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Evaluation of Ceres-Rice, Aquacrop and Oryza2000 Models in Simulation of Rice Yield Response to Different Irrigation and Nitrogen Management Strategies

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EVALUATION OF CERES-RICE, AQUACROP AND ORYZA2000 MODELS IN SIMULATION OF RICE YIELD RESPONSE TO DIFFERENT IRRIGATION AND NITROGEN MANAGEMENT STRATEGIES

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□ *This study evaluated CERES-Rice, AquaCrop, and ORYZA2000 models performance in simulation of biological and grain yield of rice in response to different irrigation intervals and nitrogen levels. These models were calibrated and validated by using three years (2005 to 2007) field experiments. Three levels of irrigation interval included pond treatment, five days interval, and eight days interval, and consisted of four levels of nitrogen. The study results showed that there were significant differences among study crop models in simulation of grain and biological yield in response to different irrigation intervals. As results showed, study models performed more accurate in estimation of rice yield under irrigation intervals than nitrogen levels. All models illustrated high performance in estimation of rice yield under different irrigation intervals. CERES-Rice and AquaCrop models showed highest accuracy in simulation of grain and biological yield of rice under different levels of nitrogen, respectively. In addition, CERES-Rice model indicated highest performance in simulation of grain yield (rRMSE = 16). However, AquaCrop model estimated biological yield more accurate compared to other models (rRMSE = 15). ORYZA2000 showed less accurate in simulating grain (rRMSE = 23) and biological (rRMSE = 21) yield of rice in comparison with other models.*

Keywords: crop growth simulation, modeling, rice, yield, irrigation, nitrogen

INTRODUCTION

Rice (*Oryza sativa* L.) is produced in at least 95 countries across the globe and provides a staple food for more than half of the world's current population. In addition, Rice is the second largest produced cereal in the world. At the beginning of the 1990s, annual production was around 350 million tons and by the end of the century it reached 410 million tons

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(Ainsworth, 2008). As population increases over this century, the demand for rice will grow to an estimated of 2000 million metric tons by 2030 (FAO, 2002).

Lowland rice fields have relatively high water requirements and their sustainability is threatened by increasing water scarcity (Feng et al., 2007). Since the early-1960s, when modern rice production technologies have become available, more than 90% of the total irrigation water developed in Asia is used for rice cultivation. Currently rice production is highly inefficient in water use. As fresh water availability for agriculture is becoming increasingly scarce, achieving higher efficiency of water use in rice production is quite essential (Bhuiyan et al., 1995). Some reports estimated that by 2025, 2 million ha of Asia's irrigated dry-season rice and 13 million ha of its irrigated wet-season rice may experience "physical water scarcity", and most of the approximately 22 million ha of irrigated dry-season rice in South and Southeast Asia may suffer "economic water scarcity" (Bouman et al., 2005).

Nitrogen application can significantly increase the yield and improve the quality of rice (Li et al., 2009). Rice production response to nitrogen is very different in flooded anaerobic soil than in non-ponded aerobic conditions. In ponded conditions, the movement of nitrate, urea and ammonium between the soil and floodwater is important, and ammonia volatilization from the floodwater can be a major source of nitrogen (N) loss (Herrero et al., 2007). Due to importance of nitrogen fertilization on rice plant grain yield, it is necessary to find its optimum amount and application timing for each variety as well as its influence on components of yield and other agronomic parameters such as plant height, lodging and moisture content of the grain (Shrawat et al., 2008). However, for many farming systems there are concerns with respect to the availability of resources, as well as excessive application of resources and their effects on environment, such as nitrate leaching (Gheysari et al., 2009). Water scarcity and concerns of environmental pollution provide strong incentives for farmers and policy makers to employ pressurized irrigation systems, which may improve water savings, irrigation uniformity, and improved management of water and fertilizer (Herrero et al., 2007). Therefore, optimizing the amount of nitrogen based on the amount of available water is needed to improve rice production at both the local and regional level. Few studies have reported that the optimum rate of nitrogen application in rice cultivation was 130 kg ha^{-1} in humid regions of Iran (Mustafavi and Sarvestani, 2003; Ghorbanli et al., 2006).

Crop modeling systems are designed to assist to analyze the growth and development of crops and the environmental variables to which they are exposed. The models are able to predict how the changes in the environment will affect the growth and development and impact final yield (Bannayan et al., 2007). Information requirements for agricultural decision making at all levels are rapidly increasing due to increased demands for agricultural products and higher pressures on land, water, and other natural resources. Traditional agronomic experiments are conducted at particular points in time and space, making obtained results site- and season-specific, and are time consuming and expensive (Bannayan et al., 2007). The Decision Support System for Agrotechnology Transfer (DSSAT) comprises of six models for simulating the growth of 16 crops of economic importance (Jones et al., 2003) and has demonstrated high reliability under different climates, soil, and management conditions (Bannayan et al., 2003). The Primary modules are for weather, soil, plant, soil-plant-atmosphere interface, and management components. CERES-Rice simulates the development, growth, and biomass partitioning of rice crop on a daily basis according to climatic data, water and nitrogen balances and cultivar characteristics (Timsina and Humphreys, 2006).

The AquaCrop model simulates the variation in attainable crop biomass and harvestable yield in response to variation in soil moisture in the root zone (Geerts et al., 2010). This is accomplished on daily basis by considering the incoming and outgoing water fluxes and by taking into account the daily transpiration rate (Araya et al., 2010). The daily increment in yield depends on the normalized transpiration for the local climate and the separation of yield into biomass and grain. Biomass growth is associated with crop parameters such as stomatal conductance, canopy senescence and harvest index (Mati et al., 2011).

Since the mid-90s, the International Rice Research Institute (IRRI) and Wageningen University and Research center (WUR) have been developing the ORYZA2000 model series to simulate the dynamics of rice growth and development for potential production (Kropff et al., 1994), N-limited (Bouman and Van Laar, 2006), and water-limited (Jing et al., 2007) conditions. ORYZA2000 follows a daily calculation scheme for the rate of dry matter production of the plant organs and for the rate of phenological development. By integrating these rates over time, dry matter production and development stage are simulated throughout the growing season (Bouman and Van Laar, 2006).

This study built on comparison of three dynamic models (CERES-Rice, AquaCrop, and ORYZA2000) performance in simulation of biological and grain yield of rice under different conditions of irrigation and nitrogen levels in north of Iran.

MATERIALS AND METHODS

Study Area

This investigation was performed in 2005, 2006, and 2007 growing seasons at the Rasht experiment station of Iran Rice Research Institute (latitude:

TABLE 1 Physical soil properties of study location

Depth (cm)	Sand (%)	Loam (%)	Clay (%)	Bulk density (g cm^{-3})	Moisture content (vol %) θ_{SAT} (−)	θ_{FC} (−)	θ_{PWP} (−)	K_{SAT} (mm/day)
0–10	14	39	47	1.10	0.65	0.40	0.27	575
10–20	17	39	44	1.20	0.62	0.40	0.30	308
20–30	9	44	47	1.32	0.62	0.41	0.30	4
30–40	11	42	47	1.31	0.60	0.42	0.30	114

Ks = saturated hydraulic conductivity; θ_{SAT} = saturated volumetric water content; θ_{FC} = volumetric water content at field capacity; θ_{PWP} = volumetric water content at permanent wilting point.

37°12′ N, longitude: 49°39′ elevation: 37 m) which situated in north of Iran (Gilan province). Climatic condition of Gilan province is extremely humid due to proximity to Caspian Sea. Annual precipitation rate in Gilan province is 1506 mm, in addition, average temperature of this region is 15.8°C (IMO, 2009). Weather data, including daily values of air temperature and humidity, wind speed and incoming solar radiation and precipitation, were collected at the meteorological station of Rasht city, located about 1 km far from the experimental station. Maximum and minimum temperatures and precipitation rate of all years of this experiment during growth period are shown in Figure 1. Bulk density measured by division of weight of the soil per unit volume (Pitty, 1979). Other soil properties of this experiment such as saturated volumetric water content, volumetric water content at field capacity and volumetric water content at permanent wilting point determined by FAO-56 (Allen et al., 1998), saturated hydraulic conductivity calculated according to Tietje and Hennings (1996) method (Table 1).

Experimental Design

The two-factor experiment was set up in a split-plot randomized complete block design with irrigation interval as main-plot factor, nitrogen levels as sub-plot factor in three replicates in 2005, 2006, and 2007. Three levels of irrigation intervals included: pond during growth period as control treatment (525 mm irrigation during growth period), five days interval (388 mm irrigation during growth period) (I_1) and eight days interval (290 mm irrigation during growth period) (I_2) and sub-plot treatments consisted of four levels of nitrogen [0 kg as control treatment, 45 kg (N_1), 60 kg (N_2) and 75 kg (N_3)] in this experiment. The size of each plot was 3 m × 5 m. ‘Hashemi’ cultivar was used in this study. Rice plants were grown in wet beds for approximately 25–30 days before cultivation and transplanting was performed at 3 plants per hill with 20×20 cm spacing. Transplants transferred to field conditions on 25 May in 2005 to 2007. Each plot was irrigated by a hose

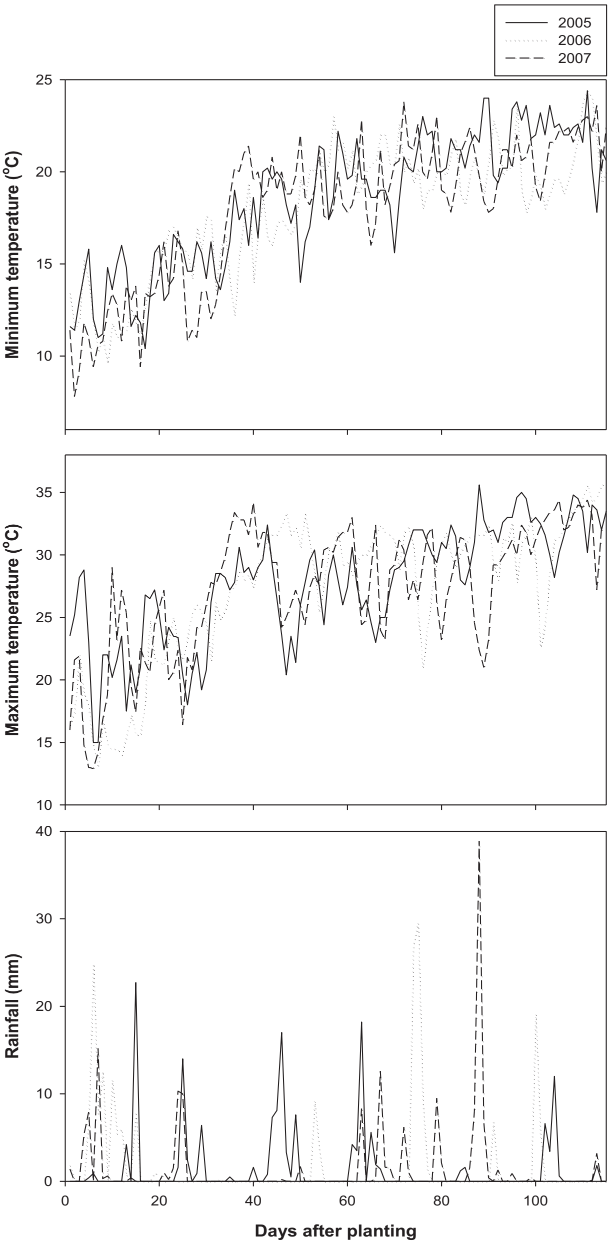

FIGURE 1 Daily values of maximum and minimum air temperature (°C) and rainfall (mm) of during growth period.

(4 cm diameter) with a counter on it. Weeds were controlled by hand when needed. Plants harvesting was on 11–15 August in all years of experiment. First year measured data of experiment used for models calibration, and second and third years of experiment data employed for model validation.

Data Collection

Dates of important phenological phases including emergence, panicle initiation, flowering, and physiological maturity were monitored and thermal time for those stages duration was calculated as growing degree-days (Thornley and Johnson, 1990) method. At different crop growth stages, dry weight of stem, leaf, and grain were measured and number of tillers and leaves were recorded. Biological and grain yield obtained from 5 m^2 from each plot. Aboveground biomass was measured after drying in an oven (75°C), until biomass reached constant weight.

Model Descriptions

CERES-Rice

The CERES (crop-environment resource synthesis) family of crop models has been used to simulate the performance of several cereal crops (Rinaldi, 2004). Ceres-rice calculates nine phenological stages. The length of each phenological stages predicted by the concept of thermal time with taking into account base temperature of 9°C, optimal temperature of 33°C and a maximum temperature of 42°C (Singh et al., 1994). In addition, a CERES model simulates dry matter accumulation as a linear function of intercepted photosynthetically active radiation (Timsina and Humphreys, 2006). Additionally, potential dry matter accumulation depends on the quantity of biomass already produced and the actual leaf area index (Eitzinger et al., 2004). CERES models define the atmospheric demand for water (E_{tp}) as the potential evaporation rate defined from some variant of the Penman equation (Ep), modified by the current value of leaf area index (LAI) (Jones et al., 2003; Timsina and Humphreys, 2006; Mahmood, 1998). The water balance of CERES models performed as (Cheyglinted et al., 2001):

$$E_{tp} = E_p \left[1 - \exp(-kLAI)\right] \tag{1}$$

Where E_{tp} and E_p are potential transpiration rate (mm d^{-1}) and potential evapotranspiration rate (mm d^{-1}), respectively; furthermore, k and LAI are extinction coefficient and leaf area index. CERES models employed the Priestley and Taylor equation, which calculates E_p as the product of the equilibrium evaporation rate, calculated from solar radiation and ambient air temperature (Singh et al., 2008). The radiation use efficiency (RUE) for rice was considered as 2.95 g MJ^{-1} (Saseendran et al., 1998). Temperature between 14°C and 32°C is considered as optimal for photosynthesis and outside this range, it drives a decreasing effect (Mall and Aggarwal, 2002). The CERES family of crop growth models divides up the same carbon and nitrogen simulation subroutine (Singh et al., 2008). CERES models simulate a one-dimensional water flow (Shaffer et al., 2001). The nitrogen dynamics of the CERES models simulates each of the major nitrogen loss process and the assistance to the nitrogen balance made by mineralization (Kersebaum et al., 2007). Plant nitrogen uptake in the CERES model series was determined by plant nitrogen requirement and soil nitrogen supply (Timsina and Humphreys, 2006). Plant nitrogen demand was collected by the nitrogen deficiency of existing biomass plus nitrogen compulsory for new growth (Singh et al., 1998). Nitrogen supply is premeditated from root length density, soil water content, and available soil ammonium (NH_4) and nitrate (NO_3) concentrations (Timsina and Humphreys, 2006). If the potential nitrogen supply is greater than crop nitrogen demand, nitrogen uptake from each soil layer is reduced proportionally to the level of demand (Timsina et al., 1998). The model also allows luxury nitrogen uptake and organic nitrogen exudation from the plant (Shaffer et al., 2001).

ORYZA2000

ORYZA2000 simulates the growth, development, and water balance of rice under potential production, and in water limited and nitrogen-limited environments (Bouman et al., 2001). The water dynamics in the ORYZA2000 model is estimated by water balance in three soil types (Yadav et al., 2011). Those are poorly drained lowland soil, regular upland, and well-drained upland. In addition, water gains by rain or irrigations are accounted by evapotranspiration and percolation losses (Bouman et al., 2001). Daily soil evaporation and plant transpiration are met preferentially from pond water layer, and then from top soil layer and all rooted layers in the absence of pond water (Bouman et al., 2001). The water balance of lowland rice in ORYZA2000 model includes:

$$dW = I + R + C - E - T - S - P - D \tag{2}$$

Where dW is the change in stored water, I is irrigation supply, R is rainfall, C is capillary rise, E is evaporation, T is transpiration, S is seepage, P is percolation, and D is surface drainage/runoff (all units are mm d^{-1}) (Bouman et al., 2001).

ORYZA2000 calculates the daily potential require for nitrogen by a variety of plant organs based on their weights, growth rate, and maximum nitrogen content (Bouman and Van Laar, 2006). Daily nitrogen translocation from the leaves, stems, and roots to the storage parts was calculated on daily basis. Translocatable nitrogen is subtracted from the daily potential demand to get the daily potential demand for uptake from soil. This potential uptake demand is limited by the daily extractable amount of nitrogen from the soil and the maximum uptake rate of the crop (Bouman et al., 2001). Actual daily crop N uptake is the lower value of potential crop uptake (demand) and the amount of nitrogen available for uptake in the soil (supply) (Jing et al., 2007). The soil nitrogen availability is modeled as a simple bookkeeping routine and does not compute the dynamics of nitrogen transformation processes in the soil (Bouman and Van Laar, 2006).

AquaCrop

AquaCrop simulates the crop green foliage (canopy cover) from crop emergence through the development and senescence of the canopy (Heng et al., 2009). The biomass growth rate is linearly proportional to transpiration through the following equation (Todorovic et al., 2009):

$$AGB = \frac{WP \times T_c}{ET_o} \tag{3}$$

Where AGB is the aboveground biomass rate, WP is the water productivity, T_c is the crop transpiration, and ET_o is the reference evapotranspiration. Soil water balance is performed on a daily basis including the processes of infiltration, runoff, deep percolation, crop uptake, evaporation, transpiration, and capillary rise. The model keeps track of the rainfall and irrigation, and separates evaporation from transpiration through the percentage of canopy cover (Todorovic et al., 2009). In AquaCrop, grain yield is obtained by multiplying biomass by harvest index. Harvest index (HI) is simulated by a linear increase with time starting from flowering up to physiological maturity (Araya et al., 2010). AquaCrop model simulates various crop growth process based on water requirement and leaf senescence process is a function of plant nitrogen. Early canopy senescence is likely to be depended on the nitrogen nutrition of the crop. Mineral nutrient stress, particularly the lack of nitrogen, can reduce canopy expansion, maximum canopy cover and the water productivity. Under long-term nutrient stress canopy cover normally undergoes steady decline once the adjusted maximum canopy cover is reached at mid-season. AquaCrop does not simulate nutrient cycles and balance, but provides categories of soil fertility levels ranging from non-limiting to severely limiting (Raes et al., 2011).

Model Calibration

CERES-Rice

Measurements including grain yield, shoot biomass, and leaf area index in different growth stages were provided for the model as observed data using ATCreate 4.5. ATCreate is a sub-program of DSSAT, which is used for declaration of observed data. A and T files, which produced by ATCreate were linked to Genetic Coefficient Estimator (Gencalc) for estimated genetically coefficients of ‘Hashemi’ cultivar (Hunt et al., 1993). Genetic coefficients of ‘Hashemi’ cultivar are represented in Table 2.

TABLE 2 The calibrated values of CERES-Rice parameters for rice cultivar Hashemi

Genetic parameters	Description	Coefficient
P1	Time period (expressed as growing degree days [GDD] in °C above a base temperature of 9°C) from seedling emergence during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as the basic vegetative phase of the plant.	300.0
P20	Critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate. At values higher than P2O developmental rate is slowed, hence there is delay due to longer day lengths.	5.0
P2R	Extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in °C) for each hour increase in photoperiod above P2O.	350.0
P5	Time period in GDD °C) from beginning of grain filling (3 to 4 days after flowering) to physiological maturity with a base temperature of 9 °C.	13.5
G1	Potential spikelet number coefficient as estimated from the number of spikelets per g of main culm dry weight (less lead blades and sheaths plus spikes) at anthesis. A typical value is 55.	55.0
G2	Single grain weight (g) under ideal growing conditions, i.e. nonlimiting light, water, nutrients, and absence of pests and diseases.	0.0250
G3	Tillering coefficient (scaler value) relative to IR64 cultivar under ideal conditions. A higher tillering cultivar would have coefficient greater than 1.0.	1.00
G4	Temperature tolerance coefficient. Usually 1.0 for varieties grown in normal environments. G4 for japonica type rice growing in a warmer environment would be 1.0 or greater. Likewise, the G4 value for indica type rice in very cool environments or season would be less than 1.0.	1.00

AquaCrop

Calibration is adjusting certain model parameters to make the model match the measured values at a given location (Farahani et al., 2009). The fluctuations in canopy cover during the growing period were measured in the field experiment. The options in the model were used to estimate the initial canopy cover from planting density, grain weight, grain number, and estimated germination rate (Heng et al., 2009). The model automatically estimated the canopy expansion rates after feeding the observed phenological dates such as dates to maximum canopy cover, senescence, maturity and emergence for 'Hashemi' cultivar. The canopy growth coefficient, canopy decline coefficient and the stress indices for water stress affecting leaf expansion and early senescence are the most important canopy cover parameters (Araya et al., 2010). 'Hashemi' cultivar crop parameters were illustrated in Table 3.

TABLE 3 The calibrated values of AquaCrop parameters for rice cultivar Hashemi

Description	Value	Units
Base temperature below which crop development does not progress	8	°C
GDDays: from transplanting to recovered transplant	100	°Cday
GDDays: from transplanting to maximum rooting depth	383	°Cday
GDDays: from transplanting to start senescence	1100	°Cday
GDDays: from transplanting to maturity	1414	°Cday
GDDays: from transplanting to flowering	814	°Cday
GDDays: building-up of Harvest Index during yield formation	550	°Cday
Canopy cover per seedling at 90% emergence (CCo)	5	Cm^2
Canopy growth coefficient (CGC)	0.096	%
Maximum canopy cover (CCx)	0.82	%
Canopy decline coefficient (CDC)	0.06038	%
Water productivity	19.0	$Gram/m^2$
Soil water depletion factor for leaf expansion, upper limit	0.00	—
Soil water depletion factor for leaf expansion, lower limit	0.40	—
Shape factor for water stress coefficient for leaf expansion	−2.0	—
Soil water depletion fraction for stomatal control	0.50	—
Shape factor for water stress coefficient for stomatal control	3.0	—
Soil water depletion factor for canopy senescence	0.60	—
Shape factor for water stress coefficient for canopy senescence	3.0	—
Soil fertility stress at calibration	38	(%)
Shape factor for the response of canopy expansion for limited soil fertility	4.70	—
Shape factor for the response of maximum canopy cover for limited soil fertility	−0.21	—
Shape factor for the response of crop Water Productivity for limited soil fertility	2.84	—
Shape factor for the response of decline of canopy cover for limited soil fertility	0.69	—
Reference harvest index (HI)	47	%
Coefficient, adjustment of HI to water stress during flowering	10.0	—
Coefficient, HI increased due to inhibition of leaf growth before flowering	0	—
HI decreased caused by water stress during yield formation	7.0	—

ORYZA2000

ORYZA2000 model parameterized for 'Hashemi' cultivar following the procedure identified by Bouman and Van Laar (2006). Development stages were computed by using the recorded dates of emergence, panicle initiation, flowering, and maturity and air temperatures of first year of experiment. Specific leaf area was calculated by observed values of leaf area index and leaf dry weight (Boling et al., 2007). Dry matter partitioning factors were first estimated from measured biomass of leaves, stems and panicles, and further fine-tuned by matching simulated and measured values of LAI and biomass of crop organs. All other crop parameters were set to the values from ORYZA2000 standard crop data file for the tropical high yielding variety IR72 (Jing et al., 2007). The calibrated values of ORYZA2000 parameters for rice cultivar 'Hashemi' were illustrated in Table 4.

TABLE 4 The calibrated values of ORYZA2000 parameters for rice cultivar Hashemi

Description	Value	Units
Base temperature below which crop development does not progress	8	°C
Development rate in juvenile phase	0.000531	$(°\text{Cday})^{-1}$
Development rate in photoperiod-sensitive phase	0.000758	$(°\text{Cday})^{-1}$
Development rate in panicle development	0.001206	$(°\text{Cday})^{-1}$
Development rate in reproductive phase	0.002210	$(°\text{Cday})^{-1}$
Maximum relative growth rate of leaf area	0.0070	$(°\text{Cday})^{-1}$
Maximum individual grain weight	0.0000249	kg grain^{-1}
Minimum relative growth rate of leaf area	0.0040	$(°\text{Cday})^{-1}$
Specific leaf area (SLA)	[DVS, SLA]: 0.00, 0.0030; 0.50, 0.0030; 0.65, 0.0028; 1.00, 0.0020; 1.37, 0.0017; 2.05, 0.0003	ha leaf kg^{-1} leaf
Fraction of stem reserves	0.5	—
Fraction of total dry matter partitioned to the shoot (FSH)	[DVS, FSH]: 0.00, 0.50; 0.43, 0.75; 1.00, 1.00; 2.50, 1.00	—
Fraction shoot dry matter partitioned to the leaves (FLV)	[DVS, FLV]: 0.000, 0.50; 0.500, 0.60; 0.700, 0.45; 1.000, 0.10; 1.600, 0.00; 2.5, 0.	—
Fraction shoot dry matter partitioned to the stems (FST)	[DVS, FST]: 0.000, 0.50; 0.500, 0.40; 0.700, 0.55; 1.000, 0.70; 1.600, 0.00; 2.5, 0.	—
Fraction shoot dry matter partitioned to the panicles (FSO)	[DVS, FSO]: 0.000, 0.000; 0.500, 0.000; 0.700, 0.000; 1.000, 0.20; 1.600, 1.00; 2.5, 1.	—
Leaf death coefficient (DRLVT)	[DVS, DRLVT]: 0.00, 0.000, 0.60, 0.000, 1.00, 0.005, 1.60, 0.045, 2.10, 0.050, 2.50, 0.050	d^{-1}

Model Validation

Several criteria were calculated to quantify the difference between simulated and observed data. The relative root mean-squared error (rRMSE) is computed to measure the coincidence between measured and simulated values, while mean deviation (RMD) is calculated to evaluate systematic bias of the model. Model efficiency (EF) is calculated to estimate model performance in relation to the observed mean (Nash and Sutcliffe, 1970). Moreover, linear regression detected between simulations and observations to evaluate model performance and correlation coefficient (R^2) determined for each simulation.

$$rRMSE = \frac{100}{\overline{O}}\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{4}$$

$$RMD = \frac{100}{\overline{O}} \sum_{i=1}^{n} \frac{P_i - O_i}{n} \quad (5)$$

$$EF = 1 - \frac{\sum_{i-1}^{n} (P_i - O_i)^2}{\sum_{i-1}^{n} (\overline{O} - O_i)^2} \quad (6)$$

Where P and O are simulated and observed data, respectively, in addition $\bar{O}$ is the mean of observed data and n is the number of observations. The rRMSE illustrated the model's simulation error by heavily weighting high errors, whilst the RMD uses same weights for all errors, which tends to smooth out discrepancies between simulated and observed data. EF indicated the efficiency of the model and can have positive or negative values (Huang et al., 2009; Bannayan and Hoogenboom, 2008).

RESULTS

CERES-Rice

The DSSAT suite of models simulate crop growth, development, and yield taking into account the effects of weather, management, genetics, and soil water, carbon and nitrogen (Timsina and Humphreys, 2006). Results of irrigation treatments showed that full irrigation treatment produced highest simulated grain yield along a high correlation (R^2 = 92%) with observed grain yield across various irrigation treatments (Figure 2). Moreover, other irrigation intervals represented more than 80% correlation between simulated and observed yield (Figure 2). Generally, CERES-Rice model illustrated high performance in simulation of grain and biological yield under various irrigation treatments in comparison with other models (Figure 3).

The model accuracy in simulation of grain and biological yield was lower under different levels of nitrogen in comparison with various irrigation intervals treatment (Figures 4 and 5). Highest correlation (R^2 = 85%) between simulated and observed rice grain yield obtained at moderate levels (N_1 and N_2) of nitrogen application (Figure 4). However, N_3 nitrogen level represented maximum correlation (R^2 = 52%) between simulated and observed biological yield of rice (Figure 5). The CERES-Rice model simulated biological yield more accurate than grain yield under various levels of nitrogen (Figure 4 and 5). In general, this model showed high precision in grain yield (rRMSE = 16 and RMD = 8) and biological yield (rRMSE = 19 and RMD = −3) estimation under different levels of nitrogen and irrigation intervals, and there was significant correlation between observed and simulated values of grain (85%) and biological (88%) yield (Table 5).

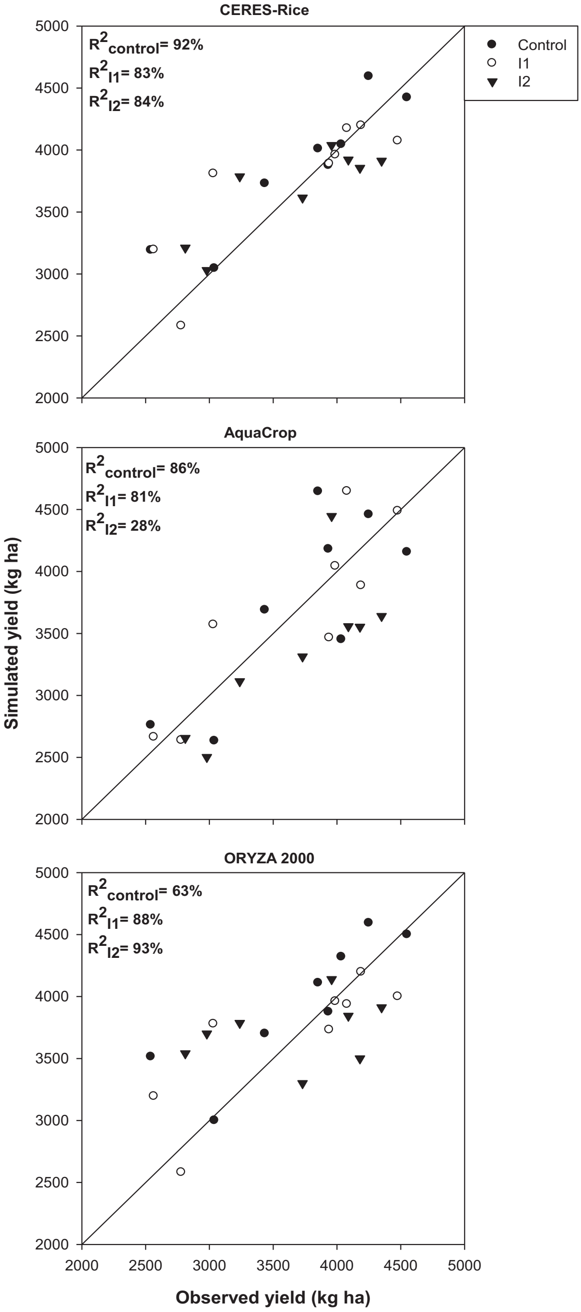

FIGURE 2 Comparison of observed and simulated grain yield in various models under different irrigation intervals (control treatment, five days interval (I_1) and eight days interval (I_2)).

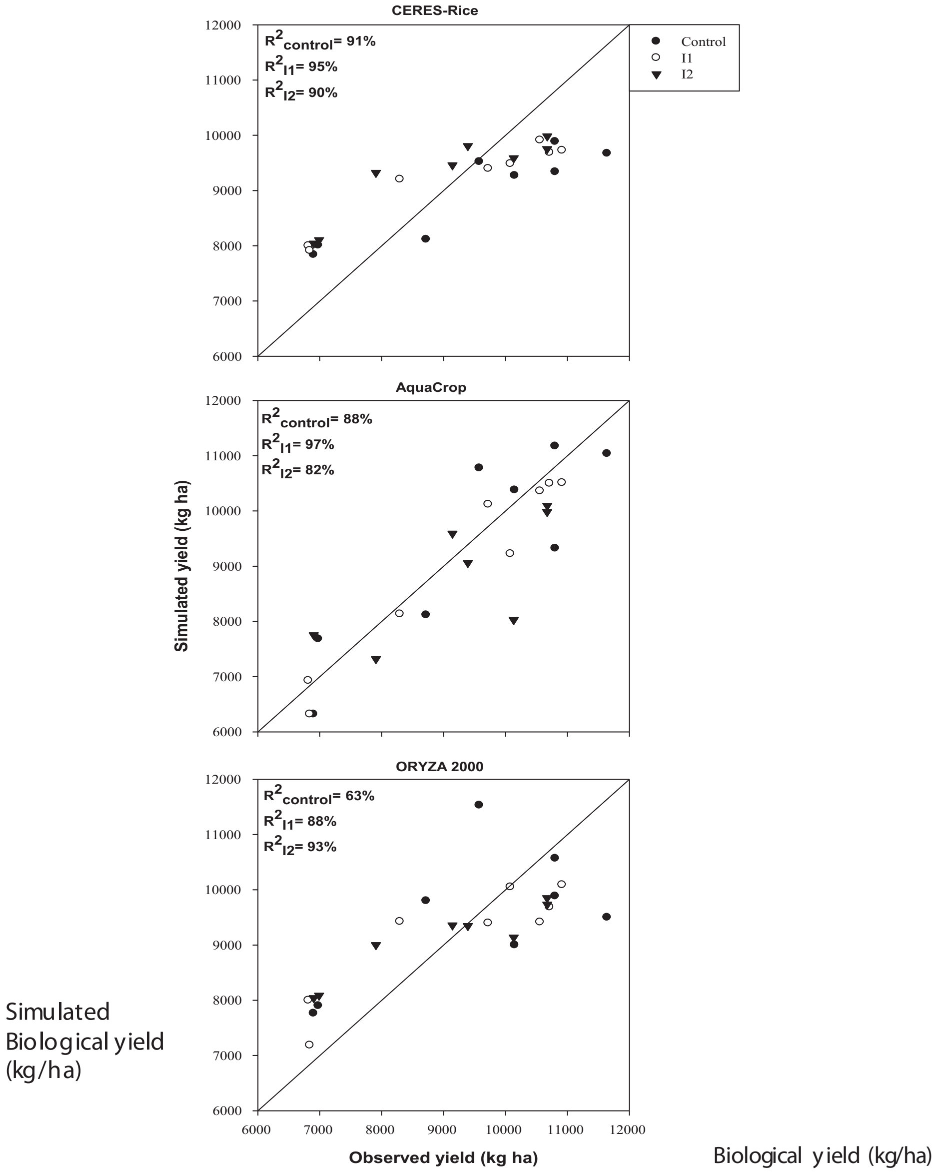

FIGURE 3 Comparison of observed and simulated biological yield in various models under different irrigation intervals [control treatment, five days interval (I_1) and eight days interval (I_2)].

AquaCrop

The recently developed AquaCrop model is a user-friendly and practitioner-oriented type of model, as it maintains an optimal balance between accuracy, robustness, and simplicity, and requires a relatively small number of parameters (Heng et al., 2009). Five days irrigation intervals

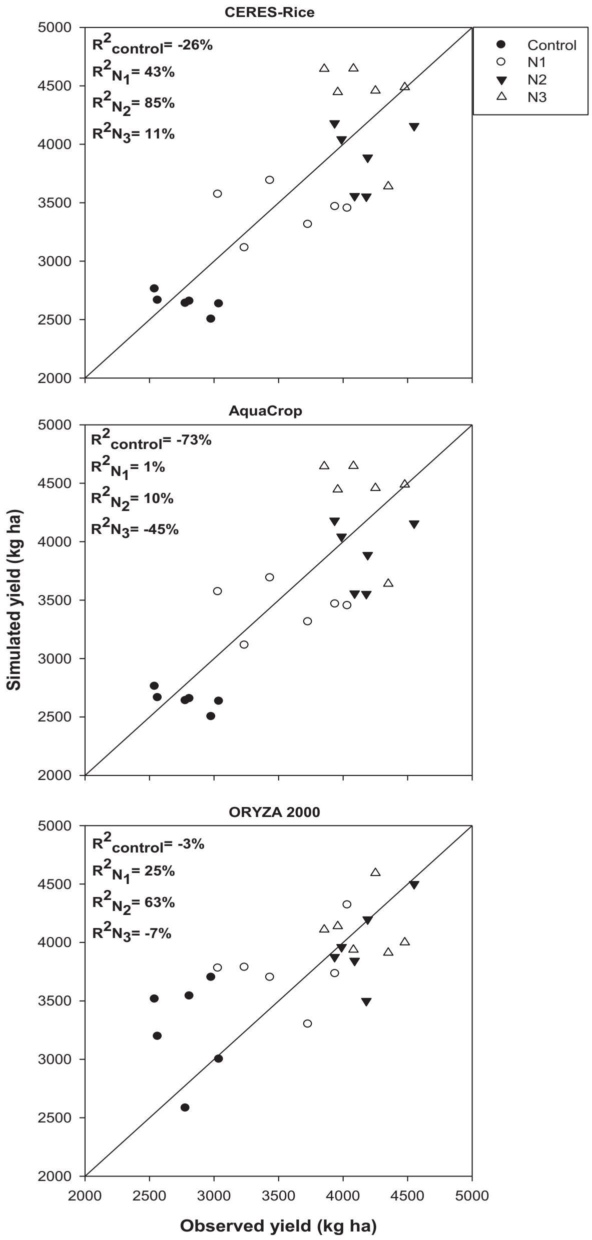

FIGURE 4 Comparison of observed and simulated grain yield in various models under various levels of nitrogen [0 kg as control treatment, 45 kg (N_1), 60 kg (N_2) and 75 kg (N_3)].

illustrated utmost accuracy in grain ($R^2 = 87\%$) and biological ($R^2 = 97\%$) yield simulation in this experiment by AquaCrop model (Figure 2 and 3). In addition, for other irrigation levels the model resulted in significant correlation between simulated and observed values especially for biological

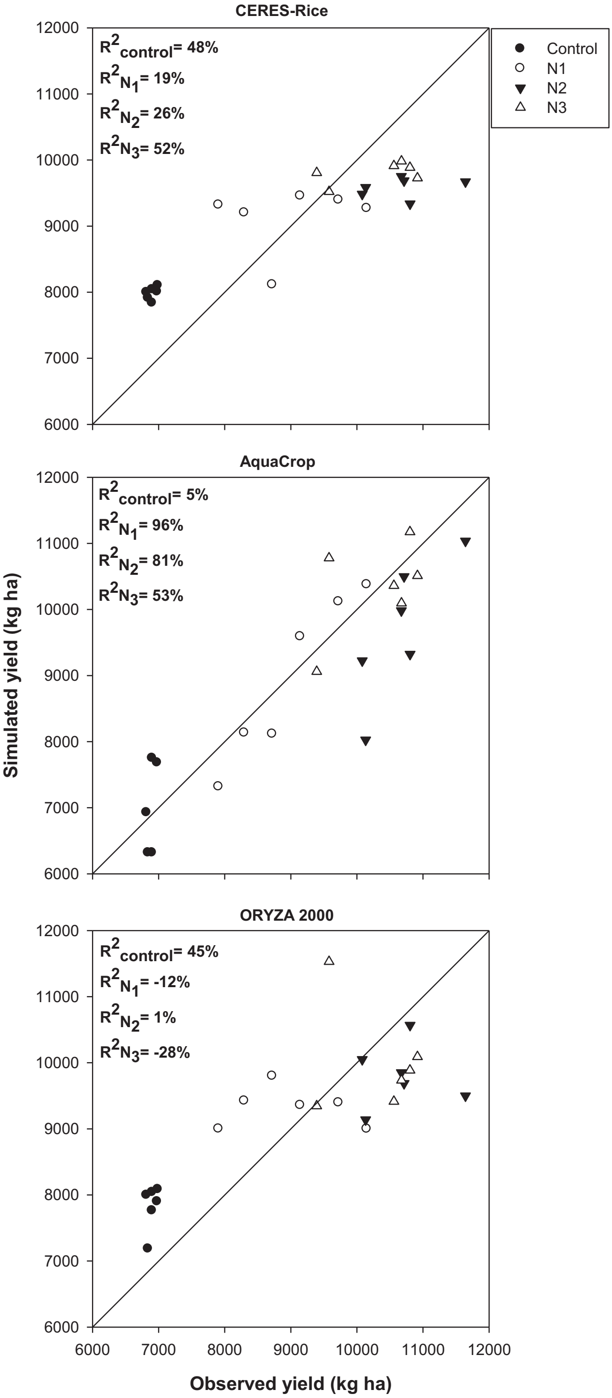

FIGURE 5 Comparison of observed and simulated biological yield in various models under various levels of nitrogen [0 kg as control treatment, 45 kg (N_1), 60 kg (N_2) and 75 kg (N_3)].

TABLE 5 Comparison of simulated and observed grain and biological yield by relative root mean-squared error (rRMSE), root mean deviation (RMD), model efficiency (EF) and R^2 values

	CERES-Rice		AquaCrop		ORYZA 2000	
Parameters	Grain yield	Crop biomass	Grain yield	Crop biomass	Grain yield	Crop biomass
rRMSE (%)	16	19	21	15	23	21
RMD (%)	8	−3	−10	−7	10	0.6
EF	0.7	0.6	0.52	0.75	0.46	0.52
R^2 (%)	85	88	79	89	0.70	0.77

yield, which showed more than 80% correlation in all irrigation intervals (Figure 2 and 3). Generally, AquaCrop model simulated biological yield by more accuracy than grain yield in this study under different irrigation intervals (Figures 2 and 3).

AquaCrop showed lower precision in grain yield simulation under unequal levels of nitrogen in comparison with simulation results under various irrigation levels. However the model showed quite promising in simulation of biological yield under different levels of nitrogen (Figures 4 and 5). Highest correlation between simulated and observed grain ($R^2 = 10\%$) and biological ($R^2 = 96\%$) yield obtained at N_1 and N_2 respectively (Figures 4 and 5). In general, AquaCrop model indicated high accuracy in biological (rRMSE = 15 and RMD = −7) yield but grain yield was not simulated perfectly (more than 20% in rRMSE) (rRMSE = 21 and RMD = −10), however, there was significant correlation between observed and simulated values of grain (79%) and biological (89%) yield (Table 5).

ORYZA2000

The ORYZA2000 model simulates crop growth and development of lowland rice at potential, N-limited and water-limited production levels (Boling et al., 2007). Grain yield simulation showed highest ($R^2 = 86\%$) and lowest ($R^2 = 28\%$) correlation between simulated and observed yield at full irrigation (control) and eight days irrigation intervals (I_2) respectively (Figures 2 and 3). Highest accuracy for rice biological yield simulation obtained at eight days irrigation interval (Figure 3).

This model outputs illustrated significant correlation ($R^2 = 63\%$) between simulated and observed grain yield only at N_2 treatment across different nitrogen applications (Figure 4). There were no significant correlations between simulated and observed biological yield across other levels of nitrogen (Figure 5). This model results showed significant correlation between observed and simulated values of grain (70%) and biological (77%) yield (Table 5). However, ORYZA2000 model indicated lowest accuracy in simulation of rice grain (rRMSE = 23 and EF = 0.46) and biological (rRMSE = 21 and EF = 0.52) yield compared to other study models (Table 5).

DISCUSSION

There are many studies on calibration and validation of CERES-Rice, AquaCrop and ORYZA2000 under different management factors on rice growth and development around the world, but there has been very little study on evaluation of these models performance under combinations of irrigation intervals and nitrogen levels. Study models showed different performances under different treatments for simulation of grain and biological yield of rice. CERES-Rice model represented highest accuracy in grain yield approximation under different irrigation intervals and nitrogen applications (Table 5). On the other hand, AquaCrop model indicated utmost precision in biological yield estimation under different treatments that employed in this experiment (Table 5). It seems, CERES-Rice model calibration process especially, genetically coefficient determination of study cultivar (Table 2) might be the main reason of accurate estimation of grain yield in this study (Timsina and Humphreys, 2006). AquaCrop model built on evapotranspiration of study crop estimates the yield from the daily transpiration, considering key physiological characteristics of the crop. Furthermore, AquaCrop model used constant harvest index for estimation of grain yield in rice, but CERES-Rice simulates grain yield using yield dynamic components such as potential spikelet number coefficient and single grain weight for each rice cultivar. In addition, there is direct relation between evapotranspiration and vegetative growths (canopy cover) of crops in comparison with grain production (Araya et al., 2010). Owing to the fact that AquaCrop estimated biological yield with higher accuracy than other study models in this experiment. ORYZA2000 model showed lowest accuracy in simulation of biological and grain yield across study models (Table 5). This model built on five phenological stages include juvenile phase, photoperiod-sensitive phase, panicle development phase and reproductive phase and used by constant development rate for each phase (Arora, 2006), but calculation of some development rate constants and partitioning coefficients such as development rate in panicle development phase or development rate in reproductive phase were not completely accurate because determination of precise time of start and end of each phase are quite difficult. Finally, ORYZA2000 model use constant values as harvest index for rice.

CONCLUSIONS

CERES-Rice and ORYZA2000 models simulated grain yield of rice more accurately than AquaCrop model. CERES-Rice and ORYZA2000 models use soil dynamic sub-models such as CENTURY which can calculate soil carbon and nitrogen dynamics in different conditions but AquaCrop model has no soil nitrogen sub-model. In conclusion, study models simulated grain and biological yield of rice more accurately under different irrigation intervals in comparison with various nitrogen levels.

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