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Rezaul Mahmood
University of Nebraska-Lincoln, rmahmood2@unl.edu

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Air temperature variations and rice productivity in Bangladesh: A comparative study of the performance of the YIELD and the CERES-Rice models

Rezaul Mahmood

Department of Geography, College of Geosciences, University of Oklahoma,
Norman, OK 73019, USA

Correspondence — R. Mahmood, IANR, School of Natural Resources, 707 South Hardin Hall,
University of Nebraska-Lincoln, Lincoln, NE 68583-0987; *email* rmahmood2@unl.edu

Abstract

Potential increase in air temperature due to climatic change and inter-annual climatic variability and its impacts on crop productivity is of major concern to crop scientists. A number of physically-based models have been developed and applied to estimate crop–environment relationships. In the present study the performance of two such models (the YIELD and the CERES-Rice) are discussed. These two models are used to estimate boro rice productivity under normal and abnormal climate scenarios in Bangladesh. This study finds that boro rice productivity at Mymensingh predicted by the YIELD is higher than the prediction by the CERES-Rice. Productivity estimates for Barisal by these two models are almost identical. Assumptions of non-identical management practices, different soil characterization procedures, different methods for calculation of dry matter production by these two models and the range of diurnal temperature variations played an important role in productivity estimates. The YIELD model predicted the lengths of

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the growing season under the normal and abnormal thermal climate conditions and they are to be shorter than the lengths predicted by the CERES-Rice model. The YIELD model's assumption of higher threshold temperature and a relatively simple relationship between phenology and air temperature has produced such estimations (shorter growing season). The complex data required by CERES-Rice may be an impediment for its extensive use. If input data for the CERES-Rice is not available, the YIELD model can be considered as a possible tool for various applications in crop–environment relationships.

Keywords: Rice, Crop models, Bangladesh

1. Introduction

Rice is an important staple food for half of the world's population. Rice farming employs a significant number of people in many rice economies. Climatic variability and predicted climatic change is of major concern to rice crop scientists because of its potential threat to rice productivity and the associated impacts on the socio-economic structure of rice growing countries. A number of model simulations and field experiments have been carried out to show the impacts of climatic variability and climatic change on the rice productivity (Baker et al., 1990; Jensen, 1990; Rosenzweig and Parry, 1994). In the present paper, performance of two rice growth simulation models YIELD and CERES-Rice are discussed. Both models were applied to sites in Bangladesh under the same thermal climate change scenarios. The YIELD model was applied to 12 meteorological stations located in the major boro rice growing regions to estimate yield, length of growing season, and evapotranspiration (Mahmood and Hayes, 1995), phenology and irrigation requirements (Mahmood, 1996, 1997), and changes in the cropping pattern (Mahmood, 1998) under abnormal thermal climatic conditions. The CERES-Rice model was applied to two of these 12 meteorological stations to estimate the length of boro rice growing season and yield (Karim et al., 1994) under the same thermal climate scenarios. This paper presents results for the two regions (Mymensingh and Barisal) where both of the models were applied. These results are accompanied by discussions on the performance of the YIELD and CERES-Rice models.

2. Model descriptions

2.1. *The YIELD model*

The YIELD model is able to simulate and predict seasonal crop yield, crop water use, length of growing season and related growth characteristics for 11 crops including rice. Its data requirements are modest (**Table 1**) and it allows flexibility (via user-selected options from programmed default scenarios) with many built-in cause and effect links. The model evolved from a crop water balance model developed by Burt et al. (Burt et al. 1980; Burt et al., 1981) and has been validated and sensitivity-tested for several major agricultural crops including rice (Burt et al., 1980, 1981; Hayes et al., 1982a,b; Terjung et al., 1984b,c). It was successfully applied to several regional studies, for example, in China (Terjung et al., 1983, 1984a,b,c,d,e,f,g, 1985, 1989; Todhunter et al., 1989), in Korea (Terjung et al., 1985), in California (Hayes, 1986), and in Bangladesh (Mahmood, 1993, 1996, 1997, 1998; Mahmood and Hayes, 1995) to estimate rice productivity and its relationship with various growth related parameters.

The YIELD model is based on the methods of Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979); Doorenbos and Kassam suggested that it is possible to determine relationships between crop yield and water supply if crop water deficits and actual yield data are simultaneously derived. Water stress adversely affects both evapotranspiration (ET) and yield. A ratio of actual ET to potential ET, called relative ET deficit, is used to calculate this stress. This ratio is related to another index known as relative yield decrease, which is the ratio of actual yield (YA) to maximum yield (YM), through an empirical yield response factor.

The methodology for derivation of relative ET deficit has been discussed extensively (Burt et al., 1980, 1981). Penman's (1948) combination equation for calculation of ET constitutes the basis of relative ET deficit. Doorenbos and Kassam (1979) successfully modified this equation for a reference crop (an extended surface covered with 8–15 cm tall green grass of uniform height, actively growing, completely shading the ground, and an optimum supply of water) by sets of tables and graphs to include the effects of crop type, crop-growth stage, selected site factors, influence of unusual climatic conditions,

Table 1 Selected data requirements for the YIELD model (modified from Hayes et al., 1982a)

Input data
Climatological
Mean monthly maximum and minimum air temperature
Mean monthly maximum and minimum relative humidity
Mean monthly daily solar radiation
Mean monthly daily wind speed
Mean monthly precipitation
Mean monthly cloud cover
Pedological and hydrological
Soil type
Percolation rate
Depth of ground water table
Agronomic
Field size
Base temperature
Slope of the field
Irrigation efficiency
Root depth
Harvest index
Maximum tolerable soil salinity
Station information
Latitude
Longitude
Elevation

crop coefficients that adjust ET for specific crops and specific crop growth stages, and soil moisture budget conditions. The essential contribution of Burt et al. (1980, 1981) and Hayes et al. (1982a,b) was to present a mathematical model as a research tool for geographic, agronomic, and climatic:environmental change studies of the human-managed soil–crop–atmosphere system. In YIELD, the calculation of ET for the reference and actual crops include a daily weather-generating submodel developed by Akima (1970) to interpolate daily values from monthly climate data.

For each crop and season, a soil water budget is calculated as a function of several variables including growth-stage-specific estimates of ET, soil water storage, effective precipitation, groundwater contributions, variable root depths, percolation losses, and irrigation frequency and amount. The average soil water potential for the root zone is determined from this calculation. The crop root zone soil water potential is unique for each scenario. At this point, the soil water potential is used for the determination of the relative ET deficit for each crop.

The yield response factor varies with crop species, crop growth-stage and temporal sequencing of crop water stress. Doorenbos and Kassam (1979) estimated this factor for many crops and climates. These empirical relationships are applicable to high yielding crop varieties grown in large fields and under optimal conditions (sufficient supply of fertilizer, herbicides, pesticides, and trace minerals). The yield response factor can be applied to relatively evenly distributed water stress conditions during a complete growing season of a crop, as well as to intermittent drought and resultant water stress situations. In the latter situations, water stress during early stages can influence the yield response factors of later stages. YIELD allows previous stresses to provide an ameliorating effect on later crop-growth-stages by physiologically hardening the crop against future water stress. The most appropriate yield response factor and its associated growth-stage-specific ET deficit is automatically chosen by the program.

The methodology for calculating relative yield decrease (YA:YM) has been discussed in Doorenbos and Kassam (1979). They defined YM as the harvested yield of a high yielding variety (HYV) crop that is well-adapted to the growing conditions and grown under optimum management. The agro-ecological zone method of Kassam (1977) is applied for the calculation of maximum or potential yield of rice. It should be noted that a method developed by de Wit (1965) has been used to compute the average gross dry matter production of a standard crop.

The YIELD model adopts a phenology submodel partially developed from Doorenbos and Pruitt (1977) and it assumes four stages of rice plant growth, namely: initial, vegetative, flowering: maturing, and harvesting stage. Burt et al. (1980) presented a detailed description of this procedure. In short, it is based upon the concept of cumulative degree-days above a crop-specific threshold temperature, which is a function of latitude. The accumulation of a certain amount of degree-days of heat marks the end of a growth stage. Thus, in the YIELD model, variations in thermal conditions can influence the estimated length of each growth-stages and hence the length of the growing season.

2.2. *The CERES-Rice model*

The CERES-Rice model was developed under the International Benchmark Sites for Agrotechnology Transfer (IBSNAT) project (Ritchie et al., 1987; Tsuji et al., 1994) and has been successfully applied to a number of regional studies (Tongyai, 1994; Escano and Buendia, 1994; Seino, 1994; Baer et al., 1994; Jin et al., 1995). The CERES-Rice model estimates yield of irrigated and rainfed rice, determines duration of growth stages, dry matter production and partitioning, root system dynamics, effect of soil water and soil nitrogen content on photosynthesis and photosynthate partitioning, carbon balance, and water balance. To estimate these detailed characteristics of growth the CERES-Rice model requires a quite detailed input data set (**Table 2**).

Ritchie et al. (1987) and Tsuji et al. (1994) have provided a detailed description of the model. In summary, the CERES-Rice model assumes nine stages of rice plant growth: pre-sowing, germination, emergence, juvenile, floral induction, heading, flowering, grain filling, and harvesting. Completion of these growth stages is determined by accumulation of degree-days. Potential dry matter production is a function of photosynthetically active radiation (PAR) absorbed by plant communities. Beer's Law has been used to estimate this solar radiation absorption. The CERES-Rice model assumes PAR = 50% of incoming solar radiation and to estimate actual dry matter production it adjusts potential dry matter production for thermal stress, water and nitrogen deficiency. Dry matter partitioning depends on the phenological stage and can be modified by water and nutrient stress. Allocation of biomass to roots influences root density and the efficiency of roots in supplying nutrients to the shoot. It has been assumed that the allocation of biomass to roots decreases as the growing season progresses and rice plant becomes mature. It is also presumed that partitioning to root will increase under water or nitrogen stress during all of the growth stages except during grain filling.

The soil water balance and nitrogen component of the model can be bypassed when a user assumes a non-limiting condition. The model calculates infiltration, runoff, drainage and evapotranspiration to estimate soil water balance. CERES-Rice estimates runoff by using USDA (1972) modified Soil Conservation Service Curve Number Technique. The difference between daily precipitation and runoff provides

Table 2 Selected data requirements for the CERES-Rice model (modified from Ritchie et al., 1987 and Tsuji et al., 1994)

Input data
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
Sowing and transplanting date
Row spacing:seeding depth
Number of plants per hill
Number of plants per square meter
Age of seedling
Base temperature to estimate phenological stages
Irrigation amount and frequency
Bund height
Floodwater depth
Fertilizer application dates, amounts
Station information:
Latitude
Longitude

estimates of infiltration. If irrigation is included as an input to the crop, the model does not estimate runoff but allows all water to infiltrate. To estimate potential ET the model offers options of using the Priestly and Taylor (1972) method and the FAO-Penman method (Doorenbos and Pruitt, 1977). The FAO-Penman method requires additional data compared with the Priestly and Taylor method. To estimate actual ET the method of Ritchie (1972) has been incorporated in the model.

The nitrogen submodel estimates the nitrogen requirement of rice, its supply and uptake. The model assumes that nitrogen deficiency adversely affects leaf expansion, photosynthesis, and its concentration in grain. The final yield, as calculated by the model, depends on the grain weight which is a function of grain growth rate and length of filling period. In the CERES-Rice model grain growth rate is assigned a value characteristic of the size classes of rice plant, namely, long, medium, and short. The model also assumes that yield is directly proportional to panicle weight.

3. Model applications and results

3.1. *Selection of the scenarios for the models applications*

To determine the effect of higher than normal air temperature on the BR3 boro rice development and production, the YIELD and the CERES-Rice models were applied for normal (T_{air}) and 2 and 4°C above normal conditions (T_{air}+2 and T_{air}+4). These models were applied to scenarios based on historic climatic conditions and to changed conditions predicted by General Circulation Models (GCMs) (Mitchell et al., 1990; Karim et al., 1994). **Fig. 1(a)** and **(b)** shows the recorded monthly mean maximum and minimum temperatures and extreme maximum and minimum temperatures for Mymensingh and Barisal during the boro rice growing season. The Goddard Institute of Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), and the UK Meteorological Office (UKMO) GCMs estimate 3–4°C, 4–6°C, 2–4°C increases in air temperature under climate change scenarios (Mitchell et al., 1990; Karim et al., 1994) (since various GCMs predict 2–6°C increase in temperature, 2–4°C increases are considered as typical). The scenario building process for the YIELD model applications consider both the recorded extreme thermal conditions during boro rice growing season (Fig. 1(a) and (b)) and the increasing air temperature simulated by the GCMs. The CERES-Rice model applications only consider the GCM predictions for air temperature changes. The inclusion

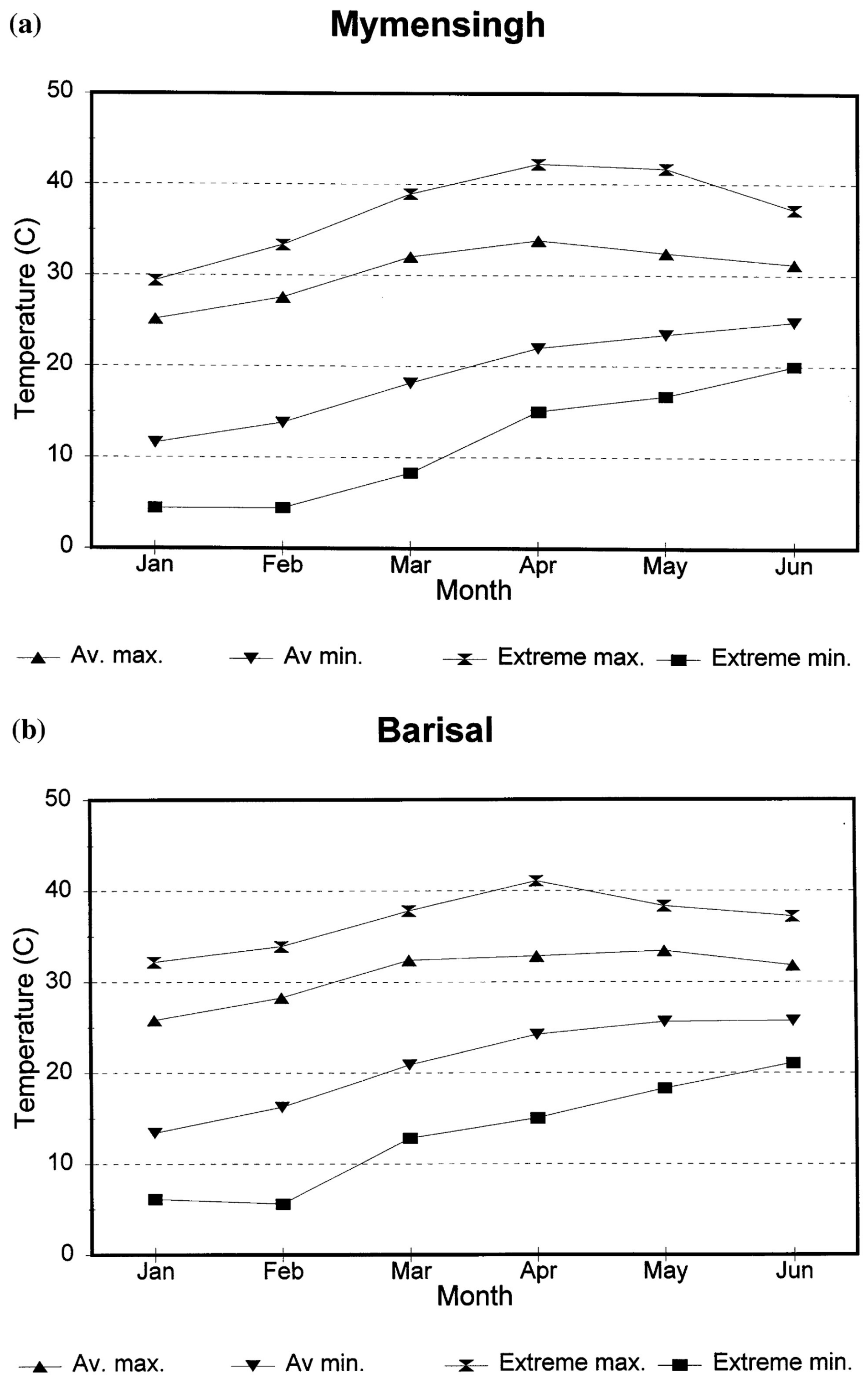

Fig. 1. Mean monthly maximum and minimum and extreme maximum and minimum temperatures for (a) Mymensingh and (b) Barisal.

of the recorded extreme thermal conditions along with the GCM-predicted increase in air temperature provided a stronger reasoning for selection of certain air temperature scenarios.

It is important to note that the boro is a dry season rice. During the initial growth stage boro rice plants grow under cool and dry conditions while the vegetative, flowering, and harvesting periods are hot and dry. As a result supply of water through irrigation is essential for the healthy growth of boro rice plants. Furthermore, from the meteorological point of view, the boro rice growing season is relatively uneventful except for a few localized thundershowers. However, it is found that temperature stress and resultant crop damage is a significant reason for reductions in boro rice yield. Moreover, supply of water through irrigation can be optimum and fulfil the crop-water requirements and can eliminate water-stress (in this paper the YIELD and the CERES-Rice models assumed optimum supply of water) while air temperature fluctuations can notably influence crop productivity. As a result, this paper investigates the impacts of air temperature variations (because it is a critical variable) on the boro rice.

Furthermore, based on our current understanding of the monsoonal circulation, it can be inferred that a few degrees of higher air temperature would not change the monsoonal circulation and make dry boro rice growing season into a wet season. Moreover, the GCMs predictions of climate change do not indicate any change in the timing of the onset of the monsoon. Zhao et al. (1988) indicated drier soil moisture conditions will exist in South Asia (including Bangladesh) during the boro rice growing season under global warming conditions. In summary, since air temperature is the critical variable that influences the dry season boro rice productivity (when water supply is not a major issue), inclusion of the variations in the other weather variables is not necessary.

4. Results and discussions

The YIELD model's estimated length of the boro rice growing season for Mymensingh and Barisal is shorter than the CERES-Rice's estimation (**Table 3**). Key reasons for differences in the estimations of the length of the growing season are due to the assumptions of the

Table 3 The CERES-Rice (CR) and the YIELD model predicted boro rice productivity and length of growing season due to air temperature variations

T_{air}+	*Mymensingh*				*Barisal*			
	Productivity (ton ha^{-1})		*Length of growing season (days)*		*Productivity (ton ha^{-1})*		*Length of growing season (days)*	
	CR	*YIELD*	*CR*	*YIELD*	*CR*	*YIELD*	*CR*	*YIELD*
0	6.39	7.86	156	145	6.81	7.09	138	135
2	5.77	6.75	150	125	6.31	6.23	131	120
4	4.94	6.16	147	115	5.65	5.66	129	110

threshold temperature for these two models. The CERES-Rice (Karim et al., 1994) and the YIELD (Mahmood and Hayes, 1995) assumed 9 and 15°C threshold temperature for their model applications, respectively. The lower threshold temperature assumed by Karim et al. (1994) resulted in longer growing seasons as compared with the YIELD model estimations. Its is important to note that the relationship between the length of the growing season and accumulation of heat is relatively linear for the YIELD model (section 2.1) as compared with the CERES-Rice model. The CERES-Rice model uses a detailed set of crop-specific genetic coefficients which allows the model to respond to various non-linear geophysical conditions in a more realistic manner.

The results show that the YIELD model's estimated boro rice productivity for Mymensingh and Barisal is higher than the CERES-Rice's estimation (Table 3). The fundamental reason is that the CERES-Rice model uses a management input scenario for boro rice which closely resembles the management practices by Bangladeshi farmers. The YIELD model assumes an optimum management practice scenario which eliminates the effect of irregularities in the supply of inputs such as irrigation water or fertilizer, and this resulted in higher yield estimations. Moreover, this model assumes a near-linear relationship between the rice productivity and supply of water. The YIELD model also assumes a single layer of soil whose depth at any time is determined by the depth of roots. The model assumptions include a generalized soil type (Mahmood and Hayes (1995) assumed loamy soil), geotropic root growth, and an absence of soil compaction. This simplified scenario of soil condition and root growth coupled with an optimum supply of water (which allowed rice plants to extract water from the soil relatively easily to maintain physiological processes including evapotranspiration) produced an ideal soil water balance and resulted in the higher productivity estimates by the YIELD model. On the other hand, the CERES-Rice model was applied to silty clay loam and silty soil for Barisal and Mymensingh, respectively. Furthermore, soils of Barisal and Mymensingh have been divided into five and six layers, respectively. Data for various soil parameters for each of these layers were used as inputs to the CERES-Rice model. These parameters include depth of layers, root growth factors, saturated hydraulic conductivity, bulk density (moist), percent of organic carbon, percent of clay, silt, sand, and nitrogen, pH in water, and cation exchange capacity. The inclusion of these parameters in the CERES-Rice model created a more realistic soil and soil-water scenario. Moreover, the CERES-Rice model does not assume a near-linear relationship between availability of water and yield. Thus, a more complex and realistic replication of soil characteristics by the CERES-Rice model resulted in lower yields (compared with the YIELD model estimates) in Mymensingh and Barisal.

It is important to note that the CERES-Rice model calculates genetic coefficients based on threshold temperature. The genetic coefficients include thermal time required to complete the juvenile stage, rate of photoinduction, optimum photoperiod, thermal time for grain filling, conversion efficiency from sunlight to assimilates, tillering rate, and grain size (Ritchie et al., 1987). These coefficients significantly influence rice productivity estimates. As a result, a separate model sensitivity study should be conducted to determine the effects of the variable threshold temperature on the calculation of genetic coefficients and yield. Furthermore, it is very likely that the different methods for estimating dry matter production by the CERES-Rice and the YIELD models contributed to the disagreement in estimates of rice productivity at Mymensingh and Barisal. The YIELD model adopted a method developed by de Wit (1965). Average gross dry matter production is a function of average observed incoming short wave radiation, average maximum photosynthetically active incoming short wave radiation (PAR) on clear days, and fraction of cloud cover (Hayes et al., 1982a,b). The CERES-Rice model assumes dry matter production is a function of PAR and leaf area index (LAI) and can be affected by the nitrogen deficiency and extreme temperatures. Also, this model explicitly includes

Table 4 Percent changes in the boro rice productivity and in the length of growing season under above normal thermal conditions as estimated by the CERES-Rice (CR) and the YIELD model

T_{air} +	*Mymensingh*				*Barisal*			
	Change in productivity (%)		*Change in length of growing season (%)*		*Change in productivity (%)*		*Change in length of growing season (%)*	
	CR	YIELD	CR	YIELD	CR	YIELD	CR	YIELD
2	9.70	14.10	3.80	13.80	7.30	12.10	5.10	11.10
4	22.70	21.60	5.80	20.70	17.00	20.20	6.50	18.50

Beer's law of light absorption by plant community during its estimation of dry matter production. However, the YIELD model includes LAI during its calculation of the final crop productivity through a correction parameter for crop development which is a function of LAI during the middle of the total growing season (Hayes et al., 1982a). Since the amount of light interception is critical for photosynthesis and dry matter production, the use of different methods to estimate this parameter by these two models obviously influenced calculation of the yield under variable thermal conditions.

A further analysis of the results show that the CERES-Rice estimates a productivity decrease of 9.7 and 22.7 for 2 and 4°C increase of air temperature in Mymensingh, respectively (**Table 4**). On the other hand, the YIELD model estimates 14.1 and 21.6% decrease in productivity due to 2 and 4°C increase of air temperature in Mymensingh. The models applications to Barisal provided similar trends in estimates (Table 4). Thus, it is clear that the productivity estimates of the CERES-Rice (YIELD) is relatively less (more) sensitive to small increase in temperature, while both of the models are nearly equally sensitive to large increase. Furthermore, it is clear that both models agree that the productivity decreases with temperature increase.

The YIELD model's predicted percent changes in the length of growing season for Mymensingh and Barisal are nearly similar and shows a near linear relationship with increasing air temperatures (Table 4). On the other hand, the CERES-Rice model's predicted changes in the length of growing season are less dramatic compared with the YIELD model predictions (Table 4). In addition, the CERES-Rice and

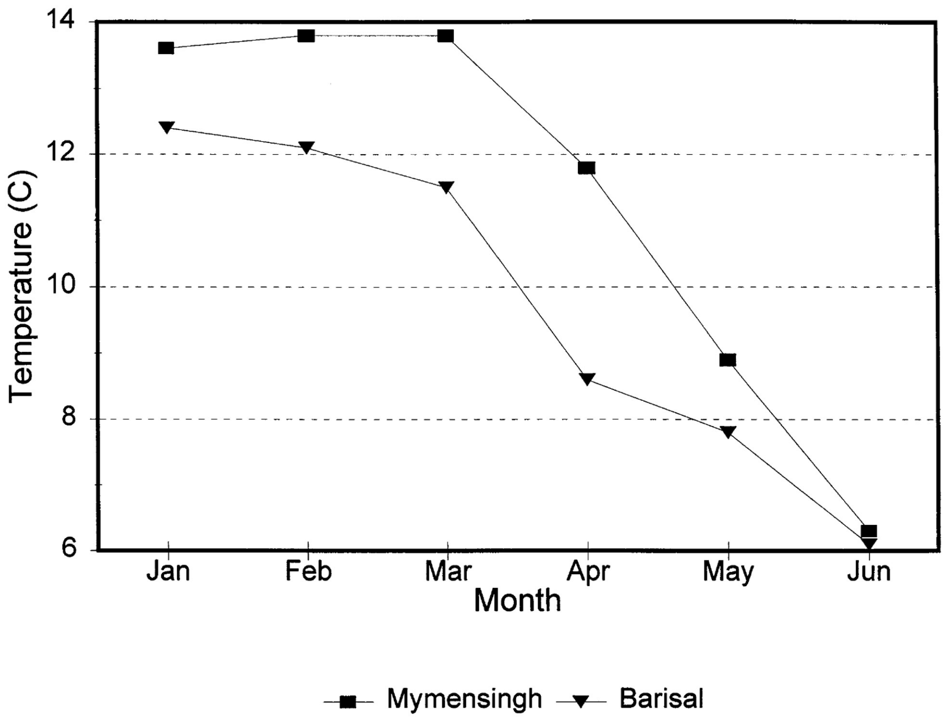

Fig. 2. Variations in the range of diurnal air temperature during boro rice growing season.

the YIELD model predicted percent changes in the yield and the length of growing season for Barisal is less than Mymensingh. It is important to note that both the YIELD and the CERES-Rice model predicts very similar boro rice productivity for all three scenarios for Barisal. This is probably because the coastal location of Barisal causes significantly less variations in diurnal temperatures as compared with Mymensingh (**Fig. 2**). Moreover, this thermal environment allows rice plants to grow under a relatively less temperature-stress environment in Barisal.

5. Conclusions and final remarks

The present study finds that YIELD model estimated lengths of the boro rice growing season from Mymensingh and Barisal are longer than the CERES-Rice model estimates. Threshold temperature inputs played a key role in the disagreement between the two models. The

CERES-Rice and YIELD model applications assumed 9 and 15°C threshold temperatures, respectively. As a result, the CERES-Rice model estimated longer boro rice growing seasons as compared with the YIELD model. Furthermore, the estimates from the YIELD model for the boro rice productivity for Barisal and Mymensingh are higher than the CERES-Rice model's estimates. The CERES-Rice model's assumption of near-optimum management practice (the YIELD model assumes optimum management practice), more realistic replication of soil characteristics, methods for estimation of dry matter production influenced these calculations. This study finds that productivity estimates of the CERES-Rice model is more sensitive to a small increase of temperature as compared with those of the YIELD model. Both of these models are nearly equally sensitive to large increase of temperature. Moreover, the YIELD model estimated length of the growing season is more sensitive to the increasing air temperature as compared with the CERES-Rice model.

Due to the limited application (only in two stations) of the CERES-Rice model in Bangladesh, it is difficult to conduct a comprehensive comparative study of the performance of the YIELD (originally applied to 12 stations) and the CERES-Rice models. However, it is clear that both the CERES-Rice and the YIELD model can be used to estimate crop productivity and related parameters. Data requirements for the CERES-Rice model are significantly complex as compared with the YIELD model. Despite the superiority in the replication of the actual bio-chemical-physical processes by the CERES-Rice model, the difficulties in the model calibration, validation, and subsequent applications due to data unavailability in many cases is an impediment to extensive application of this model. This problem is especially acute for application in developing countries. The data required to characterize physical and chemical properties of the soils for the CERES-Rice model is daunting, even for many sites in the developed nations. For example, data for percent of organic carbon and nitrogen in a particular layer of the soil or data for pH in a particular layer of the soil in a particular site or a region is very difficult to acquire. It was noted by scientists from the developing countries that sometimes a separate soil experiment project needs to be conducted to fulfil the soil data requirements of the CERES-Rice model (Hussain, S.G., 1997. Personal communication. The

Bangladesh Agricultural Research Council. Dhaka, Bangladesh). The Bangladesh Agricultural Research Council (BARC) recommended that all the (Bangladesh) government funded soil surveys should be required to fulfil the data needs for the CERES-Rice model (Hussain, S.G., 1997. Personal communication. The Bangladesh Agricultural Research Council. Dhaka, Bangladesh). On the other hand, data requirements for the YIELD model are relatively simple. For example, a simplified soil classification scheme can satisfy the model requirement and yet successfully replicate some of the growth parameters. In other words, although cause-and-effect loops have been simplified in the YIELD model, the physical basis and performance of the model is satisfactory. As a result, it appears that inclusion of a CO_2 assimilation procedure in the YIELD model would convert it to an effective tool for estimating impacts of climatic change on the crop physiology and crop productivity due to doubling of CO_2. Also, it is clear that where availability of the data is limited for the CERES-Rice model, the YIELD model can be a logical choice for various analyses of crop–environment relationships and crop productivity.

The future goals include extensive application of the CERES-Rice model so that a more detailed comparative study can be conducted for the YIELD and the CERES-Rice models. Among others, this planned study will carry out sensitivity analysis of various components of the CERES-Rice model including the affects of threshold temperature on genetic coefficients and its subsequent impacts on yield calculation. Moreover, impacts of variations in the range of diurnal air temperature on the yield and related growth parameters will also be investigated for both models.

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