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# The CERES-Rice Model-Based Estimates of Potential Monsoon Season Rainfed Rice Productivity in Bangladesh

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## Abstract

Agricultural practices in Bangladesh are largely dependent on the monsoonal rainfall. Historically, Bangladesh often experiences severe droughts and floods during the monsoon months, with significant crop losses during both extreme conditions. This article provides a quantitative assessment of potential monsoon-season *aman* rice for four transplanting dates: 1 June, 1 July, 15 July, and 15 August. A crop-growth simulation model, the CERES-Rice, is applied to sixteen locations representing major rice-growing regions of Bangladesh to determine baseline yield estimates for four transplanting dates. The applications were conducted for 1975 through 1987. Average potential yield in Bangladesh is 6,907, 5,039, 3,637, and 1,762 kg ha$^{-1}$ for the above transplanting dates, respectively. In other words, Bangladesh would obtain 27 percent, 48 percent, and 75 percent less yield for 1 July, 15 July, and 15 August transplanting, respectively, than for 1 June transplanting. Potential yield vulnerability is the least for 1 June

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transplanting (up to 5 percent) and the highest (up to 66 percent) for 15 July transplanting date. The model applications show that regional variations exist for potential yield and yield vulnerability for a particular transplanting date. In addition, response of yield and vulnerability for a region changes with transplanting dates.

**Keywords:** Bangladesh, CERES-Rice model, monsoon, vulnerability, yield

## Introduction

*A*griculture is a way of life in South Asia. The survival of the economies in this region largely depends on a stable agricultural sector. Bangladesh is a good example of the intricate relationships between the societies of this region and its agricultural activities, since Bangladesh's agriculture sector contributes 44 percent of the national gross domestic product (GDP) and employs 56.5 percent of the total employed labor force (Kurian 1992). This underscores the fact that rice is the staple food in Bangladesh and that, as in many other regions of South Asia, a very large section of the economy depends on rice production. Therefore, a restricted supply of rice due to crop loss and the resultant higher price can induce significant socioeconomic instability.

Rainfed *aman* rice of the monsoon season constitutes more than 50 percent of the total rice production in Bangladesh (BBS 1989a). It is one of the three seasonal rice crops. The *aman* rice production is largely dependent on supply of water during summer monsoon. Delayed onset of monsoon can create water stress for transplanted rice seedlings and results in lower yield. Water stress due to extended delay may even kill rice seedlings. Large departure from normal growing-season precipitation may cause flooding or drought conditions, which can be harmful to rice-plant growth and end-of-the-season yield. Cyclones and associated high wind during harvesting season results in lodging and subsequent yield loss. Precise management decisions could reduce these climate-related uncertainties and associated crop losses and thus increase potentially obtainable yield. Quantitative assessments of yield variations can play a significant role in devising field-level management plans and identify climatically sensitive regions that may notably help reduce future crop losses.

The objectives of this study are to estimate potential rainfed aman (in this case, BR11 *aman*) yield and assess vulnerability of these yields in Bangladesh under multiple transplanting dates. BR11 is a high-yielding variety (HYV) and the most popular HYV *aman*. Irrigation is not applied

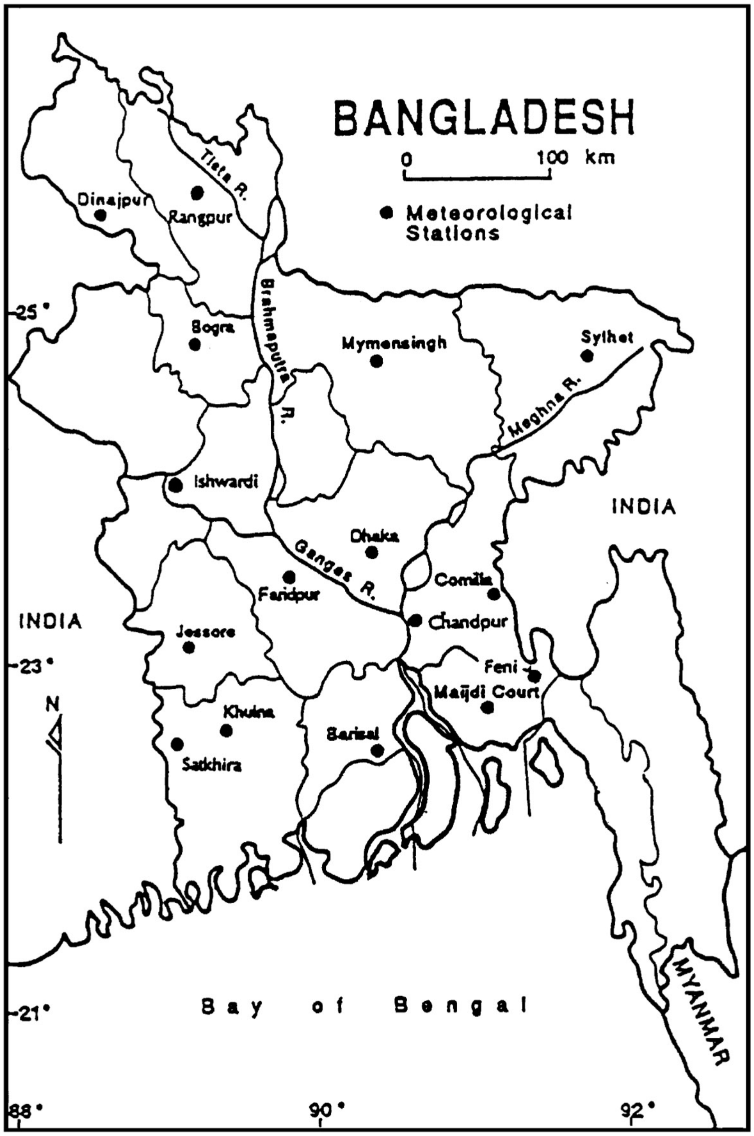

**Figure 1.** Location of meteorological stations.

during its growth; it relies on naturally occurring rainfall. A crop-growth simulation model, the CERES-Rice (Ritchie et al. 1987; Tsuji, Uhera, and Balas 1994), is applied to sixteen locations/meteorological stations distributed over the major rice-growing regions of Bangladesh (Figure 1). These locations represent the various precipitation and soil regimes of the country, and the model input data was collected from these sites.

To estimate potential yield, this study assumes optimum management, including saturated soil condition (due to puddling) at the time of transplanting and recommended supply of fertilizers. The study uses weather data from 1975 through 1987. A number of planting dates—including 1 June, 1 July, 15 July, and 15 August—are used to determine potential yield for these respective dates. Regional-scale estimates for Bangladesh will provide a benchmark for decision makers with quantitative data to determine the deficiency between current actual yield and potential yield. Interannual yield variability and vulnerability assessment would endow farmers and policymakers with a quantitative tool for minimizing economic loss. It has been argued recently that biotechnology has raised the potential rice yield to its potential ceiling (Mann 1999). However, it is also suggested that a number of developing nations could still increase their productivity and total production by improving management. Brown (1997, 20) noted that Bangladesh is one of the countries where ''the greatest remaining potential appears to lie.''

In the past, a number of studies have investigated the impacts of abnormal weather conditions on dry season irrigated rice in Bangladesh (Mahmood and Hayes 1995; Mahmood 1997, 1998a, 1998b). However, there is a complete absence of systematic analysis of regional-scale potential monsoon season aman rice productivity in Bangladesh. The present study addresses this issue and provides a quantitative assessment of potential yield for several transplanting dates. The climatic time series used in this investigation presents a variety of hydroclimatic conditions that are representative of interannual monsoon season rainfall fluctuations. Monsoon-season precipitation time series used in this study demonstrate a variation of rainfall from –20 percent to +40 percent of normal (Matsumoto 1992). Similar climate conditions recurred during post-1987 seasons (e.g., 1998's excessive precipitation had a magnitude comparable to 1987's) and will certainly reappear in the near future, because climatic cycles repeat themselves. Thus, results from this study will be very useful in the future. The CERES-Rice model applications from 1975 through 1987 and the estimation of potential yields and vulnerability assessment in the context of Bangladesh are more critical compared to the absence of a longer meteorological time series. It should be noted that unavailability of daily weather data for the period after 1987 for model input was a hindrance to a study with an extended period of observations. In recent years, a number of studies have been conducted focusing on potential impacts of global change on rice productivity (e.g., Rosenzweig and Parry 1994). However, potential yield assessment under recent climatic conditions would provide an additional advantage in decision making and planning.

## The Agroecological Setting of Rice Farming in Bangladesh

Bangladesh is a deltaic country located in eastern South Asia at the confluence of the Ganges, Brahmaputra, and Meghna rivers. The rain supplies sufficient surface water for agricultural activities during the summer monsoon months, June–October. The availability of this water varies spatially and temporally. Groundwater storage is replenished in most areas every year by the monsoon rains and provides a source of irrigation water, along with the surface-water sources, during the non-monsoon months.

Since rice is the staple food in Bangladesh, farming activities revolve around the goal of supplying food for household consumption. Thus, farming is largely subsistence in character. A survey by the Bangladesh Bureau of Statistics (BBS) showed that the net cultivated area for all crops in Bangladesh during 1984–1985 was 8.64 million hectares, and the total cultivated area was 13.15 million hectares (BBS 1989a). About 90 percent of the land is used for farming, and 78 percent of the cultivated land is used for rice production (Choudhuri 1988).

Bangladesh's loamy alluvial soils are suitable for puddling, which is essential for rice cultivation. Soil fertility is renewed every year by nutrients carried by the floodwaters from the overflowing rivers during the monsoon. Bangladesh produces three major rice crops— the *aus,* the *aman,* and the *boro*, each having different lengths of growing seasons and mean growing-season climate conditions (Table 1).

**Table 1.** Selected Features of the Climate of Bangladesh during the Three Rice-Crop Growing Seasons

| *Rice Cropping Seasons* | $T_{max}$ *(°C)* | $T_{min}$ *(°C)* | $S_{rad}$ *(MJm$^{-2}$ day$^{-1}$)* | *Precipitation (mm)* |
|---|---|---|---|---|
| Aus (March–August) | 34–31 | 16–26 | 14–23 | 1,200–3,100 |
| Aman (June–November) | 34–28 | 26–16 | 14–19 | 1,250–3,000 |
| Boro (December–May) | 24–34 | 10–26 | 14–23 | 250–550 |

*Source:* FAO (1987).

*Note:* $T_{max}$ = mean maximum air temperature; $T_{min}$ = mean minimum air temperature; $S_{rad}$ = solar radiation. Range of values for $T_{max}$, $T_{min}$, and $S_{rad}$ represents respective increase and decrease as rice-growing season progresses. Precipitation shows seasonal total (mm) with regional variation. Northeastern and southeastern regions record significantly higher average seasonal rainfall, while southwestern and west-central regions record lower average seasonal rainfall.

The aus, the aman, and the boro rice-growing seasons are nearly synchronized with the three different climatic seasons; namely, the spring (March–May), the summer monsoon ( June–October), and the dry winter (November– February), respectively. Of the total annual rice production, nearly 20 percent comes from the aus rice crop, 54 percent from the aman, and 26 percent from the boro (BBS 1989a). Aus is typically cultivated on the highest agricultural lands (3.1 to 5.0 m above sea level), boro on the lowest (0.0 to 1.0 m), and aman in between. Aman is susceptible to rainfall variability.

Mowla (1978) showed the relationship between annual rainfall and rice production and loss between 1951 and 1974 in Bangladesh. He found that the increases and decreases in seasonal rainfall significantly influence rice production. Tanaka (1978) noted that anomalous (both high and low) rainfall with a standard deviation of )1.5 or –1.5 from normal was one cause of the bad harvests in Bangladesh. He explained the relationship between the large-scale atmospheric fluctuations and their impacts on rainfall and rice yield in monsoon Asia by studying the correlation of rainfall between different parts of monsoon Asia and developing a seasonal monsoon index based on these correlation coefficients for June, July, and August. This index estimates the pattern of correlation coefficient variation among different regions. The correlation of the seasonal monsoon index with national rice yield showed that Bangladesh, India, and Thailand were significantly influenced by large-scale precipitation fluctuations.

## The CERES-Rice Model

The CERES-Rice model is representative of the current array of advanced physiologically based rice crop growth simulation models and has been widely applied to understanding the relationship between rice and its environment (Bachelet and Gay 1993; Rosenzweig and Parry 1994). Bachelet and Gay (1993) applied this model to determine impacts of climate change in Asia while Rosenzweig and Parry (1994) investigated impacts of climate change on worldwide crop productivity by using the CERES-Rice model. In addition, this model has also been successfully applied to a number of country/regional studies to estimate the impacts of climate change on rice productivity (cf. Baer, Meyer, and Erskine 1994; Escano and Buendia 1994; Tongyai 1994; Barry and Geng 1995; Jin et al.

1995; Seino 1995; Singh and Padilla 1995). The CERES-Rice model is variety-specific (e.g., the BR11 *aman*) and is able to predict more accurately rice yield and rice-plant response to various environmental conditions.

The model assumes that cultivar, soil-water conditions, and crop management are the primary influences on rice productivity (Bachelet and Gay 1993). Climatic data requirements include daily precipitation, daily maximum and minimum air temperature, and daily solar radiation (Table 2). The CERES-Rice also requires information on soil characteristics to calculate evapotranspiration and other components of the water balance, as well as detailed information on management practices, including cultivar, planting date, plant density, and nitrogen fertilization (Ritchie et al. 1987; Tsuji, Uhera, and Balas 1994; Hoogenboom et al. 1995; Hunte and Boote 1998).

**Table 2.** Selected Input Data Requirements for the CERES-Rice Model

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

*Sources:* Modified from Ritchie et al. (1987); Tsuji, Uhera, and Balas (1994).

Assumptions and key aspects of the CERES-Rice model have been discussed in detail in a number of studies (cf. Ritchie et al. 1987, 1998; Singh 1992; Singh and Padilla 1995; Godwin and Singh 1998; Ritchie 1998). The following discussion presents a summarized outline of the relevant parts of the model, including the plant growth and water balance components. Since this study assumes an optimum supply of fertilizer, as recommended by the Bangladesh Rice Research Institute (BRRI), a description of the nitrogen submodel is not included.

### *Plant Growth Submodel*

In the CERES-Rice model, rice plant development consists of both phasic and morphological development. Phasic development represents changes in growth stages and is related to significant changes in the biomass partitioning pattern. The major growth stages in the model are juvenile, floral induction, heading, flowering, grain filling, maturing, and harvesting. Completion of these growth stages is determined by accumulation of growing degree-days (GDD), calculated from

$$\begin{aligned} &\mathrm{GDD} = T - 9 && \text{for } 9^\circ\mathrm{C} < T < 34^\circ\mathrm{C};\\ &\mathrm{GDD} = (44 - T)/10(34 - T) && \text{for } 34^\circ\mathrm{C} < T < 44^\circ\mathrm{C}; \text{ and}\\ &\mathrm{GDD} = 0.0 && \text{for } T \leq 9^\circ\mathrm{C} \text{ and } T \geq 44^\circ\mathrm{C} \end{aligned} \qquad (1)$$

using a base temperature of 9°C, where T is the daily mean air temperature in °C. Note that when T reaches 34°C and approaches 44°C, GDD values decrease linearly towards zero. When temperature reaches ≥44°C, GDD is equal to zero. Morphological development includes the beginning and ending of various plant organ growth within a plant's life-cycle, and temperature plays a key role in this morphogenesis. In addition, water and nutrient stress also affect plant morphological development. Phasic and morphological development are separated to identify differences in the impacts of water or nutrient stresses on these processes.

Beer's Law is used to measure the solar radiation absorption:

$$I/I_0 = \exp(-k\ \mathrm{LAI}) \qquad (2)$$

where I/Io is the light transmission ratio, k is the extinction coefficient for rice plant (0.625), and LAI is leaf area index. Potential dry matter production, $DM_{pot}$, in $gm^{-2}$ is given by

$$DM_{po}t = RUE\ PAR[1 - \exp(k\ LAI)] \qquad (3)$$

where RUE is the radiation use efficiency ($g\ MJ^{-1}$), and PAR is the photosynthetically active radiation, assumed to equal 50 percent of the incoming solar radiation. The CERES-Rice model further adjusts potential dry matter production for thermal stress, water, and nitrogen deficiency to estimate actual dry matter production.

LAI is not an input to the model, but is simulated as a function of leaf-tip appearance rate and leaf expansion growth (thus, it is temperature-driven). The CERES-Rice model further assumes that leaf and stem growth are proportional and the proportionality changes as the crop grows. Assimilates stored in the stem are used by the plants partly or totally for grain-filling, depending on the degree of environmental stress and the resultant inadequate biomass production. In the beginning of a rice plant's growth, a small fraction of assimilates is partitioned to stems and becomes large when leaf growth stops.

Allocation of biomass into the root depends on the growth stage and influences the density of roots and their efficiency in supplying nutrients to shoots. It is assumed that the allocation of biomass to root decreases as the growing season progresses and the rice plant becomes mature. In the CERES-Rice model, partitioning to roots will increase under water or nitrogen stress during all of the growth stages except grain-filling. The model maintains a constant proportionality between root mass and length through the whole growing season. Finally, end-of-season rice-yield estimation is the product of rice grain numbers (estimated from the panicle weight at maturity), individual kernel grain weight, and the number of plants per unit area.

### *Soil Water Balance Submodel*

The soil water balance of the CERES-Rice model calculates infiltration, runoff, drainage, and evapotranspiration. Runoff is estimated using a modified soil conservation service curve number technique, with the difference between daily precipitation and runoff providing estimates of infiltration. To estimate potential evapotranspiration ($ET_p$), the model offers the option of using the Priestly-Taylor method (Priestly and Taylor 1972), given by

$$ET_p = \alpha[\Delta/(\Delta+\gamma)](R_n + S) \tag{4}$$

where $\alpha$ is an empirically derived constant, $\Delta$ is slope of saturation vapor pressure curve, $\gamma$ is a psychometric constant, $R_n$ is net radiation, and S is soil heat flux. Actual evapotranspiration from the soil and plant surface, E, is estimated by Ritchie's method (Ritchie 1972):

$$E = E_p + E_s(E_{so}) \tag{5}$$

where $E_p$ is transpiration from plant surfaces, $E_s$ is evaporation from below canopy soil surface (when soil is drying), and $E_{so}$ is potential evaporation from below canopy soil surface. Transpiration is computed from

$$E_p = E_o(-0.21 + 0.70 \times (LAI \times 0.50) \tag{6}$$

where $E_o$ is the potential evapotranspiration calculated by Penman's method. Soil evaporation below the plant canopy is given by

$$E_s = \beta t^{½} - \beta(t - 1)^{½} \tag{7}$$

where $\beta$ is a calculated coefficient that depends on the hydraulic properties of the soil and t is the number of days since the soil surface was saturated. Finally, potential soil evaporation from below the canopy is given by

$$E_{so} = [\Delta/(\Delta + \gamma)]R_n \exp - 0.398 \times LAI \tag{8}$$

The CERES-Rice model estimates potential water uptake by roots and, in conjunction with potential transpiration, calculates a water stress deficit factor—the ratio of potential root water uptake to potential transpiration. This factor ranges from the absence of water stress (equal to 0.0) to extreme water stress (equal to 1.0). The model integrates conditions measured with a daily temporal resolution over the duration of the growing season to estimate yield. In addition, the model is able to simulate rice-plant physiological processes and the phasic growth of the rice plant and soil water balance at a daily temporal resolution. This allows identification of plant responses to various soil and atmospheric conditions and crop-management practices.

As noted above, the CERES-Rice is a physiologically based model. Therefore, rice productivity, in this model and in this study, is *primarily* a function of biophysical factors (excluding labor). It is well known that modern farming practice can allow farmers to obtain potential yield based on optimum supply of biophysical inputs. Moreover, satisfactory performance of the CERES-Rice model in this and other studies, as shown below, clearly demonstrates that optimum supply of biophysical inputs can result in optimum yield. Note that, in this study, we have estimated *potential* yield, which assumed *optimum* supply of inputs. In other words, impacts of use, availability, and quality of labor were minimized.

In the past, in addition, studies have shown that rice plants largely depend on a supply of water for their growth and yield. For example, Doorenbos and Kassam (1979) noted that 80 to 85 percent of yield variation is related to supply of water. The rice plant is particularly sensitive to water stress during the time of transplanting. This study assumes optimum supply of water during this time and thus reduced posttransplanting water stress and subsequent yield loss. Moreover, this and other studies (e.g., Timsina et al. 1998) have found that optimum supply of biophysical inputs alone can help to attain potential yield. Therefore, this model, like many other physically based simulation models, does not explicitly include ''labor,'' relying more on biophysical inputs.

## Preparation of the CERES-Rice Model for Application to Bangladesh

### *Selection of the Study Period and Weather Data*

Daily maximum and minimum air temperature and rainfall data from 1975 through 1987 were obtained from the Bangladesh Meteorological Department (BMD). This period was marked by significant variations in the monsoonal rainfall (cf. Shukla 1987; Krishnamurti, Bedi, and Subramaniam 1989; Matsumoto 1992). Ahmed and Karmakar (1993) further reported remarkable interannual variations in arrival and departure dates of the monsoon (nearly two weeks) over this period. Therefore, this period presents a ''sample'' segment of a time series representing long-term monsoonal variations.

Daily solar radiation data for Bangladesh is extremely poor, and missing observations are widespread. Thus, Black's (1956) method was modified to estimate solar radiation $R_s$ from the daily cloud cover data. This modified method is given by

$$R_s = R_{so} \times 0.66667 \times (.803 - .00340C - .0000458C^2) + 0.33333 \times R_{so} \quad (9)$$

where $R_{so}$ is radiation at the top of the earth's atmosphere and C is cloud cover (percent). The 0.66667 and 0.33333 are direct- and diffuse-beam radiation, respectively, during summer monsoon months. The magnitude of these two terms was estimated from Stanhill (1966). He noted that ratio of diffuse-beam and total radiation varies from 0.3 to 0.5, and that this proportion stays remarkably constant. For Bangladesh, this proportion should be close to 0.3, due to its tropical location. Thus, we have adopted the proportions of 0.66667 and 0.33333 for direct- and diffuse-beam radiation, respectively. Cloud cover data for this method was obtained from the BMD for all sixteen locations.

### *Soils, Agronomic, and Management Data*

Soils, agronomic, and management data were collected from Hussain (1995) and the Bangladesh Agricultural Research Council (Hussain, Bangladesh Agricultural Research Council, personal communication with Mahmood, January 1997) (Table 3). Planting dates relative to the temporal distribution of monsoonal rainfall can significantly influence the final rice yield. This distribution affects not only the availability of moisture from the monsoon rain but also the solar radiation and dry weather required during maturing and harvesting stages for optimum yield. The BRRI (1995) suggests that farmers transplant rainfed *aman* rice no later than 15 August. August transplanting dates are suggested to cope with yield loss during early-season flooding or extremely dry conditions. Since agriculture is subsistence in nature, late transplanting may allow farmers to overcome imminent starvation.

Four planting dates were considered in this study to reflect actual practice and to determine potential yield for these dates (Table 3). Rice

**Table 3.** Agronomic and Management Parameter Input Data for the Study

| *Agronomic and Management Parameter* | *Input Data* |
|---|---|
| Transplanting date | 1 June, 1 July, 15 July, 15 August |
| 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: | |
| 15 days after transplanting | Application amount: 25 kg $ha^{-1}$ |
| 25 days after transplanting | Application amount: 30 kg $ha^{-1}$ |
| 50 days after transplanting | Application amount: 25 kg $ha^{-1}$ |

*Source:* After Hussain (1997).

transplanting is an ongoing process in any farming community, and there is no single specific date for this activity. Planting dates are a complex product of current hydroclimatic condition and availability of inputs to an individual farmer. The selected transplanting dates for this study are a function of BRRI recommendation, prevailing hydroclimatic condition, and past yield response. It is not efficient to run the model for every single date from 1 June through 15 August. However, it is feasible to run the model for several selected transplanting dates representing various temporal segments of the crop-growing season and to subsequently obtain yield estimates. Thus, we have selected the four dates for this study. These dates are representative of periods during which farmers transplant rice seedlings. For example, 1 June represents transplanting activities as the monsoonal rainfall begins, 15 July represents widespread midseason transplanting activities, and 15 August late-season transplanting dates. As noted above, late-season transplanting is usually the last attempt to obtain yield for subsistence.

Satisfying all of the data requirements for the CERES-Rice model is a challenge. This is a barrier for extensive application of this model. However, when all of the required data is unavailable, this model can be run under an environment in which it estimates prevailing conditions from the available data, and can provide reasonably accurate estimates of yield. This type of assessment is very helpful to scientists, decision makers and policy makers, and emergency managers.

### *Application of the CERES-Rice Model and Evaluation of Its Performance*

The CERES-Rice model was previously successfully validated by Li-Ling (1987) and Jintrawet (1991). Recently, Timsina and colleagues (1998) also evaluated the performance of the model by applying it to a rice-wheat sequence and found its performance satisfactory. Their evaluation was based on experimental field data for BR11 and BR14 aman rice grown under irrigated and rain-fed conditions and under various levels of nitrogen applications. These data were compared with the modeled yield for 1994 at Nashipur, Bangladesh (25.80°N and 88.07°E). Nashipur is located very close to Dinajpur. Timsina and colleagues (1998) found that the root mean square error (RMSE) between simulated and observed yield was 1,279.8 kg $ha^{-1}$ (1.27 t $ha^{-1}$). They noted that some of the overestimation of simulated yield was due to the model's inability to incorporate insect damage and lodging as a result of high nitrogen (N) rates.

To evaluate the CERES-Rice model performance for the present study, it was applied to Joydebpur (24.00°N and 90.43°E) from 1975 through 1987. Joydebpur is located in near proximity to Dhaka. A primary reason for selecting Joydebpur was the availability of observed yield data from experiment sites. Comparative analyses of simulated and observed yields show close agreements in most cases (Table 4). RMSE for these applications is 1.27 t $ha^{-1}$. It is reported that under favorable weather and management conditions, farmers may attain yields up to 6.5 t $ha^{-1}$ (BRRI 1995). Thus, in some cases, lower modeled yields (for the 15 July transplanting date) were the result of unfavorable weather conditions. For example, June and the first part of July were unusually dry months in 1987 (Krishnamurti, Bedi, and Subramaniam 1989). As a result, the model simulated lower yields (3.7 t $ha^{-1}$). Overall, based on close agreements between observed and simulated yields, the modeled yield estimates are satisfactory.

A comparison of modeled and observed harvest index was also conducted for comparable yields from Nashipur and Joydebpur, respectively. With 15 July as the transplanting date in both cases, the Nashipur field experiment in 1994 and the Joydebpur model run for 1987 recorded 4.1 and 3.7 t $ha^{-1}$ yields, respectively. Harvest indices for Nashipur and Joydebpur experiments were 0.35 and 0.31, respectively, which further suggests a satisfactory model performance.

**Table 4.** Comparison of Simulated and Observed Yield

| *Simulated Yield (t ha$^{-1}$)* | *Observed Yield (t ha$^{-1}$)* |
|---|---|
| 15/07/1987: 3.7 | 3.8–4.2 [a] |
| 15/07/1986: 5.5 | 3.3–3.6 [b] |
| 15/06/1986: 7.3 | 6.7 [b] |
| 01/08/1986: 2.6 | 2.94 [b] |
| 07/08/1986: 3.8 | 3.62 [b] |
| 15/07/1985: 3.4 | 3.4 [c] |
| | 3.8 [c] |
| 15/07/1983: 5.3 | 4.0–4.9 [d] |
| 01/07/1981: 4.7 | 3.8 [e] |

*Sources:* a. BRRI (1990), b. BRRI (1988), c. BRRI (1987), d. BRRI (1985b), e. BRRI (1985a).

## The CERES-Rice Model Application and Yield

The model was run for sixteen locations and four transplanting dates: 1 June, 1 July, 15 July, and 15 August. Baseline yields were determined for each station and each transplanting date by computing the average (Table 5). Results show that Barisal has the highest simulated rice yield (8,371 kg ha$^{-1}$) and Mymensingh has the lowest (5,505 kg ha$^{-1}$) for the 1 June rice transplanting date (Table 5). Note that two locations have simulated yields that exceed 8,000 kg ha$^{-1}$ while all stations except Mymensingh, Bogra, and Ishwardi have simulated yields above 6,000 kg ha$^{-1}$. If the transplanting date is moved to 1 July, Dhaka and Ishwardi have the highest (6,736 kg ha$^{-1}$) and the lowest (3,634 kg ha$^{-1}$) simulated yields, respectively. For this planting date, only three locations have simulated yields over 6,000 kg ha$^{-1}$. For the 15 July transplanting date, Dhaka and Ishwardi again record the highest (5,341 kg ha$^{-1}$) and the lowest (2,615 kg ha$^{-1}$) simulated yields, respectively. At all sixteen evaluation stations, simulated yields fell to below 2,500 kg ha$^{-1}$ for the 15 August transplanting date. Reduction of yield with the progression of the transplanting date is related to moisture stress during flowering and maturing stages due to late transplanting.

In Table 5, the model-application sites represent four regions and are aggregated based on proximity of location and similarity in hydroclimatic conditions (Manalo 1976). Hence, Chandpur, Comilla, Feni, Maijdi Court, and Sylhet represent the eastern region; Barisal, Dhaka, Faridpur,

**Table 5.** Baseline Yield Estimates (kg ha–1) for Four Transplanting Dates for the Sixteen Evaluation Stations

| *Station* | *1 June* | *1 July* | *15 July* | *15 August* |
|---|---|---|---|---|
| Eastern Region | | | | |
| Chandpur | 7,220 | 4,853 | 3,082 | 2,033 |
| Comilla | 6,357 | 4,709 | 3,344 | 1,881 |
| Feni | 6,999 | 4,944 | 3,468 | 2,071 |
| Maijdi Court | 8,070 | 5,057 | 3,236 | 1,789 |
| Sylhet | 6,030 | 4,985 | 3,895 | 1,634 |
| *Average* | *6,935* | *4,909* | *3,405* | *1,882* |
| Central Region | | | | |
| Barisal | 8,371 | 6,019 | 4,929 | 1,903 |
| Dhaka | 7,564 | 6,736 | 5,341 | 2,013 |
| Faridpur | 6,743 | 4,385 | 3,468 | 1,820 |
| Mymensingh | 5,505 | 4,166 | 3,152 | 1,601 |
| *Average* | *7,045* | *5,326* | *4,222* | *1,834* |
| Southwestern Region | | | | |
| Jessore | 6,344 | 4,797 | 3,384 | 1,533 |
| Khulna | 7,670 | 5,263 | 3,756 | 2,011 |
| Satkhira | 7,353 | 5,484 | 3,693 | 1,904 |
| *Average* | *7,122* | *5,181* | *3,611* | *1,816* |
| Northwestern Region | | | | |
| Bogra | 5,751 | 4,205 | 2,788 | 1,345 |
| Dinajpur | 7,021 | 5,037 | 3,686 | 1,742 |
| Ishwardi | 5,709 | 3,634 | 2,615 | 1,448 |
| Rangpur | 7,618 | 6,092 | 4,190 | 1,532 |
| *Average* | *6,525* | *4,742* | | *1,516* |
| Country average | 6,907 | 5,039 | 3,639 | 1,762 |
| % yield loss | | 27 | 48 | 75 |

and Mymensingh represent the central region; Jessore, Khulna, and Satkhira represent the southwestern region; and Bogra, Dinajpur, Ishwardi, and Rangpur represent the northwestern region. It is noticeable in Table 5 that regional potential-yield response varies with transplanting date. For example, the southwestern region is the most productive for the 1 June transplanting date, with an average yield of 7,122 kg $ha^{-1}$. However, the central region is the most productive for the 1 July and 15 July transplanting dates (average yield=5,326 kg $ha^{-1}$ and 4,222 kg $ha^{-1}$, respectively), and the eastern region is the most productive for the 15 August transplanting date (average yield=1,882 kg $ha^{-1}$).

As noted previously, agriculture in Bangladesh is predominantly subsistence in character (Choudhuri 1988). In some years, this underlying socioeconomic condition forces farmers to transplant and cultivate rice under circumstances in which low yield is inevitable. For example, due to adverse hydroclimatic conditions, farmers may lose all the crops from an earlier, timely transplant. Usually, in this kind of situation, Bangladeshi farmers attempt another transplanting and harvesting with governmental support. The potential and actual yield of this effort will obviously be low, due to the late transplanting of rice. Nevertheless, it allows a farming family to obtain quantitative estimates of potential yields for late transplanting and for various locations. These estimates will certainly allow farmers and policymakers to plan during abnormal hydroclimatic conditions.

The CERES-Rice model simulations show that stations located in the northwestern Bangladesh consistently produce relatively lower potential yield for all transplanting dates. A relatively early departure of the monsoon over the northwestern and west-central part of Bangladesh results in an early occurrence of moisture stress, which, in turn, causes relatively high yield losses. Analysis of moisture-stress data for northwestern sites reports higher flowering- and maturing-stage water stress compared to sites located in the central and eastern part of Bangladesh. When the monsoon departs a few days later over the eastern regions of Bangladesh, relatively higher yields result from this extra moisture, which helps to reduce water stress when rice is transplanted at the beginning of August. Farmers would attain 62– 89 percent, 60–68 percent, and 20–26 percent of potential yield if they transplanted on 1 July, 15 July, and 15 August, respectively. On the average, Bangladesh would lose 27 percent, 48 percent, and 75 percent of potential yield for these transplanting dates, respectively.

### *Actual Yield in Bangladesh during the Study Period*

During the study period (1975–1987), actual average rain-fed monsoon-season rice yield in Bangladesh ranged between 1,100 and 1,500 kg $ha^{-1}$ (BBS 1980, 1985, 1986, 1989b). This amount is approximately one-sixth of the highest potential yield (6,907 kg $ha^{-1}$). To further illustrate this point, Figure 2 presents examples from Dhaka and Jessore. Comparison of actual and potential yields clearly demonstrates the recent (1975–1987) gap between the two locations. Low actual yield is a function of the unavailability of inputs such as fertilizers and pesticides, cultivation of low-yielding traditional varieties (more than 50 percent of total land

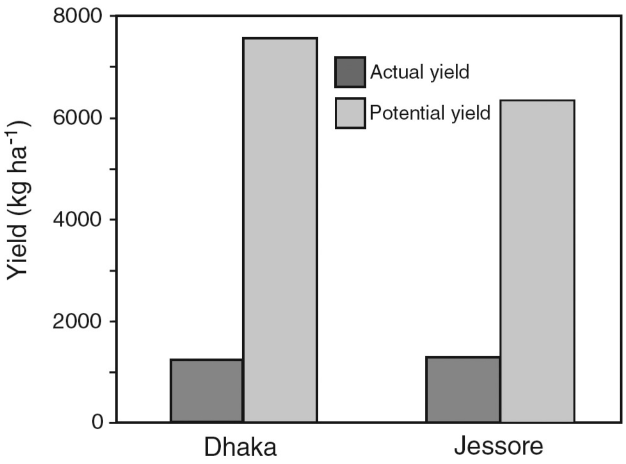

**Figure 2.** Average actual and potential rice yields for Dhaka and Jessore (1975–1987).

use remains under these varieties), and lack of access to timely information on hydroclimatic conditions. However, based on recent statistics from the Food and Agricultural Organization of the United Nations (FAO 2001), it is possible to conclude that rice productivity doubled (2,910 kg ha$^{-1}$) in Bangladesh compared to the average yield for the period from 1975 through 1987. Nevertheless, overall actual rice yield in Bangladesh is nearly 50 percent lower than that of other major rice-growing countries (Figure 3) (FAO 2001).

Brown (1997) noted that grain productivity has increased globally 2.1 percent per year from 1950 through 1990. The rate of this increase fell to 1 percent from 1990 through 1995 (Brown 1997). With the ever-increasing global population, this reduction in yield rate is a major concern

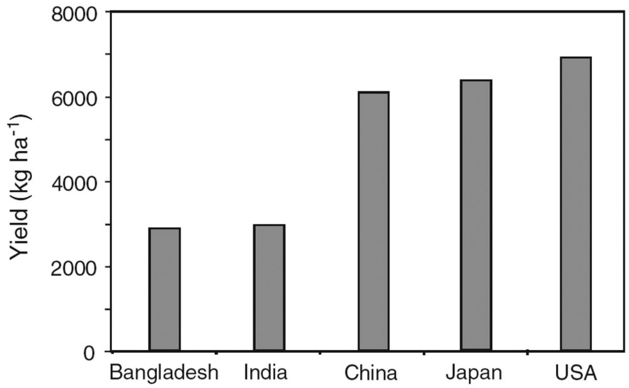

**Figure 3.** Actual average yield for Bangladesh and other major rice-growing countries for 1991–2000. Source: FAO (2001).

for policymakers and planners. In the mid-1990s, Bangladesh attained self-sufficiency in food production; it has barely maintained this status since then. It is estimated that Bangladesh's current population of 129 million will increase to 178 million by 2025 (FAO 2001). Thus, a rapid increase in rice productivity in the near future is absolutely essential to meet the demand of this huge population. Availability of food is not only food for survival. The present study provides important for maintaining healthy nutritional level of a population, but also critical for socioeconomic and political stability.

### *Variability and Vulnerability of Potential Yield*

The coefficient of variation (CV) was calculated for sixteen stations to estimate variability and vulnerability of potential yield (Figure 4). The higher and lower variability represents the higher and lower vulnerability. It is important to note that higher and lower CVs for various stations do not represent higher and lower potential yields. Here, CV is a function of interannual yield variations. It helps us to understand crop-yield variability and the vulnerability of a particular region and allows crop planners to devise strategies to minimize crop and financial loss of individual farmers. We are aware of a broader definition of vulnerability in which the socioeconomic context of a society is explicitly included. In this study, we estimate potential yield under the assumption that supply of input is optimum. In other words, we implicitly include socioeconomic status and its impacts on vulnerability. Note that vulnerability due to socioeconomic condition (e.g., farmers' inability to supply required fertilizer due to their financial status) is minimized as a result of the assumption of optimum management. These underlying assumptions justify our present use of the term ''vulnerability.''

The results show that, overall, the lowest and the highest variability and vulnerability in potential yield can be attained by transplanting rice on 1 June and 15 July. In other words, farmers of Bangladesh will experience higher interannual variability in yield if they transplant rice on 15 July. Therefore, from a farmer's perspective, 1 June is the safest day in the context of vulnerability. Figure 4A shows that southern and northeastern Bangladesh would experience the lowest vulnerability for the 1 June transplanting date (CV = 5–10 percent), while the north central region would experience the highest (CV = 35–40 percent). For the 1 July

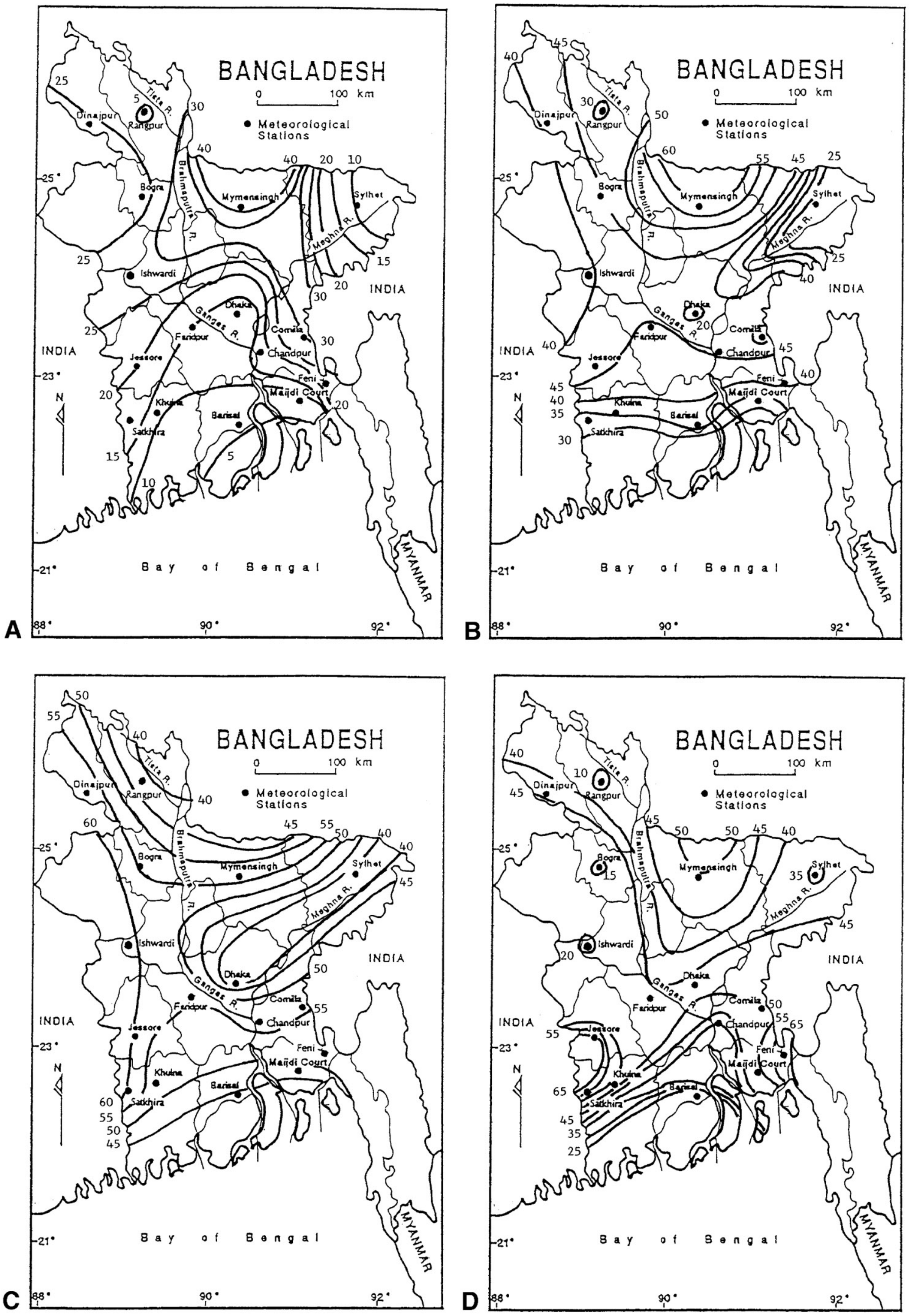

Figure 4. Yield vulnerability for: (A) 1 June; (B) 1 July; (C) 15 July; (D) 15 August.

transplanting date, vulnerability of potential yield increases notably for all regions (Figure 4B), up to six times (CV = 33–35 percent) for certain parts of southern Bangladesh. The north central part of Bangladesh also shows a significant increase (CV = 60 percent) in vulnerability for the 1 July transplanting date. Overall, the southern and northeastern region of Bangladesh would experience least vulnerability for this transplanting date. Potential yield vulnerability for the 15 July transplanting date increases for most of Bangladesh except the north central region (Figure 4C). In fact, vulnerability *decreases* over the north central region for this date compared to 1 July. Northeastern and western Bangladesh would experience the lowest and the highest variability in potential yield, respectively, for the 15 July transplanting date. Compared to 15 July, potential yield vulnerability is less for most locations for the 15 August transplanting date (Figure 4D). However, yield variability would be higher for this transplanting date at most locations compared to 1 July. Again, the southern region would experience the lowest vulnerability, while southwestern Bangladesh would record the highest vulnerability.

Figure 4 clearly demonstrates that intensity and distribution of vulnerability of potential yield changes with transplanting date. Increasing vulnerability with late transplanting follows, to some extent, the trend of loss of yield with such transplanting dates. However, regional distribution does not show a similar linear trend. The results are particularly valuable to farmers and policymakers because they provide estimates of vulnerability for the whole country. Therefore, one could know the potentiality of yield variability for a transplanting date during a particular time at a particular location.

## Summary

The CERES-Rice model was applied to sixteen major rice-growing locations for a weather dataset from 1975 through 1987. These applications provide a quantitative assessment of potential rainfed *aman* rice productivity and vulnerability in Bangladesh during the monsoon season for multiple transplanting dates, including 1 June, 1 July, 15 July, and 15 August. The results of this study would be valuable for Bangladeshi farmers and policymakers for short- and long-term planning to maximize resource use. The actual yield during the study period was one-sixth of the potential yield, and rice productivity in Bangladesh is currently 50 percent lower than that of other major rice-producing countries (FAO2001). The estimates provided in this study can be used as a benchmark for future planning.

The present study assumed BRRI-recommended fertilizer supply and saturated and puddled soils during transplanting. The model's performance was evaluated for yield estimation, and we found that the model estimations are satisfactory. The study finds that, on the average, the southwestern region of Bangladesh is the most productive region for the 1 June transplanting date, with a potential yield estimate of 7,122 kg $ha^{-1}$. For the 1 July, 15 July, and 15 August transplanting dates, the central (1 July and 15 July), and eastern (15 August) regions are the most productive, with average yields of 5,326, 4,222, and 1,882 kg $ha^{-1}$, respectively. Hence, it is clear that regional response varies with the transplanting dates. It is also clear that potential yield decreases rapidly as transplanting occurs later. End-of-the-season moisture stress due to the departure of the monsoon is primarily responsible for the yield reduction. Compared to the 1 June transplanting date, Bangladesh would lose, on average, 27 percent, 48 percent, and 75 percent of potential yield using the 1 July, 15 July, and 15 August transplanting dates, respectively.

The coefficient of variation of yields for each transplanting date and for each station was also computed. The higher and lower variability of yields represent the higher and lower vulnerability. Note that higher and lower yields do not always represent higher and lower CVs. Vulnerability in yields increase as the transplanting dates are moved further into the monsoon season. We found that transplanting on 1 June and 15 July would result in the lowest (up to 5 percent) and the highest vulnerability (up to 66 percent) of yield in Bangladesh, respectively. Thus, 1 June is the safest transplanting date in the context of yield vulnerability. Potential yield vulnerability also shows notable regional differences for each transplanting date.'

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