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Application of the CSM-CERES-Rice model for evaluation of plant density and nitrogen management of fine transplanted rice for an irrigated semiarid environment

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Abstract The objectives of this study were to evaluate the performance of the cropping system model (CSM)-CERES-Rice to simulate growth and development of an aromatic rice variety under irrigated conditions in a semiarid environment of Pakistan and to determine the impact of various plant densities and nitrogen (N) application rates on grain yield and economic return. The crop simulation model was evaluated with experimental data collected in experiments that were conducted in 2000 and 2001 in Faisalabad, Punjab, Pakistan. The experimental design was a randomized complete block design with three replications and included three plant densities (one seedling hill^{-1}, PD_1; two seedlings hill^{-1}, PD_2; and three seedlings hill^{-1}, PD_3) and five N fertilizer regimes (control, N_0; 50 kg ha^{-1}, N_{50}; 100 kg ha^{-1}, N_{100}; 150 kg ha^{-1}, N_{150}; and 200 kg ha^{-1}, N_{200}). To determine the most appropriate combination of plant density and N levels, four plant densities from one seedling hill^{-1} to four seedlings hill^{-1} and 13 N levels ranging from 0 to 300 kg N ha^{-1} (52 scenarios) were simulated for 35 years of historical daily weather data under irrigated conditions. The evaluation of CSM-CERES-Rice showed that the

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model was able to simulate growth and yield of irrigated rice in the semiarid conditions, with an average error of 11% between simulated and observed grain yield. The results of the stimulation analysis result showed that two seedlings hill^{-1} along with 200 kg N ha^{-1} (PD_2N_{200}) produced the highest yield as compared to all other scenarios. Furthermore, the economic analysis through the mean gini dominance also showed the dominance of this treatment (PD_2N_{200}) compared to the other treatment combinations. Thus, the management scenario that consisted of two seedlings hill^{-1} and 200 kg N ha^{-1} was the best for high yield and monitory return of irrigated rice in the semiarid environment. The mean monetary returns ranged from 291 US \$ ha^{-1} to 1 460 US \$ ha^{-1} among the 52 production options that were simulated. This approaching was demonstrated as effective way to optimize the density and N management for high yield and monetary return. It will help the rice production.

Keywords Crop management · Crop modeling · Biomass · Decision support system for agrotechnology transfer · Grain yield

Abbreviations

CSM	Cropping system model
GDP	Gross domestic product
RMSE	Root mean square error
LAI	Leaf area index

Introduction

Lowland rice (*Oryza sativa* L.) is the most predominant cropping system in Asia (Singh et al. 1999b; Jing et al. 2009). Rice and wheat-based cropping system occupy 24 million ha of cultivated land in Asia (GOP 2007). Pakistan grows sufficient high quality rice (*Oryza sativa* L.) to meet domestic demand and for export. Rice is the second important food crop after wheat (*Triticum estivum* L.) in Pakistan. In 2008, rice contributed 5.9% in value added agriculture and 1.35% in gross domestic product (GDP) (GOP 2009). In spite of a structural shift towards industrialization, the agricultural sector is still the largest sector of the Pakistan's economy having a 22% share in GDP. It also remained the dominant sector with its ability to absorb 44% of the country's labor force (GOP 2009). In 2008, rice was cultivated on 2.963 M ha with an average yield of 2.35 t ha^{-1} and for a total production of 6.952 M ton (GOP 2009). However, the yield of rice in Pakistan is low compared to other countries, e.g., Iraq, 2.95; India, 3.37; Iran, 3.95; Bangladesh, 4.01; Chile, 6.13; Argentina, 6.25; China, 6.61; Japan, 6.78; Korea, 6.99; Turkey, 7.00; Peru, 7.36; USA, 7.68; Uruguay, 8.01; Egypt, 10.04; Oceania, 11.33; and Australia, 11.33 t ha^{-1} (IRRI 2009; USDA 2009; FAO 2009). The assurance of optimum plant densities and nitrogen (N) application rates are two key management practices for crop production systems (Singh 1994; Godwin and Singh 1998; Ritchie et al. 1998; Sarkar and Kar 2006). Excessive use of inorganic fertilizers, especially N, may cause ground water pollution due to leaching, which in turn could lead to eutrophication (Kropff et al. 1993; Ma et al. 2009; Maraseni et al. 2009). In Pakistan, low N fertilization is the main cause for the low yield levels, and normally there is no N leaching under the prevailing soil and weather conditions (Niaz et al. 2003; Tahir and Rasheed 2008). So, marginally higher rates of N fertilizer could be applied, as rice and wheat are relatively exhaustive feeders for macro elements, with annual nutrient (N, P, and K) removals exceeding 500 kg ha^{-1} for both rice and wheat in a 1 year rotation

(Singh and Singh 2001; Singh et al. 2004; 2009). Therefore, using higher N rates for increasing rice yield is still a promising management recommendation in order to increase profits for the low income farmers, to improve food security and to expand exports.

Crop simulation models and their associated decision support systems have been used successfully in many countries around the world for a wide range of applications (Tsuji et al. 1998; Hoogenboom et al. 2004). The crop simulation models can be very useful for evaluating soil–plant-atmosphere relationships for single crops and crop rotations through seasonal, sequential and spatial analysis. One of the main goals of a crop simulation model is to estimate crop production, resource use and environmental impact as a function of local weather and soil conditions and crop management (Hoogenboom 2000; Jones et al. 2003; Bannayan et al. 2003). The Decision Support System for Agrotechnology Transfer (DSSAT; Tsuji et al. 1998; Hoogenboom et al. 2004) is a widely used decision support system that includes the cropping system model (CSM)-CERES-Rice (Jintrawet 1995; Ritchie et al. 1998; St'astna et al. 2002; Sarkar and Kar 2006). The CSM-CERES-Rice model simulates rice crop growth and development from either planting or transplanting to harvest maturity and is based on the physiological processes that describe the response of rice to local soil and weather conditions. Potential growth is mainly dependent upon photosynthetically active radiation (PAR), light interception and the light conversion efficiency, while actual growth is a constraint of crop management, soil and weather interactions. The input data required to run the DSSAT models include daily weather data, i.e., maximum and minimum temperature, rainfall, and solar radiation; soil characterization data (physical, chemical, and morphological properties for each layer); genetic information through cultivar coefficients; and crop management information, such as transplanting date, age of nursery transplanting seedlings, row and plant spacing, rates, and dates and amount of fertilizer and irrigation application. Many scientists have evaluated the rice model successfully and predicted phenology, growth, development, and yield parameters for rice (Buresh et al. 1991; Singh et al. 1999a; Cheyglinted et al. 2001; Kumar and Sharma 2004; Sarkar and Kar 2006). These models have also been applied towards increasing resource use efficiency of cropping systems (Kropff et al. 2001; Timsina and Connor 2001; Timsina and Humphreys 2006).

Most of the recent studies have used crop simulation models with single or multiple factors, without considering the economic impact for producers (Buresh et al. 1991; Kropff et al. 1994; Cheyglinted et al. 2001; St'astna et al. 2002; Kumar and Sharma 2004; Soler et al. 2007a, b; Banterng et al. 2010). Limited scientific information is available regarding the application of the CSM-CERES-Rice for the interaction of two factors for a rice crop such as plant density and nitrogen rates for irrigated semiarid conditions. The overall goal of this study was to integrate the crop simulation models with the targeted field experiments for identifying optimum management practices for rice. The specific objectives included (1) the evaluation of the performance of the CSM-CERES-Rice model for plant density and N management for irrigated rice for a semiarid environment and (2) to determine the best management options to increase rice productivity for local conditions in Pakistan.

Materials and methods

Description of experimental site

Field trials were conducted in 2000 and 2001 at the experimental farm of the Department of Agronomy, University of Agriculture, Faisalabad (UAF), Punjab, Pakistan (36.25°N, 73.09°E, and 184.4 m altitude). The experimental site is located in the rice-based cropping zone in the semiarid area of Pakistan. The soil is a Lyallpur clay loam (aridisol-fine-silty, mixed, hyperthermic Ustalfic, Haplarged in UDSA classification and Haplic Yermosols in FAO classification). The soil samples that were taken at transplanting in 2000 had a pH of 7.8, an organic matter content of 0.73%, total N of 0.046%, available P of 6.15 ppm and available K of 193 ppm. In 2001, these values were 7.9, 0.76%, 0.048%, 6.19 ppm and 195 ppm, respectively. The climate of the area is semi-arid with an average annual maximum and minimum temperatures of 31.2 and 17.2°C, respectively, and annual rainfall that ranges from 400 to 800 mm. However, during the rice cropping season (May–October), the average seasonal maximum and minimum temperatures are 37.1 and 24.3°C, respectively. Overall, 75% of the total annual precipitation occurs during the rice season (GOP 2009). The monthly average solar radiation during the rice season ranges from 20 to 24.5 MJ m^{-2} d^{-1} versus an annual average of 14–16 MJ m^{-2} d^{-1}. The detailed weather data for 2000 and 2001 are presented in Fig. 1.

Experimental procedures

An aromatic variety (Basmati-385) was grown during both years of the experiment. The land for nursery and planting was done by partial wet method, i.e., soils were dry 50% of the time and soils are wet 50% of the time when cultivated under standing water. The experiment included the following treatment combinations: three plant densities, viz., one seedling $hill^{-1}$, (PD_1), two seedlings $hill^{-1}$ (PD_2) and three seedlings $hill^{-1}$ (PD_3) and five N fertilizer application rates, viz., N_0 = control (N_0), $N_1 = 50$ (N_{50}), $N_2 = 100$ (N_{100}), $N_3 = 150$ (N_{150}) and $N_4 = 200$ (N_{200}) kg N ha^{-1}. A randomized complete block design (RCBD) was employed with three replications. There were eight rows $plot^{-1}$ and 12 hills row^{-1}. The seed rate for nursery sowing was 20 g m^{-2}. Thirty-day-old seedlings were transplanted on 4 July in 2000 and 3 July in 2001 manually in a puddle field in standing water at 22.5 cm by 22.5 cm of hill and row spaces in both years. Each N treatment consisted of two applications of urea. The first half of the N fertilizer was applied during puddling before transplanting on 4 July in 2000 and 3 July in 2001. The second dose of fertilizer was applied 22 days after transplanting (DAT) on 26 July in 2000 and 25 July in 2001. In addition, phosphorus and potassium (P_2O_5 and K_2O; 65 kg ha^{-1} each) in the form of single super phosphate (SSP) and potassium sulphate were also applied during puddling prior to final cultivation. Zinc at a rate of 25 kg ha^{-1} was applied at puddling before final cultivation to avoid zinc deficiencies under standing water conditions. A total of 16 irrigations were applied at a rate of 100 mm each to all treatments at 7 day intervals. All other agronomic practices such as weeding and plant protection measures were standard and uniform for all the treatments. Additional details on crop management can be found in Ahmad et al. (2008, 2009).

Plant sampling and measurements

Phenology and development were recorded during both the vegetative and reproductive phases in both years. Anthesis was recorded when panicles were visible outside the leaf sheath on 50% of the plants in each plot. Physiological maturity was determined by regularly sampling grains from primary tillers. For growth analysis, a total of six harvests were conducted at 14-day intervals during each growing season. Four randomly selected hills were harvested from each plot and border effects were avoided. The plants were

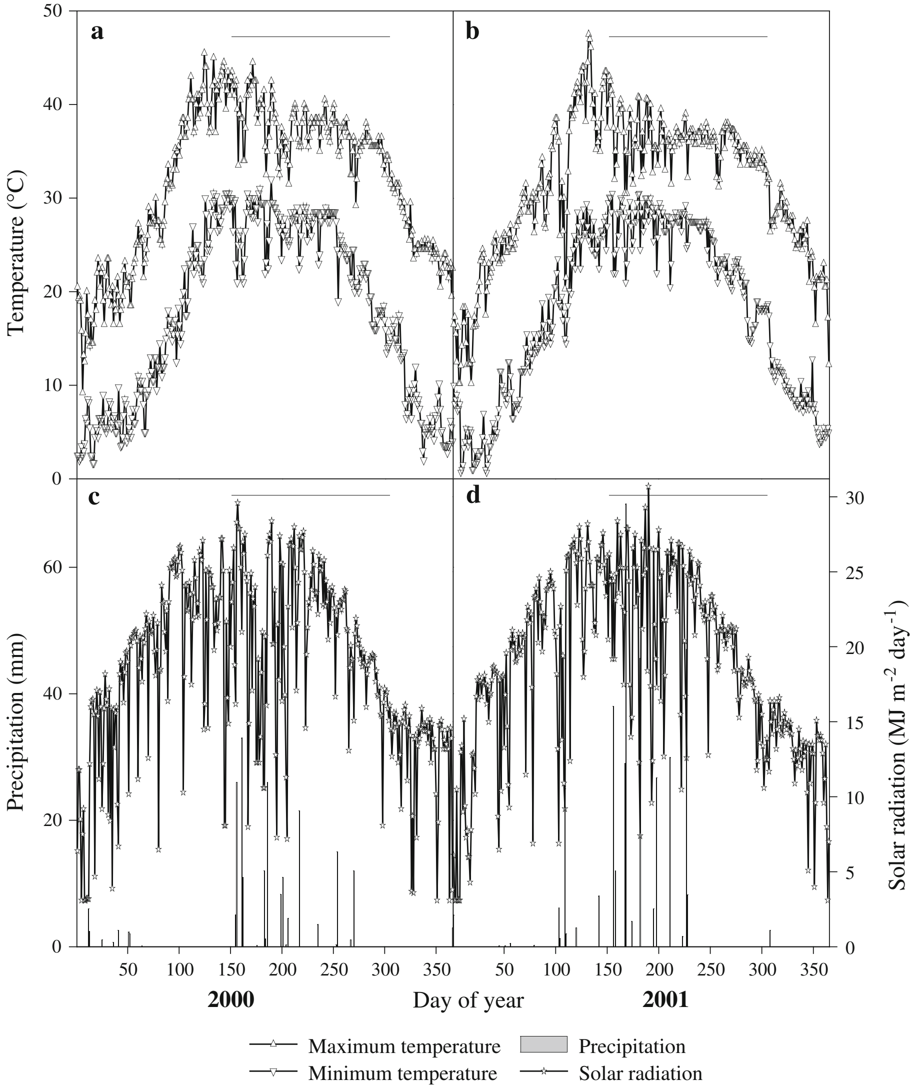

Fig. 1 Daily average maximum air temperature and minimum air temperature during 2000 (**a**) and 2001 (**b**), solar radiation and precipitation during 2000 (**c**) and 2001 (**d**) for Faisalabad, Pakistan (*horizontal bar* represents the rice growing season)

separated into leaves, stem and grains (when present). A sub-sample of 100–200 g of green leaves and branches were oven dried to a constant weight at 80°C for determining leaf dry weight. A sub-sample of 50–100 g of green leaves was taken and leaf area was measured with an electronic leaf area meter (Licor, model 3100). The leaf area index (LAI) was calculated as the ratio of total leaf area to occupied surface area. The final harvest was conducted manually for the two central rows for 1 m of each row for determining final biomass, grain yield and yield components.

Calibration and evaluation of the CSM-CERES-Rice model

The CERES-Rice model embedded in Decision Support System for Agro-technology Transfer-DSSAT v4.5 (Jones et al. 2003; Hoogenboom et al. 2010) was used in this study. It is a physiologically based and management oriented model that utilizes carbon, N, water and energy balance principles' to simulate the growth and development of rice plant. The model calculates the growth and development of rice plants on a daily time steps, and the final crop yield is computed on the date of harvest. Inputs required for model execution include management practices, i.e., plant genetics, plant density, row spacing, transplanting and harvest dates, fertilizer application amounts, dates and method), environmental factors (soil physical and chemical properties etc.) and weather conditions (daily minimum and maximum temperature, solar radiation, and precipitation). The CSM-CERES-Rice model was calibrated with the data obtained from the 2000 field experiment for the treatment that consisted of a plant density of two seedlings hill^{-1} and a N application of 200 kg N ha^{-1} as it had the best performance. The cultivar coefficients were determined sequentially, starting with phenological parameters followed by the grain filling parameters and finally total biomass and grain yield (GY) (Hunt and Boote 1998). To select the most suitable set of coefficients for each growth and development coefficient an iterative procedure was used (Hunt et al. 1993). A detailed description of the cultivar coefficients used by the CSM-CERES-Rice is presented in Table 1. After the calibration of the cultivar coefficients, the accuracy of the model was checked with observed data for the remaining 14 treatments. The experimental data collected in 2001 were used for independent model evaluation. As part of the calibration and evaluation process the simulated data for anthesis date, maturity date, grain yield and total biomass were compared with the observed values.

Table 1 Calibrated genetic coefficients of rice cultivar Basmati-385 used with CSM-CERES-Rice model

Cultivar trait	Genetic coefficients	Unit	Value
Vegetative growth			
1. Time from seed emergence to the end of juvenile phase	*P1*	Photothermal day	126.0
2. Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod	*P2O*	h	250.0
3. Extent to which phasic development from vegetative to panicle initiation is delayed for each hour increase in photoperiod above *P2O*, i.e., 12.5 h	*P2R*	Photothermal day	500.0
Reproductive growth			
4. Time starting from grain filling to physical maturity	*P5*	Photothermal day	10.9
5. Maximum spikelet number coefficient	*G1*	–	52.0
6. Maximum possible single grain size	*G2*	g	0.0235
7. Scalar vegetative growth coefficient for tillering relative to IR64	*G3*	–	1.03
8. Temperature tolerance scalar coefficient	*G4*	–	0.90

Statistics

Different statistical indexes were used for model calibration and evaluation, including the root mean square error (RMSE) (Wallach and Goffinet 1987) and the index of agreement (d-value) (Willmott 1982). The computed values of RMSE and d-value determine the degree of agreement between the predicted values with their respective observed values, and a low RMSE value and a d-value that approaches one are desirable. The RMSE was calculated according to Eq. 1.

$$\text{RMSE (root mean square error)} = \left[\sqrt{\frac{\sum_{i=1}^{n}(Pi - Oi)^2}{n}}\right] \tag{1}$$

where P_i and O_i refer to the predicted and observed values for the studied variables, respectively, e.g., leaf area index, grain yield and total biomass and n is the population number of the observed variables. Normalized RMSE ($\mathrm{RMSE_n}$) gives a measure (%) of the relative difference of simulated verses observed data. The simulation is considered excellent with a normalized RMSE less than 10%, good if the normalized RMSE is greater than ten and less than 20%, fair if the normalized RMSE is greater than 20% and less than 30%, and poor if the normalized RMSE is greater than 30% (Loague and Green 1991). The $\mathrm{RMSE_n}$ was calculated following Eq. 2.

$$\text{Normalized root mean square error} = \left[\frac{\text{RMSE} \times 100}{\bar{\text{O}}}\right] \tag{2}$$

The index of agreement (d) proposed by Willmott et al. (1982) was estimated by Eq. 3.

$$\text{Index of agreement } (d) = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P'_i| + |O'_i|)^2}\right], \quad 0 \le d \le 1 \tag{3}$$

where n is the number of observations, P_i the predicted observation, O_i is a measured observation, $P'_i = P_i - M$ and $O'_i = O_i - M$ (M is the mean of the observed variable). The percentage deviations (PD) were also calculated.

Stimulation scenario analysis

The CSM-CERES-Rice model was used for long term simulations of the aromatic rice cultivar Basmati-385. The seasonal analysis program of DSSAT v4.5 was used to evaluate and compare different combinations of crop management practices (Thornton and Hoogenboom 1994; Thornton et al. 1998). The simulations were conducted for 35 years using observed daily weather data starting in 1974 and ending in 2008. The overall goal was to determine the best management option for an irrigated rice grown under semiarid conditions in Faisalabad, Pakistan. The scenarios that were evaluated included combinations of four plant densities and 13 N levels for a total of 52 treatments. The simulation results were analyzed using the strategy analysis program of DSSAT (Thornton et al. 1995, 1998) to compare percentile distributions for grain yield.

Economic analysis

The results of each strategy, i.e., each combination of plant density (one seedling hill^{-1}, two seedlings hill^{-1}, and three seedlings hill^{-1}) and N rates (control, 50 kg ha^{-1}, 100 kg ha^{-1}, 150 kg ha^{-1}, and 200 kg ha^{-1}), were also evaluated using the Mean-Gini Dominance Analysis (Buccola and Subaei 1984; Fawcett and Thornton 1989) an evaluation procedure of the seasonal analysis program that calculates monetary return for each treatment combination and identifies the most dominant treatment based on the highest economic return (Gini coefficient). The gross margin (US \$ t^{-1}) for each combination of treatment was determined with the following equation.

$$GM = Y \times P - N \times C - V \tag{4}$$

where Y is the simulated rice grain yield (kg ha^{-1}), P is the price of rice (297 US \$ t^{-1}) (average of last 3 years, 2007–2009; Fig. 2), N is the N application rate (kg ha^{-1}) per treatment, C is the cost of N (0.38 US \$ kg^{-1}) and V is the base production cost (275 US \$ ha^{-1}) for all treatments during 2009. The base production cost for a rice crop was taken from the Department of Agriculture Extension, Punjab, Pakistan (unpublished data). The rice and N fertilizer prices were taken from the Economic Survey of Pakistan, Finance Division, (available online) (GOP 2009).

Results and discussion

Model calibration

The CSM-CERES-Rice model was calibrated with experimental data collected during the 2000 rice crop season. The cultivar coefficients of Basmati-385 were estimated through trial and error and comparison of model-simulated and experimental data using CSM-CERES-Rice model. The final values for the eight cultivar coefficients that determine vegetative (P1, P2O, and P2R) and reproductive (P5, G1, G2, G3, and G4) growth and development are presented in Table 1.

A close agreement was obtained between observed and simulated values for rice phenology. The model predicted the dates from transplanting to anthesis and transplanting to maturity with a difference of 1 day between observed and simulated dates for cultivar Basmati-385 (Table 2). The simulated and observed values were in good agreement for

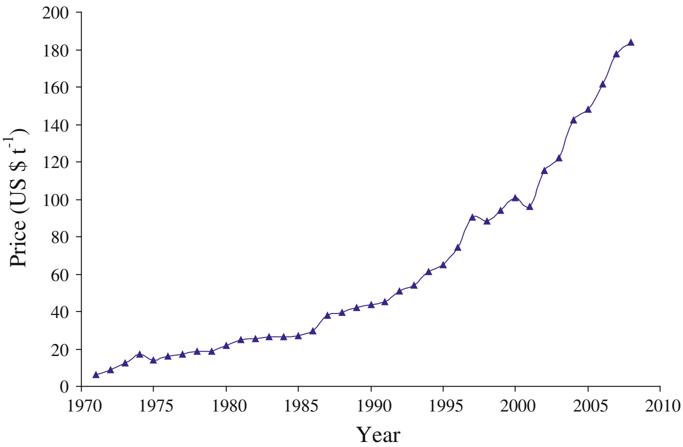

Fig. 2 Rice price in Pakistan from 1974 to 2009 (*Source* FAO 2011)

Table 2 Simulated (S) and observed (O) phenology, root mean square error and *d*-value for growth characteristics from model calibration (2000) and model evaluation (2001) for rice cultivar Basmati-385 with three plant densities and five N rates ($n = 15$)

Transplanting date	Crop characteristics		
05 July 2000	Phenology	S (DAT)	O (DAT)
	Anthesis date	71	72
	Maturity date	102	103
	Growth	RMSE	*d*-value
	LAI (m^2 m^{-2})	1.40	0.92
	Top weight (kg ha^{-1})	369	0.97
04 July 2001	Phenology	S (DAT)	O (DAT)
	Anthesis date	72	72
	Maturity date	103	103
	Growth	RMSE	*d*-value
	LAI (m^2 m^{-2})	1.83	0.94
	Top weight (kg ha^{-1})	382	0.98

DAT days after transplanting; *LAI* leaf area index

LAI and total above-ground biomass at different phenological stages for the different combinations of plant density and N rates (Fig. 3). The lower values for RMSE and higher *d*-values close to one reflected that the model predicted LAI and above-ground biomass quite well. At final harvest, the simulated values were also in good agreement with the observed values, and the differences ranged from 1.12 to 12% for total above-ground biomass. However, the RMSE for grain yield at final harvest ranged from 175[1] to 191 kg ha^{-1}, while normalized RMSE varied from 1.5 to 2.3% and *d*-values varied from 0.88 to 0.97 (Table 3). The regression line between simulated and observed grain yield had a high value for r^2 (0.97) for the 15 treatment combinations of plant density and N rates (Fig. 5), showing the ability of model to simulate rice growth and development under irrigated conditions for a semiarid environment.

Model evaluation

The CSM-CERES-Rice model was evaluated with the experimental data collected during the 2001 season. A perfect match was obtained between the observed and simulated values for rice phenology. The model predicted the dates from transplanting to anthesis and transplanting to maturity with 0 (zero) difference between the observed and simulated dates for cultivar Basmati-385 (Table 2). The simulated and observed values for LAI and total above-ground biomass at different phenological stages for the different combinations of plant density and N rates were in good agreement (Fig. 4). The value for the *d*-value for LAI ranged from 0.96 to 0.99 (Table 3), while the RMSE ranged from 1.77 to 1.92 m^2 m^{-2} (Table 2). The *d*-value for above-ground biomass ranged from 0.95 to 0.99, while the RMSE ranged from 371 to 392 kg ha^{-1} (Table 2). The lower values for RMSE and higher *d*-values close to one revealed that the model predicted LAI and above-ground biomass quite well. At final harvest, the simulated values were also in good agreement with the observed values, and the difference ranges from 2.05 to 15% for total above-ground biomass. However, the RMSE for grain yield at final harvest ranged from 206 to 263 kg ha^{-1}, while normalized RMSE varied from 2.1 to 3.4% and *d*-values varied from

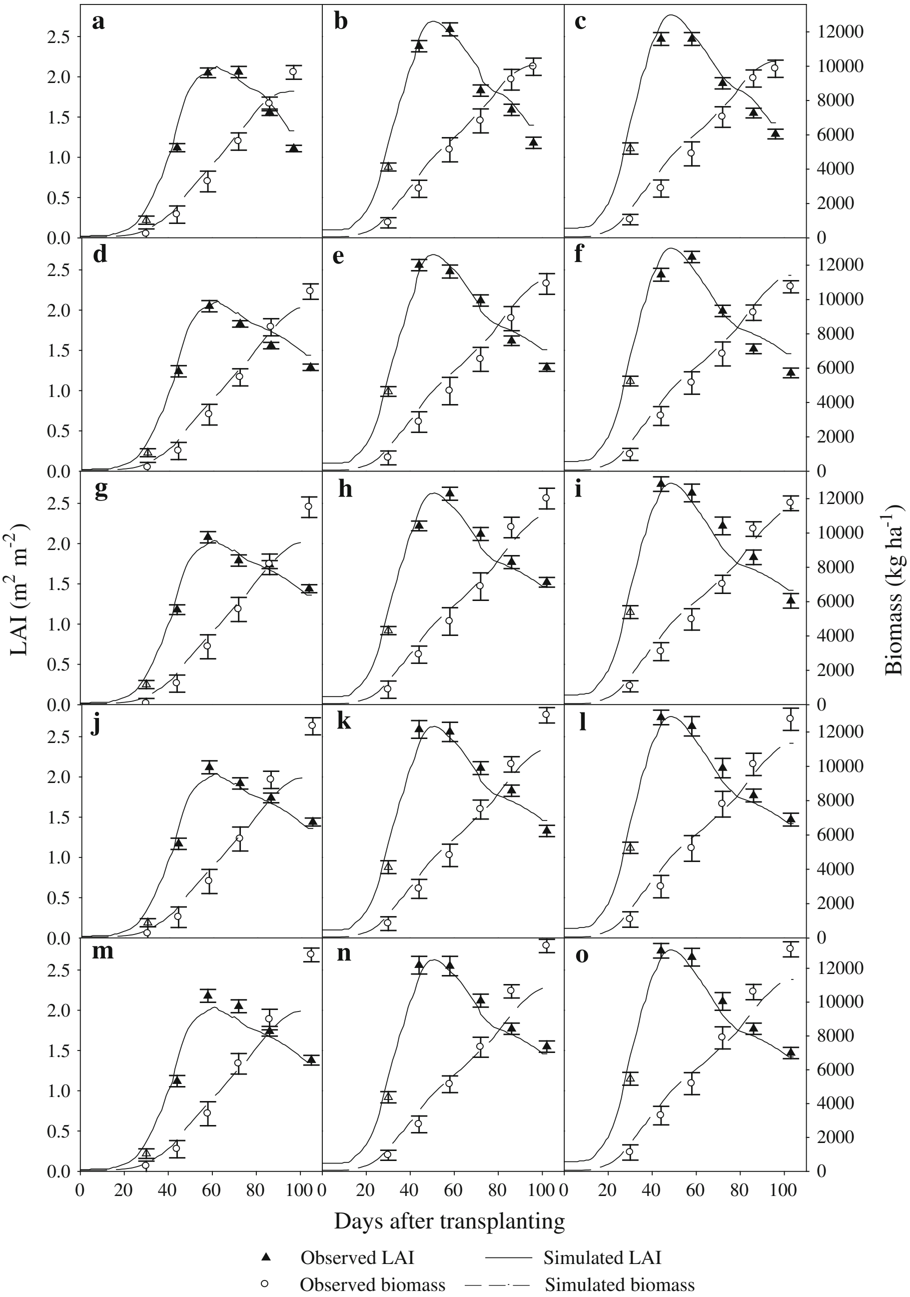

Fig. 3 Simulated (*continuous line*) and observed (*triangular symbols*) leaf area index and simulated (*dotted lines*) and observed (*round symbols*) biomass of rice Basmati-385 at variable plant density and N application rates, i.e., $PD_1 + N_0$ (**a**), $PD_2 + N_0$ (**b**), $PD_3 + N_0$ (**c**), $PD_1 + N_{50}$ (**d**), $PD_2 + N_{50}$ (**e**), $PD_3 + N_{50}$ (**f**), $PD_1 + N_{100}$ (**g**), $PD_2 + N_{100}$ (**h**), $PD_3 + N_{100}$ (**i**), $PD_1 + N_{150}$ (**j**), $PD_2 + N_{150}$ (**k**), $PD_3 + N_{150}$ (**l**), $PD_1 + N_{200}$ (**m**), $PD_2 + N_{200}$ (**n**), and $PD_3 + N_{200}$ (**o**) under irrigated semiarid conditions at Faisalabad, Pakistan during 2000 used for model calibration

Table 3 Model calibration (2000) and evaluation (2001) for simulated (S) and observed (O) grain yield of Basmati-385 at Faisalabad, Pakistan as affected by plant density and N application rates

N rates	Grain yield (kg ha^{-1})		PD	GY	RMSEn	RMSE	MSE[e]	MSEs[f]	MSEu[g]	LAI	Biomass
(kg ha^{-1})	Sim.	Obs.	(%)[a]	(*d*-stat[b])	(%)[c]	(kg ha^{-1})[d]				(*d*-stat[h])	(*d*-stat[i])
2000											
One seedling hill^{-1}											
0 kg (N_0)	2 704	2 760	−2.1							0.96	0.97
50 kg (N_{50})	3 382	3 090	8.6							0.97	0.98
100 kg (N_{100})	3 562	3 440	3.4							0.96	0.98
150 kg (N_{150})	4 273	4 090	4.3							0.95	0.96
200 kg (N_{200})	4 442	4 230	4.8							0.99	0.97
Statistics				0.92	1.8	191	36 343	24 906	11 437		
Two seedlings hill^{-1}											
0 kg (N_0)	3 075	3 110	−1.2							0.97	0.96
50 kg (N_{50})	3 642	3 400	6.6							0.95	0.97
100 kg (N_{100})	4 274	4 010	6.2							0.95	0.98
150 kg (N_{150})	4 472	4 380	2.1							0.96	0.98
200 kg (N_{200})	4 842	4 720	2.5							0.97	0.99
Statistics				0.88	2.3	175	30 567	20 948	9 619		
Three seedlings hill^{-1}											
0 kg (N_0)	2 983	3 130	−4.9							0.95	0.96
50 kg (N_{50})	3 476	3 360	3.3							0.98	0.96
100 kg (N_{100})	3 905	3 750	4.0							0.97	0.98
150 kg (N_{150})	4 395	4 230	3.8							0.94	0.96
200 kg (N_{200})	4 729	4 460	5.7							0.99	0.98
Statistics				0.97	1.5	178	31 735	21 748	9 987		
2001											
One seedling hill^{-1}											
0 kg (N_0)	2 983	2 870	−3.8							0.99	0.96
50 kg (N_{50})	3 574	3 260	8.7							0.96	0.99

Table 3 continued

N rates	Grain yield (kg ha^{-1})		PD	GY	RMSEn	RMSE	MSE[e]	MSEs[f]	MSEu[g]	LAI	Biomass
(kg ha^{-1})	Sim.	Obs.	(%)[a]	(*d*-stat[b])	(%)[c]	(kg ha^{-1})[d]				(*d*-stat[h])	(*d*-stat[i])
100 kg (N_{100})	3 769	3 620	4.0							0.98	0.96
150 kg (N_{150})	4 511	4 310	4.5							0.98	0.96
200 kg (N_{200})	4 730	4 460	5.7							0.99	0.98
Statistics				0.95	2.5	223	49 590	33 984	15 606		
Two seedlings hill^{-1}											
0 kg (N_0)	3 387	3 270	−3.5							0.98	0.95
50 kg (N_{50})	3 865	3 530	8.7							0.97	0.98
100 kg (N_{100})	4 390	4 230	3.7							0.98	0.96
150 kg (N_{150})	4 817	4 610	4.3							0.98	0.97
200 kg (N_{200})	5 294	4 970	6.1							0.97	0.99
Statistics				0.89	2.1	206	42 241	28 948	13 293		
Three seedlings hill^{-1}											
0 kg (N_0)	3 050	3 290	−7.7							0.98	0.97
50 kg (N_{50})	3 672	3 540	3.6							0.96	0.97
100 kg (N_{100})	4 039	3 600	10.9							0.96	0.98
150 kg (N_{150})	4 682	4 460	4.7							0.96	0.99
200 kg (N_{200})	4 870	4 700	3.6							0.99	0.98
Statistics				0.96	3.4	263	69 126	47 372	21 574		

[a] Percentage prediction deviation

[b,h,i] Index of agreement

[c] Normalized root mean square error

[d] Root mean square error

[e] Mean square error

[f] Systematic MSE

[g] Unsystematic MSE

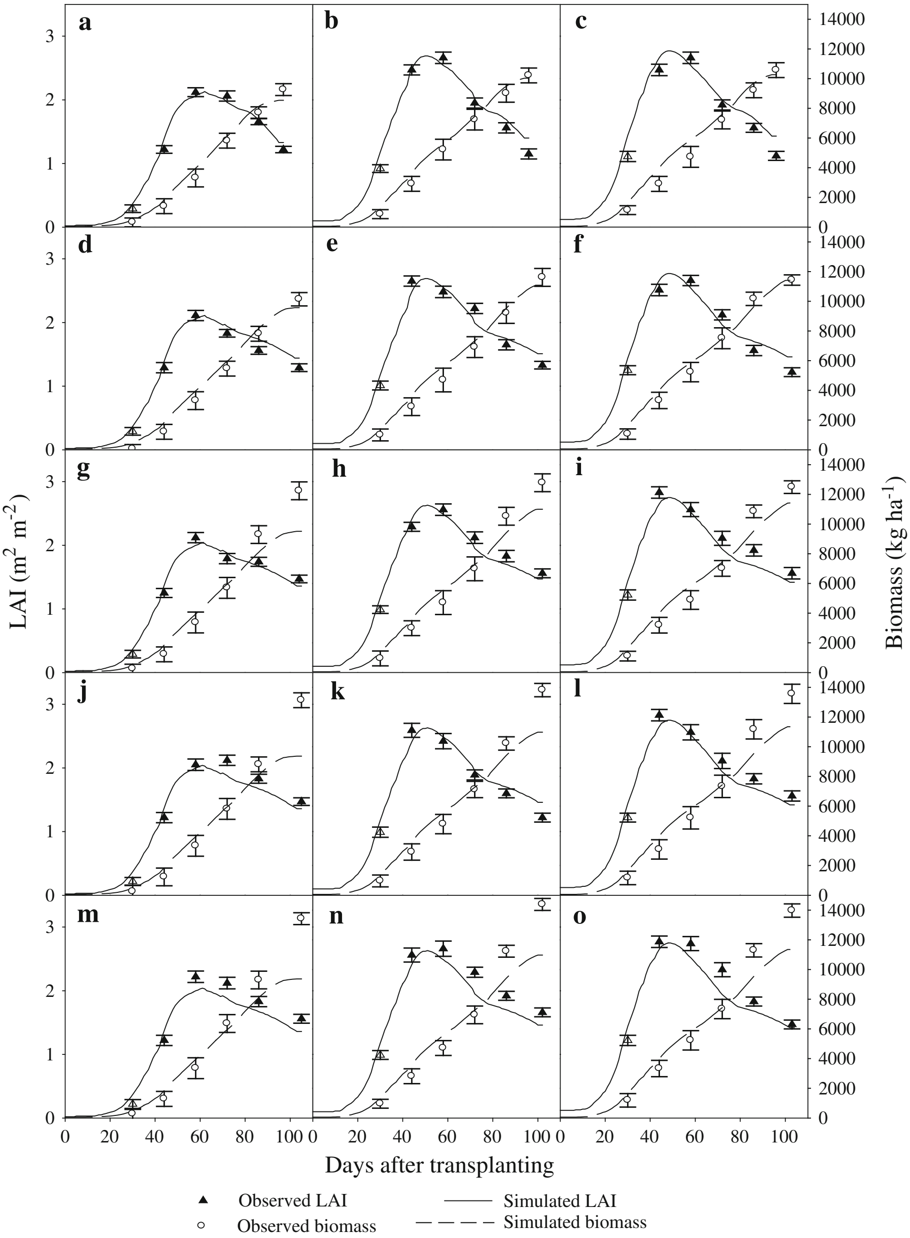

Fig. 4 Simulated (*continuous line*) and observed (*triangular symbols*) leaf area index and simulated (*dotted lines*) and observed (*round symbols*) biomass of rice Basmati-385 at variable plant density and N application rates, i.e., $PD_1 + N_0$ (**a**), $PD_2 + N_0$ (**b**), $PD_3 + N_0$ (**c**), $PD_1 + N_{50}$ (**d**), $PD_2 + N_{50}$ (**e**), $PD_3 + N_{50}$ (**f**), $PD_1 + N_{100}$ (**g**), $PD_2 + N_{100}$ (**h**), $PD_3 + N_{100}$ (**i**), $PD_1 + N_{150}$ (**j**), $PD_2 + N_{150}$ (**k**), $PD_3 + N_{150}$ (**l**), $PD_1 + N_{200}$ (**m**), $PD_2 + N_{200}$ (**n**), and $PD_3 + N_{200}$ (**o**) under irrigated semiarid conditions at Faisalabad, Pakistan during 2001 used for model evaluation. RMSE and *d*-value are derived for simulated and observed values. The RMSE (root mean square error) and index of agreement (*d*-value) are derived from simulated and observed values both (it is also mentioned in the material and method section, where Eqs. 1 and 3 are given)

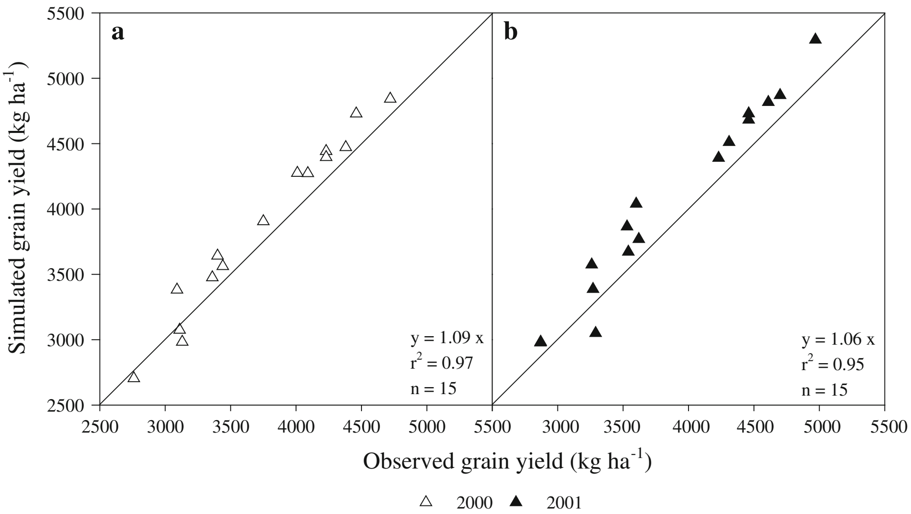

Fig. 5 Observed and simulated rice grain yields of rice cultivar-385 at Faisalabad, Pakistan during 2000 (**a**) used for model calibration and 2001 (**b**) used for model evaluation

0.89 to 0.96 (Table 3). The regression line between simulated and observed grain yield had a high value for r^2 (0.95) for the 15 treatment combinations of plant density and N rates (Fig. 5). In general, the results for model evaluation with the observed data sets indicated that the CSM-CERES-Rice model was able to simulate yield accurately for transplanted rice for treatment combinations of plant density and N rates under irrigated conditions for a semiarid environment in Faisalabad, Pakistan.

Model application

An analysis for identifying the optimum combination of plant density and N level for rice production using crop simulations was conducted. The CSM-CERES-Rice model was used to simulate grain yield for rice for 52 different scenarios (treatment combinations; four plant densities $\times$ 13 N levels) ranging from one seedling hill^{-1} to four seedlings hill^{-1} and N rates ranging from zero (0) to 300 kg ha^{-1} under irrigated conditions for a semiarid environment for 35 years using historical daily weather data from 1974 to 2008. Simulated rice yield ranged from 374 to 9 340 kg ha^{-1}, with an average yield of 5 358 kg ha^{-1} for the 52 scenarios that were simulated (Fig. 6). The simulation scenarios showed that a plant density of two seedlings hill^{-1} along with 200 kg N ha^{-1} predicted the highest average grain yield for all combinations of plant density and N rates (Fig. 6). The range of the simulated rice grain yield around the median for two seedlings hill^{-1} and 200 kg N ha^{-1} (PD_2N_{200}) was smaller than for all other scenarios. The simulated rice grain yield for all 52 scenarios is depicted in Fig. 6, showing the minimum, 25% percentile, median, 75% percentile and maximum values. As nitrogen is the integral part of the plant constituent (chlorophyll), that is why the yield increases with the addition of N fertilizer application rate. The presence of outliers is quite common in the lab, field and computer based simulation experiments. So, whenever there is data collection, there are outliers. Because, in this study we simulate for 35 years that's why there are some outliers in Figs. 6 and 7.

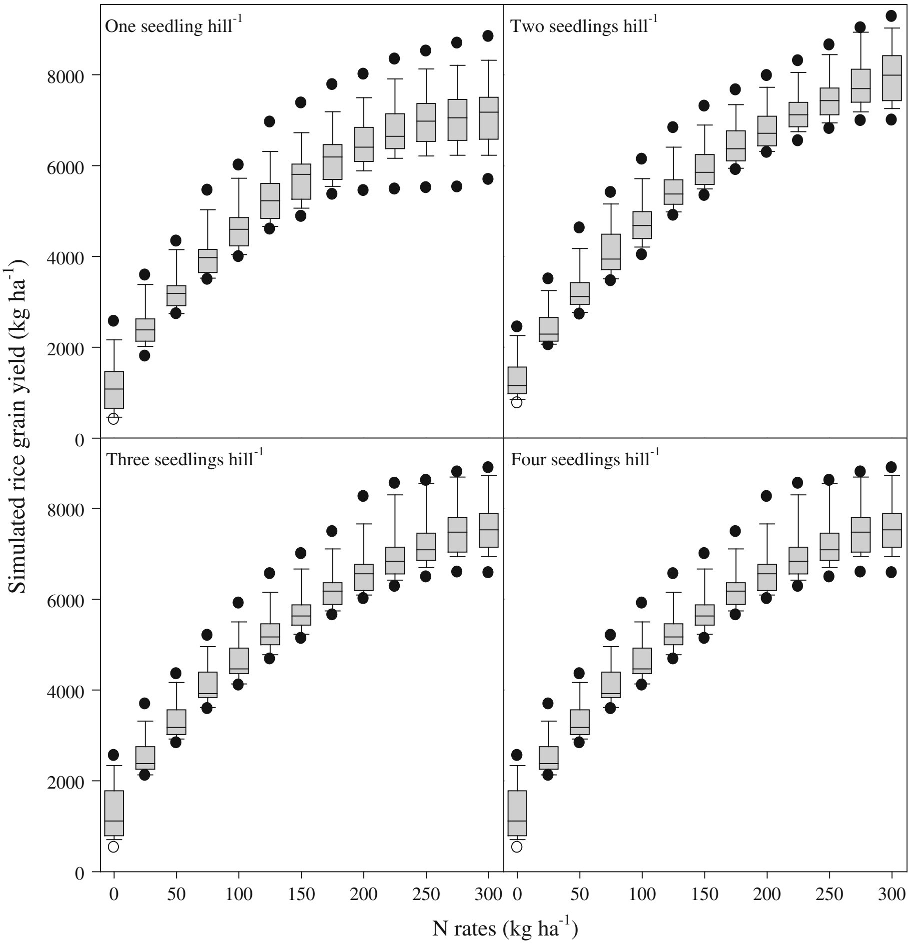

Fig. 6 Simulated grain yield for rice Basmati-385 at variable plant density and N application rates. *Box limits* represent the 25th and 75th percentiles, *box central line* represents the median, and *outliers* represent the minimum and maximum values. The simulated results were obtained from the combination of historical weather data for 35 years, four plant densities, and 13 N application levels under irrigated semiarid environment of Faisalabad, Pakistan

The monetary returns ha^{-1} for all 52 scenarios is presented in Fig. 7. For the strategy analysis all 52 scenarios were used. The mean monetary return varied from −291 to 1460 US $ ha^{-1} among the 52 scenarios that were simulated. The results from the strategic analysis of monetary returns ha^{-1} (Fig. 7) showed that the treatment combination of two seedlings hill^{-1} and 200 kg N ha^{-1} ($PD_2 \times N_{200}$) was dominant among the 52 scenarios that were simulated. These results are in line with another study that applied the CERES-Rice model (Sarkar and Kar 2006). This study which was conducted for transplanted and direct seeded rice in Bengal, India demonstrated that the treatment in which 120 kg N ha^{-1} was applied had dominance compared to the other treatments. However, their study was conducted under sub-humid environmental conditions, using other rice cultivars and management strategies than in our study and the maximum N application rate

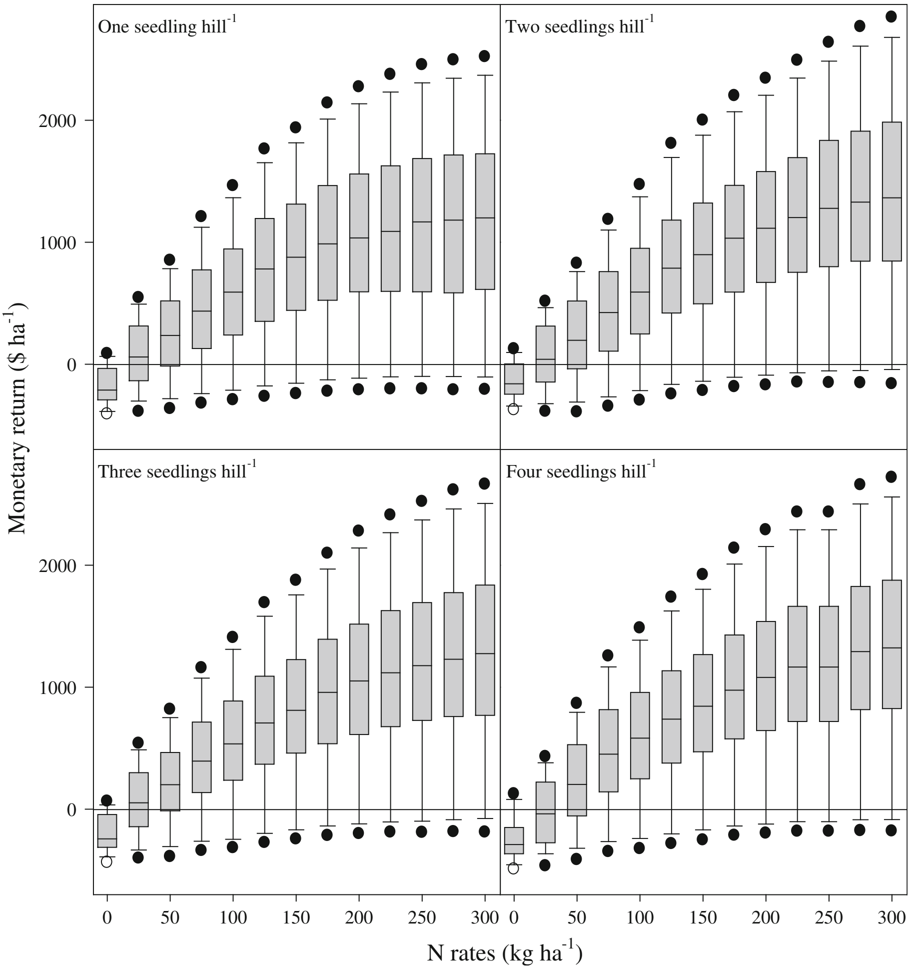

Fig. 7 Monetary return (US \$ ha^{-1}) percentiles for rice Basmati-385 at variable plant density and N application rates. *Box limits* represent the 25th and 75th percentiles, *box central line* represents the median, and *outliers* represent the minimum and maximum values

was 120 kg N ha^{-1}. The application of systems analysis that combines both experimental field research and crop modeling to determine optimum farming practices in different countries has become common. For instance, Soler et al. (2007a, b) applied the crop simulation model CSM-CERES-Maize for optimum planting dates for maize in Brazil while Banterng et al. (2010) used the CSM-CROPGRO-Soybean model to determine optimum management practices for soybean in Thailand.

Conclusions

The results for model calibration showed the model between simulated and observed values for phenology and growth of rice. This study also showed the CSM-CERES-Rice model to serve as a tool for determining the best combination of plant density and N levels for growing rice under irrigated conditions in a semiarid environment in Pakistan. This study illustrates the potential for using crop simulation models as an information technology tool for determining suitable management strategies for rice production in the Faisalabad district in the Punjab Province of Pakistan. Therefore, we can conclude that the CSM-CERES-Rice model could potentially assist resource-poor farmers in Pakistan by providing them with alternate management options. However, we suggest that in order to be able to identify the optimum management practices for a specific region and for a specific crop, a few years of actual field experiments should be conducted for model evaluation and that long-term historical weather records be used for management scenario analysis.

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