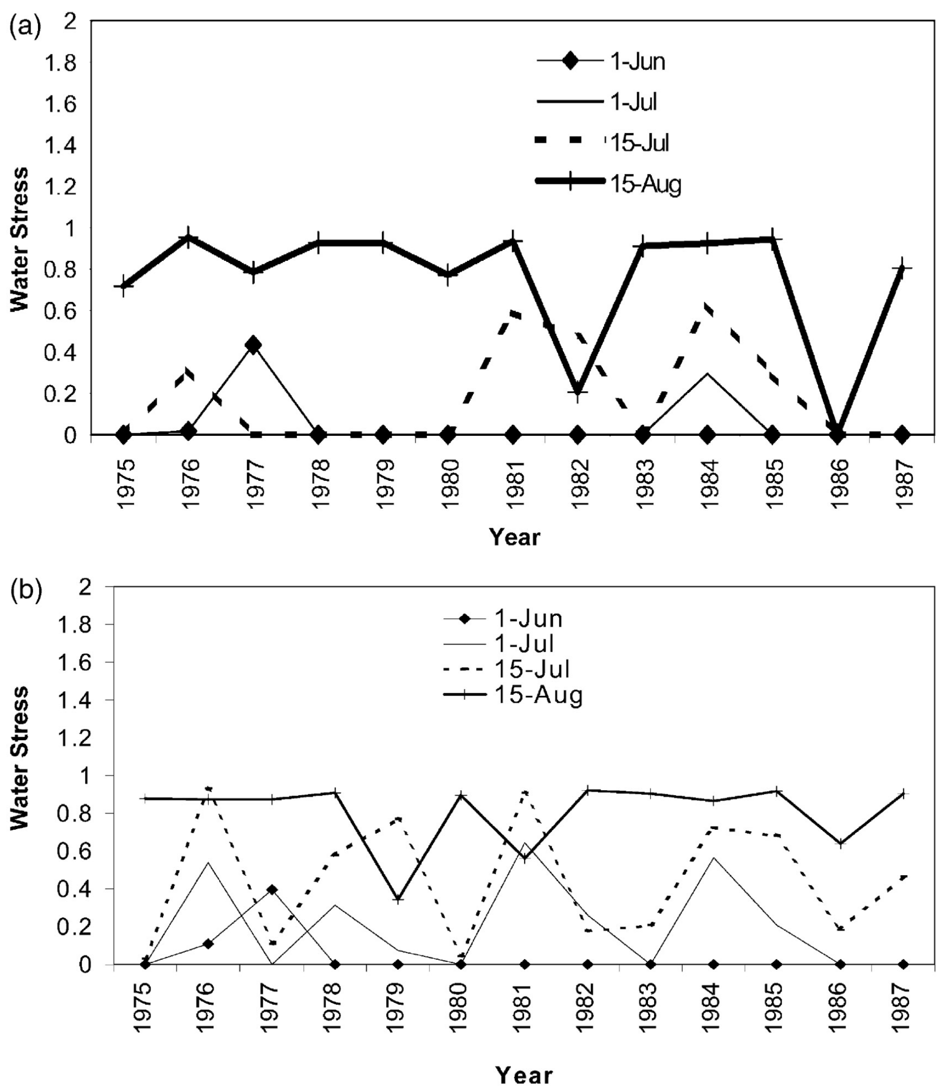


**Fig. 6.** Water stress under: (a) flowering; and (b) maturing stages.

water stress is very occasional during the flowering stage for a 15 July transplant date, it becomes significant during maturing stage and thus adversely affects the simulated yield.

For the 15 August transplanting, high water stress reduces yield noticeably. All locations experience high to severe water stress during the flowering and maturing stages with this transplanting date. Note that the crop loss for the 15 August transplanting date results from the combined water stress that occurs during the last two growth stages.

Thus, water stress plays a key role in determining the yield of rainfed transplanted BR11 *aman* rice. During the monsoon season, rain is usually plentiful in Bangladesh and soil water availability is not limited. As a result, the intra-seasonal rainfall variability does not play a major role. By transplanting rice seedlings at the appropriate time, however, farmers can ensure an optimum yield. Water stress at the end of the rice-growing season caused by a late transplanting date can significantly reduce yield.

For future agricultural and socio-economic planning, quantitative estimates of potential BR11 *aman* yield under water stress during flowering and maturing stages are essential. To fulfill this objective, we surveyed the data to determine a critical value over which yield declines noticeably. It is found that when $SW_{DEF}$ is 0.5 during flowering and or maturing stage potential yield reduces significantly. Thus, SW DEF $< 0.5$ and $\geq 0.5$ are designated as indication of low and high water stress, respectively. The model estimates that the average yield for the eastern region of Bangladesh is 7507 kg $ha^{-1}$ under low water stress during both flowering and maturing stages for the 1 June transplanting date. Potential yield declines 34% and 78% for high water stress during maturing stage only and during both flowering and maturing stages, respectively (Fig. 7a). For a 1 July transplanting date, potential yield in the eastern region is 6396 kg $ha^{-1}$ under low water stress during flowering and maturing stages. However, this region loses 37%, 75%, and 73% yield when high water stress occurs during maturing stage, flowering stage, and both flowering and maturing stages, respectively (Fig. 7a). For a 15 July transplanting, eastern Bangladesh would produce 5831 kg $ha^{-1}$ BR11 *aman* under low water stress during both flowering and maturing stages. Potential yield declines 43%, 75%, and 68% for high water stress during maturing stage, flowering stage, and both flowering and maturing stages, respectively (Fig. 7a). For a 15 August transplanting date, a similar trend in yield loss is observed for high water stress

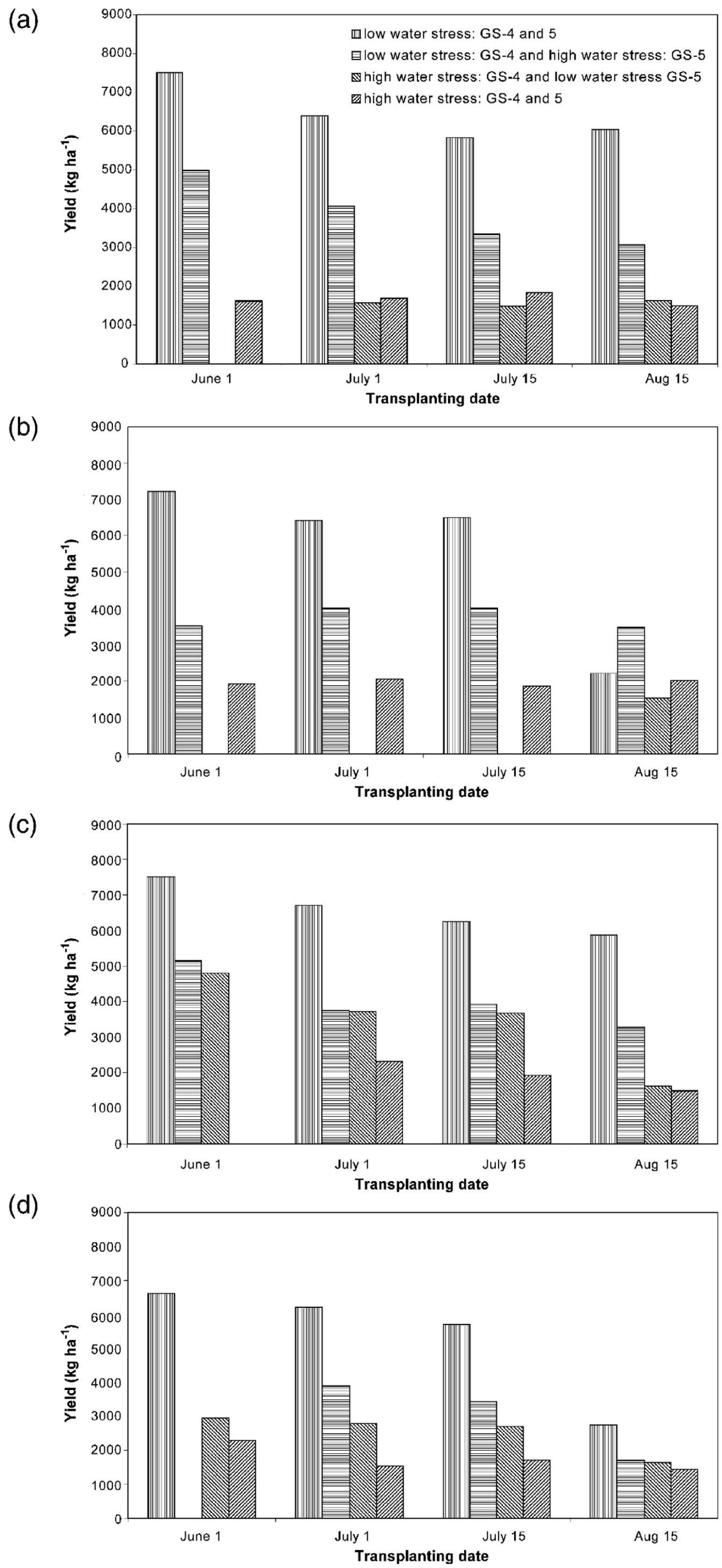


**Fig. 7.** Water stress and regional potential yield in Bangladesh under four transplanting dates:

(a) eastern region;
(b) central region;
(c) southwestern region; and
(d) northwestern region.

GS:4 = Flowering stage and
GS:5 = Maturing stage.

during flowering and maturing stages. High water stress during the maturing stage, flowering stage, and both flowering and maturing stages results in 49%, 73%, and 75% yield loss compared to low water stress conditions for this transplanting date (Fig. 7a). Note that frequency of high water stress during the flowering stage only is lower compared to the high water stress during both flowering and maturing stages. Analysis of the data suggests that high water stress during the flowering stage is usually associated with dry conditions for the growing season. Therefore, greater potential yield reduction under high water stress during the flowering stage only (as compared to the water stress during both flowering and maturing stages) is a result of highly anomalous hydroclimatic conditions.

The central region did not exhibit high water stress during the flowering stage for either of the 1 June, 1 July, or 15 July transplanting dates. Average yields under low water stress during the flowering and maturing stages for these dates are 7233, 6426, and 6513 kg $ha^{-1}$, respectively, while yield loss due to high water stress during maturing stage only is estimated as 51%, 38%, and 38% for these dates (Fig. 7b). Thus, high water stress during the maturing stage for a 1 June transplanting date is very unusual. For a 15 August transplanting date, however, high water stress during both flowering and maturing stage is quite frequent and results in significant yield loss. One event of low yield under low water stress during both the flowering and the maturing stage skewed the results in that, although the water stress was less than 0.5, a low water stress was evident for all growth stages. Thus, low water stress over the whole growing season reduced the yield in this single particular case.

In the southwestern region of Bangladesh, potential yield for a 1 June transplanting date under low water stress during flowering and maturing stage is 7508 kg $ha^{-1}$ (Fig. 7c). Potential yield loss due to high water stress during the flowering and maturing stages is 36% and 38%, respectively (Fig. 7c). For a 1 July transplanting date, the potential yield under low water stress during the flowering and maturing stage is 6709 kg $ha^{-1}$ and the loss is 45%, 44%, and 65% for high water stress during flowering, maturing, and both flowering and maturing stages, respectively (Fig. 7c). For the 15 July and the 15 August transplanting dates, potential yield under low water stress during both flowering and maturing stages is 6257 and 5873 kg $ha^{-1}$, respectively. However, potential yield loss due to high water stress during maturing, flowering, and both

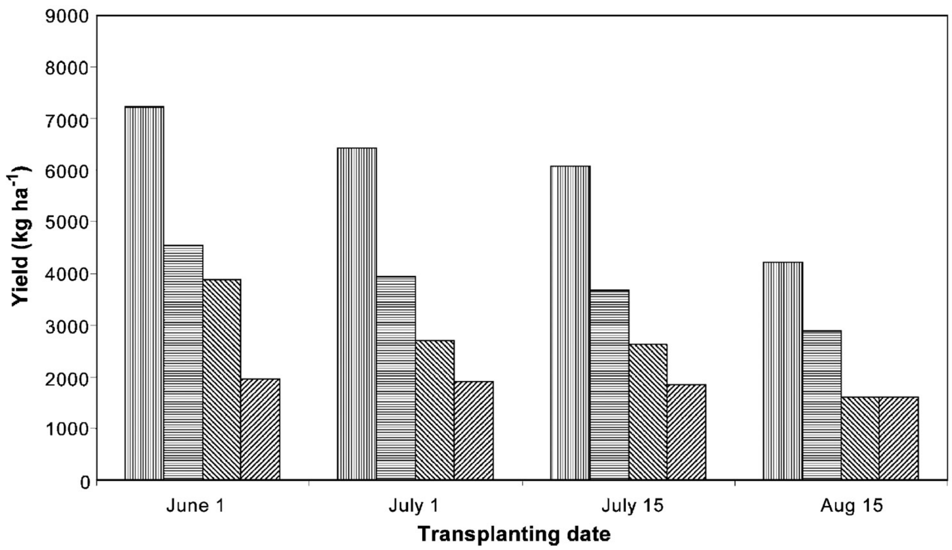


**Fig. 8.** Water stress and potential yield in Bangladesh. See Fig. 7 for legend.

flowering and maturing stages is 37%, 41%, and 69%, respectively for the 15 July transplanting date (Fig. 7c). For a 15 August transplanting date, the loss under similar condition is 44%, 73%, and 75%, respectively. Potential yields in the northwestern region, for the four transplanting dates, show responses similar to that of the southwestern region (Fig. 7d)

On average, potential yield for a 1 June transplanting date and under low water stress during both the flowering and maturing stages is 7218 kg ha$^{-1}$. Potential yield reduction is 37%, 46%, and 73% for a high water stress during maturing, flowering, and both flowering and maturing stages, respectively (Fig. 8). For a 1 July transplanting date, the average potential yield under low water stress during both flowering and maturing stages is 6435 kg ha$^{-1}$. Potential yield loss for this transplanting date under high water stress during maturing, flowering, and both flowering and maturing stage is 39%, 58%, and 70%, respectively (Fig. 8). Average potential yield under low water stress during both flowering and maturing stage for a 15 July transplanting date is 6077 kg ha$^{-1}$. Potential yield loss, for this transplanting date, due to high water stress during maturing, flowering, and both flowering and maturing stages is 39%, 57%, and 70%, respectively (Fig. 8). For a 15 August transplanting, the average potential yield is 4217 kg ha$^{-1}$ and loss is 32%, 38%, and 38% for high water stress during maturing, flowering, and both flowering and maturing stages, respectively (Fig. 8). Since sufficient water supply was assumed during all four transplanting dates, it is expected that water stress may appear during the flowering and maturing stages. This analysis shows that the frequency of occurrence of high water stress increases with the later transplanting dates. Impacts of combined water stress on yield loss for all four transplanting remain quite similar for all regions. Potential yields under low water stress during both flowering and maturing stages also are higher for eastern and southwestern region.

## Discussion and concluding remarks

The CERES-Rice model was applied to determine the impacts of soil water stress on the regional scale *potential* rainfed BR11 *aman* rice productivity in Bangladesh. This study assumed the BRRI-recommended fertilizer supply and saturated/puddled soils during transplanting for four dates—1 June, 1 July, 15 July, and 15 August. The CERES-Rice model was tuned to represent agro-ecological conditions in Bangladesh and the model's performance for yield estimation and harvest index was satisfactory.

The CERES-Rice model was applied to 16 representative locations in Bangladesh to obtain baseline estimates for the major growing regions. Baseline estimates reveal that rice yield decreases as the transplanting dates were moved well into the monsoon. Average potential yield in Bangladesh for a 1 June transplanting date is 6907 kg $ha^{-1}$. Compared to a 1 June transplanting date, however, the model applications report 27%, 48%, and 75% yield reduction for 1 July, 15 July, and 15 August transplanting, respectively. To further understand the role of water stress during flowering and maturing stages on potential yields, a quantified estimate of potential yield loss for four regions and for whole Bangladesh is calculated for water stress during the flowering, maturing, and both flowering and maturing stages. For example, in Bangladesh, average potential yield for 1 June transplanting date and under low water stress during both flowering and maturing stages is 7218 kg $ha^{-1}$. Potential yield reduction is 37%, 46%, and 73% for high water stress during maturing, flowering, and both flowering and maturing stages, respectively. For 15 July transplanting date average potential yield under low water stress during both flowering and maturing stage is 6077 kg ha$^{-1}$. Potential yield losses are 39%, 57%, and 70% for this transplanting date, due to high water stress during maturing, flowering, and both flowering and maturing stages, respectively.

Mahmood et al. (2003) have already demonstrated that this type of modeling studies can be useful in regional yield vulnerability assessment. In our opinion, these assessments can be conducted in other parts of the world, under different climatic conditions, and for crops in addition to rice. For example, it is possible to use the CERES-Wheat or the CERES-Maize models for respective crops to complete a similar investigation. Moreover, this type of modeling studies can be performed to determine crop-water requirement, crop water deficits, irrigation management and planning, increase water use efficiency, optimizing yield, and eventually to develop strategies for yield loss mitigation and policy response.

Furthermore, as indicated previously, this study can be a first step to determine impacts of climate change on water consumption and soil water stress on crops during flowering and maturing stages and subsequent affect on productivity in Bangladesh and other regions of the world. For example, increased levels of $CO_2$ scenarios can be superimposed over the actual conditions presented here. Subsequently the CERES-Rice model can be applied to quantify plant response and yield. Based on the results, it is also possible to design crop-water supply scheme to mitigate any negative impacts on crop productivity. Hence, strategies for adaptation of agriculture to climate variability, extreme climatic conditions, climate change can be proposed. Rosenberg (1992) noted that adaptation requires advance knowledge of climate change. He also suggested that agricultural vulnerabilities to current climatic conditions and a range of realistic scenarios could provide us guidance on development of adaptation strategies. The current modeling activities are an essential step for achieving such goal. In other words, based on the present type of investigation, various national, regional, and local governments can develop plans ahead of abnormal hydroclimatic conditions that would reduce socio-economic vulnerability.

The authors also suggest that the process of scenario development for future agricultural planning can also use the results from this or similar studies (cf., Mavromatis & Jones, 1998; Lamb, 1987; Robinson & Finkelstein, 1990, 1991). Robinson and Finkelstein (1991) noted that the scenarios should be ‘scientifically sound’ and ‘internally consistent’.

The results from a baseline assessment similar to the present one fulfill these basic requirements and subsequently it is possible to develop a range of scenarios which may depict potential deviation of hydroclimatic conditions. For example, we can apply statistical methods to the recorded data and develop a series of potential hydroclimatic conditions that may occur in the future. As a follow-up, we can apply the model for these scenarios and obtain yield estimates and assessment of crop-water use. Hence, we can devise mitigation strategies and propose policies to reduce socio-economic vulnerability. Note that knowledge on water stress, ensuing agricultural planning and reduction of vulnerability, also addresses food security issues. This is particularly true where agriculture is subsistence in nature (most of Asia and Africa, for example).

It is to be noted that the scenario development, model applications for crop water use pattern, and yield can be part of complete system wide simulation activities (also known as integrated assessment) where perturbation of one component flows through rest of the system. Obviously this allows evaluation of system wide response. Frederick (1994) correctly noted that climate impact assessments help to diagnose implications of policies by investigating issues such as vulnerability of societal and natural systems, uncertainty, and risk.

This study has provided quantified estimates of regional scale potential yield of BR11 rainfed *aman* rice and its loss in Bangladesh under various levels of water stress during flowering and maturing stages. These results can be utilized in future agricultural planning and decision making. Similar applications will be undertaken for other parts of monsoonal Asia to conduct regional-scale yield assessment for various levels of soil water conditions. Such results can be used to further understand the relationship between soil water and potential yield and for future agricultural planning.

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