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Identifying irrigation and nitrogen best management practices for aerobic rice–maize cropping system for semi-arid tropics using CERES-rice and maize models

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ABSTRACT

Research based development of best management options for aerobic rice–maize cropping systems must be developed to improve water and nitrogen use efficiency. The main objective of this study was to identify water saving rice production technology for rice grown in sandy loam soils in semi-arid conditions using the calibrated CERES-Rice and Maize models of the Decision Support System for Agro Technology Transfer (DSSAT). A two-year experiment with two different crop establishment methods viz., aerobic rice and flooded rice with four nitrogen rates followed by maize under zero tilled conditions was used to calibrate and evaluate DSSAT CERES-Rice and CERES-Maize models. The calibrated models were used to develop best management options for an aerobic rice–maize sequence which can produce similar yields with water savings relative to that of traditional flooded rice–maize system. The results showed that application of 180 kg N ha^{-1} in four splits and automatic irrigation with 40 mm, when soil available water (ASW) in top 30 cm fell below to 60% was the best management combination for aerobic rice, saving 41% of water while producing 96% of the yield attainable under flooded conditions. Similarly for maize, application of 120 kg N ha^{-1} and irrigation with 30 mm of water at 40% ASW in the top 30 cm soil was the most dominant management option. Further, application of 180 kg N ha^{-1} with rice followed by 120 kg N ha^{-1} in maize provided stable yield for both aerobic and flooded rice systems over time as simulated by the model. The results illustrate that DSSAT model is a useful tool for evaluating alternative management options aimed at maintaining yields and saving water in rice–maize systems in semi-arid regions.

1. Introduction

Rice–maize double cropping (R–M) is the most important emerging cropping system in South Asia. R–M systems currently occupy around 3.5 M ha in Asia (Timsina et al., 2010). The growing water shortage conditions for continuous rice cultivation have prompted studies to look for alternate rice-based cropping systems. The development of short duration rice varieties coupled with high yielding maize hybrids provide an opportunity for increasing the area under R–M cropping in this region (Timsina et al., 2010; Buresh and Haefele, 2010). Both crops in R–M systems require high nutrient input in view of the respective large grain and by-product yields that require high amounts of nutrient extraction from soils. Hence, strategies that optimize nutrient management need to be developed for R–M systems with an aim to supply adequate fertilizers to meet crop requirement while minimizing the nutrient losses and maximizing nutrient use efficiency. Field experiments conducted in R–M sequences usually focus either on rice or maize independently without considering the influence of the previous crop and its associated growing conditions. Stand establishment in maize, typically planted immediately after rice in R–M systems, is influenced to a great extent by soil moisture content and soil physico-chemical conditions after rice. However, cropping system based field experiments for quantifying optimal crop N and water requirements are time consuming, requiring extensive numerous resources and years to draw valid conclusions.

Crop simulation models consider the complex interactions among crop, weather, soil and management factors that influence crop performance. These models are useful for supplementing

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field experiments for identifying best management strategies in a cropping sequence using soil and weather parameters (He et al., 2012). Crop growth models such as those in Decision Support System for Agro technology Transfer (DSSAT) have been used successfully in many places around the world for a wide range of conditions and applications (Tsuji et al., 1998; Jones et al., 2003; Hoogenboom et al., 2010). The DSSAT is a package of 26 crop growth models derived from DSSAT-CROPGRO and CERES models that use the soil, weather and crop management files to predict the crop growth and yield (Jones et al., 2003; Hoogenboom et al., 2010). CERES (Crop Estimation through Resource and Environment Synthesis)-Rice and -Maize are process-based models embedded in DSSAT simulate the main processes of crop growth and development such as phenological development, canopy leaf area growth, dry matter accumulation and grain yield. The CERES-Rice and -Maize models were evaluated by many researchers across locations (Sarkar and Kar, 2006; Timsina and Humphreys, 2006; O'Neal et al., 2002; Behera and Panda, 2009; Liu et al., 2011; He et al., 2012; Salmerón et al., 2012; Jeong et al., 2014; Ngwira et al., 2014) with good agreements between predicted and observed values. Even though simulation results generally will have some uncertainties associated with inputs and model parameters, but still the simulation models can be effectively utilized as a scientific tool to increase the resource use efficiency of cropping systems (Timsina and Connor, 2001; Sarkar and Kar, 2008; Timsina and Humphreys, 2006; Timsina et al., 2008). None of the previous studies have, however, included rice and maize yield predictions in response to changes in rice establishment methods-switching from a traditional flooded to a water saving aerobic rice method and the associated N and water balances. In addition, long term studies on alternate irrigation management practices in rice–maize systems (R–M systems) with an aim to reduce water requirements have not been conducted. Therefore, our study was done with the following main objectives to: (1) evaluate the DSSAT cropping system model for prediction of soil water, N balance, rice and maize yields in response to methods of rice establishment and N rates in R–M cropping system, and (2) determine best management options to increase water productivity of aerobic R–M system for semi-arid tropics using long term weather data.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted from 2009 to 2011 at the experimental farm of Acharya NG Ranga Agricultural University, Hyderabad, India. The experimental site was located in the Southern Telangana Agro climatic zone of Andhra Pradesh, India (17°19′N, 78°28′E and 534 m above mean sea level). The physico-chemical characters of the sandy loam soil at the experimental site are presented in Table 1. The climate of the area is semi-arid in nature with annual rainfall of 850 mm, 80% of which is received during the south west monsoon period (June–October).

2.2. Treatment details

Rice and maize crops were grown in a rice-fallow-maize-fallow sequence. Rice was grown during the monsoon season from July to October and maize was grown in the dry season from November to March. The experiment was described in detail by Kadiyala et al. (2012). Briefly, the experimental design was a split plot with rice establishment methods as the main plots and four N rates as subplot treatments. The two rice establishment methods were aerobic rice (AR) and flooded rice (FR) and the four N treatments were 0, 60, 120 and 180 kg N ha^{-1}. Nitrogen was applied in three equal split rates, at the time of planting, at maximum tillering and at panicle initiation stages in both aerobic and flooded plots. A popular high yielding low land rice variety MTU 1010, was selected for both aerobic and flooded methods. Rice seeds were directly sown in rows 22.5 cm apart in the first week of July for AR treatments. The AR was irrigated with 50 mm of water whenever the soil moisture tension in the top 10 cm reached −30 kPa using Delta-T Devices-ML2 capacitance probes. In FR treatments, a seedling nursery was planted on the same day that the AR crop was planted. After 30 days, seedlings were transplanted at a hill spacing of 20 × 15 cm with two seedlings per hill. After rice harvest, maize, DeKalb 800 M hybrid, was planted at a spacing of 60 × 20 cm under no- till conditions. Rice crop was harvested to the ground without leaving any residue except the roots. The post rainy season maize crop was irrigated with 50 mm water whenever the ratio of irrigation water to cumulative pan evaporation (IW/CPE) reached 1.0. Maize crop received 120 kg N, 26 kg P and 33 kg K ha^{-1}. Fertilizer N was applied in three split doses- at the time of sowing, at knee height stage and at silking, whereas entire P and K amounts were applied at the time of planting. Pests, diseases and weeds were intensively controlled during the crop growth period.

2.3. Measurements

Weather data (maximum and minimum temperatures, rainfall, and sunshine hours) were taken from the meteorological observatory at Agricultural Research Institute (ARI), Rajendranagar, Hyderabad located approximately 100 m away from the experimental plots. The daily bright sunshine hours were converted to solar radiation (MJ m^{-2} day^{-1}) using the DSSAT Weatherman conversion that uses the Angstrom Formula (Allen et al., 1998). Soil parameters such as soil texture, soil pH, bulk density, drained upper (DUL) and lower moisture limits (DLL), hydraulic conductivity and organic carbon were estimated using International pipette method (Piper, 1966), Beckman pH meter (Jackson, 1967), core sampler method, pressure plate apparatus, constant-head method and Wet digestion method (Walkley and Black, 1934), respectively. Crop

Table 1
Physical and chemical properties of the experimental plot used in model evaluation and application.

Depth	LLV (cm^3 cm^{-3})	DUL (cm^3 cm^{-3})	SAT (cm^3 cm^{-3})	SRGF	BD (g cm^{-3})	SOC (%)	Clay (%)	Sand (%)	Silt (%)	pH	CEC (cmol kg$^{-1)}$
0–15	0.13	0.23	0.42	1.00	1.37	0.51	33.4	53.6	13	8.0	26.9
15–30	0.15	0.24	0.43	0.90	1.42	0.48	35.4	53.6	11	8.2	18.0
30–45	0.14	0.26	0.42	0.70	1.56	0.34	33.4	59.6	7	8.2	13.3
45–60	0.08	0.23	0.36	0.30	1.53	0.14	25.4	65.6	9	8.1	9.0
60–75	0.10	0.24	0.37	0.10	1.44	0.31	31.4	60.6	8	8.1	8.4
75–90	0.13	0.23	0.38	0.02	1.56	0.04	21.4	69.6	9	8.2	5.1
90–105	0.08	0.26	0.40	0.01	1.59	0.08	27.4	65.6	7	8.2	6.6
105–120	0.08	0.24	0.41	0.01	1.49	0.08	21.4	67.6	11	8.2	6.9
120–135	0.09	0.24	0.40	0.01	1.69	0.11	21.4	76.6	2	8.4	5.5
135–150	0.08	0.20	0.38	0.01	1.52	0.07	18.4	75.6	6	8.5	4.7

LL: lower limit; DUL: drained upper limit; SAT: saturation; SRGF: relative root distribution; BD: bulk density; SOC: soil organic carbon.

physiological and nutrient data such as leaf area index, dry matter accumulation, and N content in plants, were taken at 30 day intervals, coinciding with crop phenological stages. The volumetric water content (VWC) was measured using a theta probe with a PR2 sensor (Delta-T Devices), a *multi-sensor* capacitance probe which consisting of a consisting of a scaled polycarbonate rods with six pairs of stainless steel rings centered at 10, 20, 30, 40 60 and 100 cm. The probe was initially calibrated by gravimetric method. The volumetric water content was measured at each depth increment (10, 20, 30, and 60) in each access tube at weekly intervals and between two irrigations.

2.4. Model calibration and evaluation

The CERES-Rice and CERES-Maize models in DSSAT v 4.5 (Hoogenboom et al., 2010) were used in the study. Model calibration involves the estimation of genotype coefficients to confirm an agreement between model predictions and observed values. The CERES-Rice model was calibrated with the data obtained from the 2009 field experiment with the treatment receiving 120 kg N ha^{-1} under flooded conditions, the treatment with minimum soil constraints (Jones et al., 2010). Similarly, the CERES-Maize was calibrated using data from the treatment that followed the FR receiving 120 kg N ha^{-1}. The cultivar coefficients were estimated using the Generalized Likelihood Uncertainty Estimation (GLUE) method (Beven and Binley, 1992; Franks et al., 1998; Shulz et al., 1999; Jones et al., 2010). In this method, the parameter space is first discretized by generating a large number (6000) of parameter values from the prior distribution. Likelihood values are then calculated for each set of coefficients using differences between model predictions and measurements. Weights and probabilities are calculated with the Bayesian equation, and the posterior coefficients are estimated.

After estimating cultivar coefficients for rice and maize, the models were evaluated by comparing observed and predicted results for the remaining treatments in 2009. The days to anthesis and maturity, measured crop yield, and biomass factors were used to calibrate and validate the models. Finally, model predictions were evaluated using independent data from experiment conducted in 2010

2.5. Statistics

Performance of the model was evaluated using the coefficient of determination (R^2), absolute and normalized root mean square error (RMSE), and the Wilmot d index (Willmott et al., 1985), and modeling efficiency (ME). The values of RMSE and d-index determine the ability of the model to predict the experimental data. Low RMSE and a d-value close to one indicate good agreement between the experimental data and model output. The normalized RMSE (%) indicates the relative difference between simulated and observed values. In this paper, the model simulations were considered excellent, good, fair, and poor based on the respective normalized RMSE (NRMSE) values of <10%, 10–20%, 20–30%, and >30% (Loague and Green, 1991). Modeling efficiency varies between minus infinity to 1.0. A negative ME means that mean value of the experimental data is a better predictor than the model whereas a ME of 1.0 signifies a perfect model agreement with observations. The equations for the model performance measures are as follows (Wallach and Goffinet, 1987):

$$\text{RMSE} = \left[n - 1 \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{0.5} \quad (1)$$

where P_i and O_i are the predicted and observed values, n is the number of observations

$$\text{normalized RMSE}\,(\%) = \left(\frac{\text{absolute RMSE}}{\bar{O}} \right) \times 100 \quad (2)$$

$\bar{O}$ = average observed value (Willmott et al., 1985):

$$d\text{-index} = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left[\left| P'_i \right| + \left| O'_i \right| \right]^2} \right] \quad (3)$$

where n is the number of observations, P_i is 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) (Garnier et al., 2001):

$$\text{modeling efficiency} = \frac{\left[\sum_{i=1}^{n} \left(O_i - \bar{O} \right) - \sum_{i=1}^{n} (P_i - O_i)^2 \right]}{\sum_{i=1}^{n} \left(O_i - \bar{O} \right)^2} \quad (4)$$

where P_i, O_i are the predicted and observed values, n is the number of observations, $\bar{o}$ is the mean of the observed variable.

2.6. Analysis of rice–maize crop management

The seasonal analysis option of DSSAT was utilized to simulate the effects of weather variability on yields for irrigation and N management scenarios in AR using historical weather data. The approach we used in this simulation was to first determine the set of management practices that best suited for each crop and then evaluate them as the best management practice options for rice–maize cropping systems in our study area.

In AR, a total of twelve scenarios featuring different irrigation, N rates, and N application times were simulated. The irrigation treatments in AR were implemented with automatic irrigation, where 40 mm of water was applied when the available soil water was less than 60, 80 or 100% of the field capacity in the top 30 cm of the profile. The N rates tested were 120 and 180 kg N ha^{-1} applied in either three or four splits doses.

In FR, two scenarios featuring two N rates (120 kg and 180 kg ha^{-1}) applied in three splits doses were simulated. Simulation of potential yield was also included in the analysis, obtained by disabling the water and N limitations of CERES-Rice to determine maximum yields for comparison with the 14 selected scenarios.

Similarly for maize, nine scenarios with different irrigation and N rates, including one potential production scenario, were simulated. In maize, automatic irrigation of 30 mm was implemented when the simulated available soil water was less than or equal to 20, 30, 40 and 50% of field capacity in the top 30 cm of the profile. Though the depth of the soil profile should ideally change with crop rooting depth, a constant depth in both AR and maize adopted in this study was a simplistic approach used by many irrigation scheduling programs. Two N rates of 120 and 180 kg ha^{-1} applied in three split doses were used as management options in maize.

Simulations were performed using weather data collected for a 25-year period (1985–2009) from the Agricultural Research Institute, Rajendranagar, Hyderabad weather station. The scenarios were analyzed for yield, water and nitrogen dynamics. Best scenarios- four in flooded and AR and two in maize-were identified for subsequent analysis on crop rotation. The Priestley–Taylor method was used for estimating evapotranspiration and the CENTURY method was used for soil organic matter (SOM) simulations, in DSSAT. The DSSAT-CENTURY model was initialized by providing estimates of stable soil organic carbon fraction (SOM3 fraction) based on the historical field data. Once stable C (SOM3) was estimated, the fractions of SOM1 and SOM2 are assumed to be 5% and 95% of the remaining (non-SOM3) amount, respectively (Porter et al., 2009; Basso et al., 2011). The results of various management scenarios were compared with biophysical and strategic analysis of yields, N and water balance outputs using mean responses and cumulative probability distributions.

2.7. Analysis of rice–maize cropping systems

Crop yields, N and water balance of rice–fallow–maize–fallow crop rotation systems were simulated using the sequential analysis module of DSSAT, with rice planted in the rainy season followed by maize in the post rainy season. The sequence analysis module simulates water and nitrogen dynamics not only in crops but also during fallow period, which allows studying the carryover of the soil water and nutrient status from one cropping season or crop to the subsequent one in the rotation. From the analyses of sole rice and maize management described above, the scenarios that were most effective for each crop were run in four sequences of FR-fallow-maize-fallow and AR-fallow-maize-fallow, to identify the best rotation combination. Treatment combinations are presented in Table 2. These sequences were run for 25 years using measured weather data from 1985 to 2009. Simulated crop yields, N uptake, leaching, and water balance components were analyzed using various statistical parameters. Stability analysis was carried out for crop yield to identify the crop sequence with minimum variability across different years. Four stability indicators used in this study were:

$$\text{the variance } \left(S_i^2\right) \text{ of a system} = \sum_{j=1}^{q} \frac{\left[X_{ij} - \overline{x_i}\right]^2}{q-1} \quad (5)$$

where X_{ij} is observed yield of ith cropping system in jth year, is $\bar{x}_i$ mean yield of cropping system across years and q is number of years

$$\text{coefficient of variation}\,(\text{CV}_i) = \left[\frac{S_j}{\overline{X_i}}\right] \times 100 \quad (6)$$

where S_j is the standard deviation of cropping system across years and $\bar{x}_i$ is the mean yield of cropping system across years.

$$\text{Wrickie's ecovalance } \left(W_i{}^2\right) = \sum_{j=1}^{q} \left[X_{ij} - \overline{X}_{i.} - \overline{X}_{.j} + \bar{X}\ldots\right]^2 \quad (7)$$

where X_{ij} is the performance of cropping system i in jth year, X_i and X_j are cropping system and year means, $\bar{x}$. is over all mean

$$\text{Finlay \& Wilkinson's regression coefficient } \left(\beta_i\right) = \frac{\sum_{j=1}^{q} X_{ij}\overline{X}_{.j} - \left(\overline{X}_{i.}\overline{X}/q\right)}{\sum_{j=1}^{q} \overline{X}_{.j}^2 - \left(\overline{X}^2/q\right)} \quad (8)$$

where X_{ij} is the performance of cropping system i in jth year, $\bar{x}_{.j}$ is the mean of cropping systems in jth year, $\bar{x}_{.i}$ is mean of cropping system over years, $\bar{x}$ is the overall mean and q is number of years.

Wrickie's Ecovalance (1962) considers the cropping system and year interaction mean-squares for stability analysis. Smaller $W_i{}^2$ values indicate a more stable system and vice versa. Finlay and Wilkinson's regression coefficient (1963) was estimated by regressing observed yields of the cropping systems with an environmental index, defined as the difference between the marginal mean yield of the environments and the overall mean.

3. Results and discussion

3.1. Model calibration

The CERES-Rice and CERES-Maize models were calibrated with the experimental data collected during 2009. The estimated cultivar coefficients for the rice cultivar MTU 1010 and Maize cultivar DeKalb 800 M are presented in Tables 3 and 4. A close agreement was observed between the simulated and observed values for anthesis, maturity, grain yield, biomass yield and N uptake in both crops (Table 5). The data collected from the remaining treatments in rice were also used to evaluate the accuracy of the model during 2009. The statistical indices (RMSE and ME) used to evaluate the accuracy of the model are presented in Table 6. The model accurately predicted the days to anthesis and maturity, grain yield, tops weight, and N uptake, in both aerobic and FR establishment methods, with NRMSE of 14.5%, d-values of 0.93 and with ME of 0.73 indicating acceptable performance. However, the model under-predicted leaf area index and over-predicted soil moisture content as suggested by the negative ME values. The model simulated grain yield under various N rates and different establishment methods with high r^2 values.

3.2. Model validation

The CERES-Rice and Maize models were validated using independent experimental data on phenology, growth, grain, straw yields and N uptake, both in grain and straw, collected during the 2010–2011. This was done to ensure that applications of the models to assess different seasonal conditions in the study region are reliable.

3.2.1. Phenology and growth

The model predicted the phenological events of anthesis and maturity in rice accurately with low RMSE (2.0) and high d-index

Table 2
The treatment combinations used for rice–maize cropping system analysis.

Scenario	Rice		Maize	
	Nitrogen	Irrigation	Nitrogen	Irrigation
AR-120-M-120	120 kg N ha^{-1} in four splits	40 mm when ASW in top 30 cm equaled 60%	120 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
AR-120-M-90	120 kg N ha^{-1} in four splits	40 mm when ASW in top 30 cm equaled 60%	90 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
AR-180-M-120	180 kg N ha^{-1} in four splits	40 mm when ASW in top 30 cm equaled 60%	120 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
AR-120-M-90	180 kg N ha^{-1} in four splits	40 mm when ASW in top 30 cm equaled 60%	90 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
FR-120-M-120	120 kg N ha^{-1} in three splits	Flood conditions	120 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
FR-120-M-90	120 kg N ha^{-1} in three splits	Flood conditions	90 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
FR-180-M-120	180 kg N ha^{-1} in three splits	Flood conditions	120 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%
FR-120-M-90	180 kg N ha^{-1} in three splits	Flood conditions	90 kg N ha^{-1} in three splits	30 mm when ASW in top 30 cm equaled 40%

Table 3
Genetic coefficients developed for rice variety MTU-1010.

Genetic parameters	Description	Coefficient for MTU-1010
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	407.0
P20	Critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate. At values higher than P20 developmental rate is slowed, hence there is delay due to longer day lengths	173.0
P2R	Extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in °C) for each hour increase in photoperiod above P20	367
P5	Time period in GDD (°C) from beginning of grain filling (3–4 days after flowering) to physiological maturity with a base temperature of 9 °C	11.7
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	61.3
G2	Single grain weight (g) under ideal growing conditions, i.e. non-limiting light, water, nutrients, and absence of pests and diseases	0.022
G3	Tillering coefficient (scalar value) relative to IR64 cultivar under ideal conditions. A higher tillering cultivar would have coefficient greater than 1.0	1.0
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	1.11

Table 4
Genetic coefficients developed for maize variety DeKalb 800 M.

Genetic parameters	Description	Coefficient for DeKalb 800 M
P1	Thermal time from seedling emergence to the end of Juvenile phase during which the plants are not responsive to changes in photoperiod (degree days)	176.6
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h (days)	0.650
P5	Thermal time from silking to physiological maturity (degree days)	885.0
G2	Maximum possible number of kernels per plant	531.0
G3	Grain filling rate during the linear grain filling stage and under optimum conditions (mg/day)	8.5
PHINT	Phyllochron interval (degree days)	60.0

Table 5
Simulated and observed phenological dates, growth characters and grain yield of rice and maize during 2009–2010 in flooded rice—120 kg N and Maize fallowed by flooded rice with 120 kg N treatments.

Crop-variety	Anthesis (DAS)		Maturity (DAS)		Tops weight ($t\,ha^{-1}$)		Grain N at maturity ($kg\,ha^{-1}$)		Tops N at maturity ($kg\,ha^{-1}$)		Unit grain weight (g)		Grain yield ($t\,ha^{-1}$)	
	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim
Rice MTU-1010	95	96	127	128	12.3	12.2	75.6	83	109	113	0.02	0.02	5.9	6.0
Maize DeKalb 900 M	66	67	115	114	11.1	13.3	88.0	89	130	115	0.28	0.27	5.7	5.6

Sim—simulated; Obs—observed. DAS—days after sowing.

(0.90). There was a good agreement between observed and simulated values of above ground biomass at various growth stages for different N rates under both aerobic and FR conditions was observed with acceptable NRMSE (23%) and high "*d*" (0.97) and "*r*" (0.95) values. Simulations for LAI were poor as the model under-predicted the LAI most of the times. The predictions were better for higher N rates than the lower rates (Table 7). Changes in soil water content during the AR crop growth were well simulated by the model at 15 and 30 cm depth with an overall NRMSE of 15.5% *d*-index of 0.56 and $r = 0.9$. With regard to the soil moisture

Table 6
Descriptive statistics showing the performance of CERES-Rice for treatments in 2009 that were not used to estimate cultivar parameters.

Variable	Data numbers	Obs	SD	Sim	SD	RMSE	NRMSE (%)	*d*-Index	ME	*r*
PI date (DAS)	7	60.00	5.60	57.0	4.30	3.50	5.80	0.86	0.56	0.99
Anthesis date (DAS)	7	91.50	4.10	91.5	4.80	0.86	0.90	0.99	0.95	0.99
Maturity date (DAS)	7	123.00	4.10	123	6.01	1.80	1.40	0.96	0.79	0.99
LAI ($cm^2\,cm^{-2}$)	25	1.89	0.77	1.19	0.91	0.97	51.0	0.62	-0.62	0.68
Tops weight ($t\,ha^{-1}$)	25	4.80	3.40	4.80	3.70	1.10	23.0	0.97	0.89	0.95
SWC 0–15 cm ($cm^3\,cm^{-3}$)	18	0.25	0.03	0.27	0.07	0.05	22.2	0.62	-3.3	0.76
SWC 15–30 $cm^3\,cm^{-3}$	18	0.31	0.03	0.27	0.05	0.05	16.0	0.65	-1.5	0.89
Grain yield ($t\,ha^{-1}$)	7	4.16	1.50	3.92	1.80	0.70	17.8	0.95	0.75	0.93
Straw yield ($t\,ha^{-1}$)	7	4.76	1.50	4.30	2.10	1.00	21.0	0.91	0.50	0.90
Tops N at maturity ($kg\,ha^{-1}$)	7	75.7	26.4	81.2	38.0	18.4	24.3	0.90	0.44	0.89
Grain N at maturity ($kg\,ha^{-1}$)	7	52.3	29.0	54.6	21.5	14.9	28.4	0.89	0.70	0.84

Sim—simulated; Obs—observed; SD—standard deviation; RMSE—root mean square error; ME—modeling efficiency; *r*—Spearman correlation coefficient.

Table 7
Descriptive statistics showing the performance of CERES-Rice when compared with independent data collected in the 2010 experiment.

Variable	Data numbers	Obs	SD	Sim	SD	RMSE	NRMSE (%)	*d*-Index	ME	*r*
PI date (DAS)	8	61.00	4.30	58.00	3.20	3.16	5.20	0.79	0.38	1.00
Anthesis date (DAS)	8	92.60	3.60	93.50	3.70	0.93	1.00	0.98	0.92	0.99
Maturity date (DAS)	8	122.70	4.00	124.50	4.80	1.93	1.00	0.94	0.73	0.99
LAI (cm^2 cm^{-2})	28	2.37	0.72	1.25	0.78	1.30	54.80	0.12	-2.30	0.59
Tops weight (t ha^{-1})	28	5.40	3.70	4.90	3.60	1.20	23.00	0.97	0.88	0.95
SWC 0–15 cm (cm^3 cm^{-3})	18	0.31	0.03	0.27	0.06	0.05	16.90	0.58	-2.40	0.88
SWC 15–30 cm^3 cm^{-3}	18	0.32	0.03	0.28	0.04	0.04	14.10	0.54	-1.92	0.91
Grain yield (t ha^{-1})	8	4.35	1.30	4.15	1.60	0.57	10.30	0.97	0.87	0.98
Straw yield (t ha^{-1})	8	5.29	1.30	4.20	1.60	1.20	22.30	0.80	0.06	0.96
Tops N at maturity (kg ha^{-1})	8	81.90	27.20	87.60	29.50	12.40	15.10	0.94	0.76	0.92
Grain N at maturity (kg ha^{-1})	8	52.60	19.40	56.40	23.40	6.60	12.50	0.97	0.87	0.98

Sim—simulated; Obs—observed; SD—standard deviation; RMSE—root mean square error; ME—modeling efficiency; *r*-Spearman correlation coefficient.

Table 8
Descriptive statistics showing the performance of CERES-Maize during the evaluation phase 2010–2011.

Variable	Data numbers	Obs	SD	Sim	SD	RMSE	NRMSE (%)	*d*-Index	ME	*r*
Anthesis date (DAS)	3	68.30	2.80	67.00	2.10	1.40	2.00	0.79	0.31	0.97
Maturity date (DAS)	3	118.30	3.50	119.00	4.90	1.15	9.00	0.95	0.76	0.96
Tops weight (t ha^{-1})	9	8.39	4.46	7.87	5.50	1.55	18.40	0.97	0.86	0.97
Grain yield (t ha^{-1})	3	6.23	0.32	6.02	0.20	0.23	3.60	0.71	0.24	0.99

Sim—simulated; Obs—observed; SD—standard deviation; RMSE—root mean square error; ME—modeling efficiency; *r*-spearman correlation coefficient.

content, the model slightly over-predicted during the drought year of 2009 and under-predicted it during the well distributed rainfall during the monsoon period of 2010. The reason for mismatch in the volumetric water content could be due to the fact that we tried to compare the VWC of the capacitance probe readings from 10–20 cm to 20–30 cm with simulated VWC readings of 5–15 and 15–30 cm, respectively. Similarly, the model predicted phenological and growth characters accurately in maize. Even though the model underestimated the leaf area, the phenology and yield predictions were however were at reasonably acceptable limits. Mall and Aggarwal (2002) and Meyer et al. (1994) also reported under estimation of LAI especially peak LAI and attributed the reasons due to limited calibration and inaccurate initialization of soil mineral N and soil water. The average values of predicted and observed N uptake matched well. High *r* values, *d* index and acceptable NRMSE values clarified the good simulation of N uptake of rice by CERES-Rice model. Meyer et al. (1994), Timsina et al. (1998) also reported good prediction of CERES-Rice for N uptake under different N levels.

3.2.2. Grain yield

There was good agreement between predicted and observed grain yields both in rice and maize crops. The models predicted the grain yields of aerobic and FR adequately with RMSE of 0.57 t ha^{-1}, NRMSE of 10.3, ME of 0.87 and a *d*-values of 0.97 (Table 7). Similarly, maize grain yields were also simulated by the model reasonably well with RMSE of 0.23 t ha^{-1}, NRMSE of 3.6% and *d*-values of 0.71 (Table 8) indicating that the model was able to simulate grain yield well within the bounds of experimental uncertainty. The model evaluation indicated that CERES-Rice model can simulate rice phenology, growth and yield in various rice crop establishment (aerobic and flood) systems accurately.

3.3. Exploration of possible nitrogen and irrigation options to rice

Results of model evaluations demonstrated that the models accurately predict phenological development, grain and total biomass, soil water content variations over time in response to variable weather conditions, response to different N levels and crop sequences. Thus, a model-based analysis was carried out to explore a range of management practices and identify the optimum management options for irrigation and N for aerobic, FR systems and maize. This was achieved in two steps. First, different management practices were simulated for a single season using the seasonal analysis subroutine in DSSAT to identify a smaller subset of practices to analyze cropping systems. This procedure enabled rejection of certain individual crop management practices not well suited for this region due to seasonal variability in weather conditions.

3.3.1. Grain yield and nitrogen uptake

The outputs obtained from the analysis for different irrigation regimes and N rates are presented in Table 9. The analysis predicted grain yields of 7.96 t ha^{-1} under non-limiting (potential) conditions in AR are achievable, revealing the potential for achieving higher yields in AR, if limiting factors such as water, weeds, nutrient, and disease stresses are eliminated. In AR, optimum irrigation regimes are crucial for high yields and thus need to be identified for best management practices. In this study, automatic irrigation water applications were triggered in AR simulations by using threshold values of 60, 80 and 100% of the field capacity in the top 30 cm of the profile. These different thresholds resulted in significant yield differences (Table 9). Changing the threshold from 60% to 80% or 100%, resulted in corresponding yield reductions coupled with high leaching losses of N, suggesting that the 60% threshold level was the best option from among those tested for AR. Cumulative distribution function plots also showed that application of 180 kg N in four splits and irrigation at the 60% threshold level in aerobic rice resulted in the highest yields among all management options tested (Fig. 1). Higher water productivity also occurred at the 60% soil water threshold level. Mean grain yields of AR and FR increased when the rate of N was increased from 120 kg to 180 kg ha^{-1}. Similar increases in simulated yields by the CERES-Rice model under increased rates of N were also reported by Aggarwal et al. (1997) and Sarkar and Kar (2006). Nitrogen uptake followed a similar increasing pattern in both AR and FR with the increase in N fertilizer rates. Increasing the number of split applications of N fertilizers from three to four in AR showed considerable increases in yields and reductions in N leaching, suggesting an advantage of splitting applications of N.

3.3.2. Drainage and nitrogen leaching

Unlike the traditional flooded system of rice production, the soil in AR is well aerated and therefore N leaching is of considerable

Table 9
Yield, water and nitrogen balance components in the rice with CERES-Rice model.

Scenarios	Grain yield (t ha^{-1})	Water applied I + R (mm)	WP_{I+R} (g grain kg^{-1} water)	Drainage (mm)	N uptake (kg ha^{-1})	N leached (kg ha^{-1})	Mineralized N (kg ha^{-1})
AR-120 N-3 splits-60% ASW	6.27 ± 0.65	893	0.70	227	142	40	53.5
AR-120 N-3 splits-80% AW	5.58 ± 0.55	1117	0.50	423	117	70	47.8
AR-120 N-3 splits-100% AW	4.75 ± 0.34	1407	0.34	681	93	98	40.8
AR-180 N-3 splits-60% AW	7.24 ± 0.51	888	0.81	222	176	45	72.2
AR-180 N-3 splits-80% AW	6.79 ± 0.50	1093	0.62	403	162	76	67.3
AR-180 N-3 splits-100% AW	6.20 ± 0.43	1376	0.45	656	137	106	55.4
AR-120 N-4 splits-60% AW	6.52 ± 0.51	904	0.72	238	147	39	54.7
AR-120 N-4 splits-80% AW	5.92 ± 0.44	1117	0.53	426	123	68	50.2
AR-120 N-4 splits-100% AW	5.12 ± 0.28	1405	0.36	685	98	94	44.3
AR-180 N-4 splits-60% AW	7.52 ± 0.40	891	0.84	224	184	42	76.5
AR-180 N-4 splits-80% AW	7.23 ± 0.39	1098	0.66	411	173	72	71.0
AR-180 N-4 splits-100% AW	6.80 ± 0.32	1384	0.49	668	151	100	59.5
FR-120 N-3 splits	6.11 ± 0.17	1503	0.41	505	116	12	34.9
FR-180 N-3 splits	7.84 ± 0.24	1519	0.52	518	166	12	45.9
AR-Potential production	7.96 ± 0.38	–	–	–	–	–	–
LSD (0.05)	0.38	78	0.1	78.0	12.6	13.2	6.3

AR—aerobic rice; FR—flooded rice; ASW—available soil water; WP: water productivity.

importance as most of the N is in nitrate form, which is mobile in solution. Drainage occurs when irrigation supply exceeds water holding capacity of the soil. On an average in the AR scenario, irrigating at the 100% ASW threshold resulted in significantly higher amount of drainage (656–685 mm) as compared to irrigating at 60% ASW (224 to 238 mm). When drainage was high, leaching was also high indicating that N leaching was greatly influenced by irrigation threshold rates in AR. Increased irrigation thresholds also increased N leaching losses. The probability of exceeding 64 kg of leached N ha^{-1} crop^{-1} was about 20% in the 60% threshold and 52% in 80% threshold (Fig. 2). In FR, due to puddled soil conditions, leaching losses were very low as mineral N exists as ammoniacal form and is bound to clay particles. Rinaldi et al. (2007) also reported similar results from analysis of tomato where higher N leaching associated with higher drainage was observed in well drained soils.

3.4. Exploration of possible best rice–maize sequence

An analysis was conducted to identify the best management practices for rice–maize sequence using the scenarios found to be the best for each crop grown as sole crops each season. Various stability indices were used to identify the most stable R–M cropping system over an analysis time period of 25 years, during which time rice–maize crop rotations were practiced. Observed weather data from 1985 to 2009 were used for the analysis.

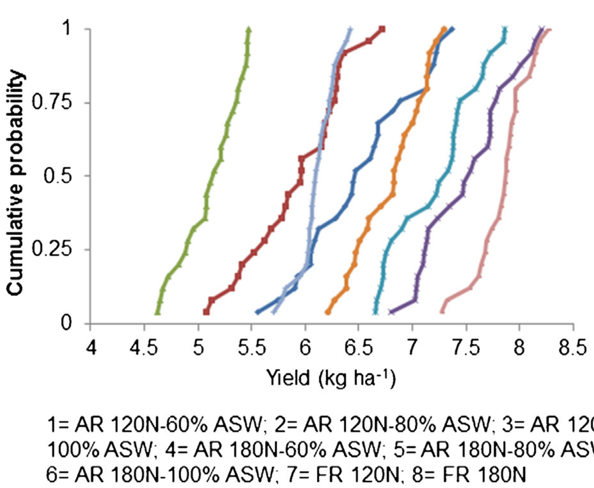

Fig. 1. Cumulative functional plots showing rice yields for different treatments of rice.

3.4.1. Yield and water productivity

The rice–maize sequence analysis results indicated that the highest predicted average yields in AR can be obtained with application of 180 kg N ha^{-1} combined with an average of 40 mm irrigation using the 60% ASW irrigation threshold. This simulated system produced 96% of the rice yields produced by FR system with 38% saving in irrigation water (Table 10). Considering all of the R–M system scenarios tested, the highest yields were obtained with FR receiving 180 kg N ha^{-1} followed by maize with 120 kg N ha^{-1}. Application of 90 kg N ha^{-1} to maize was found to be equally effective; Reducing N rate was not, however, associated with reduction in yields of maize. Even though application of 180 kg N for

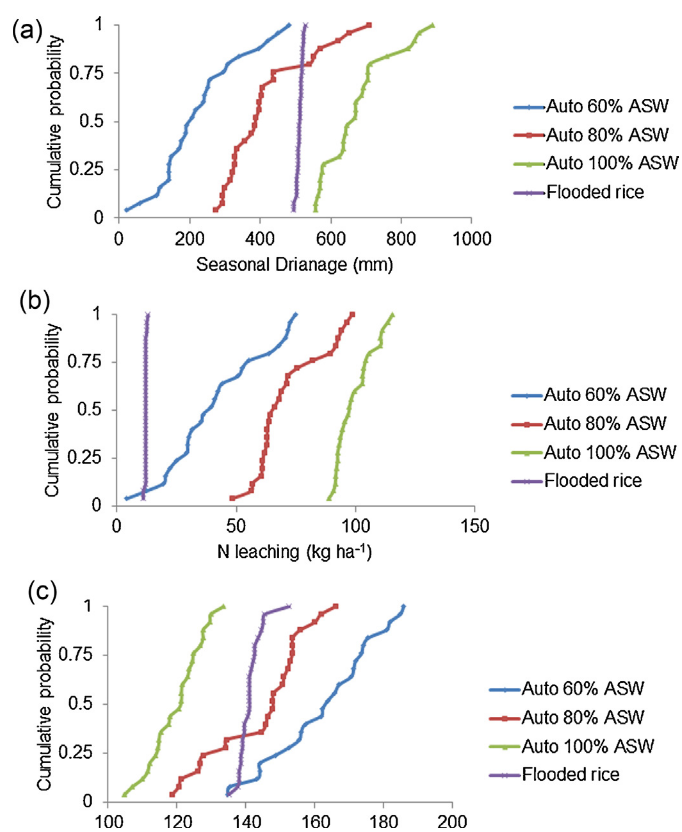

Fig. 2. Cumulative probability function plots, (a) seasonal drainage, (b) N uptake and (c) N leaching for irrigation scenarios in aerobic and flooded rice.

Table 10
Simulated average yield, water productivity of the aerobic and flooded rice–maize crop rotation.

Treatment	Grain yield ($t\,ha^{-1}$)		WP (g grain kg^{-1} water)		Yield ($t\,ha^{-1}$)	WP (g grain kg^{-1} water)
	Rice	Maize	Rice	Maize	Rice–maize system	
AR-120 N-M-120 N	6.48 ± 0.48	6.86 ± 0.45	0.76	1.90	13.3	1.09
AR-120 N-M-90 N	6.42 ± 0.49	6.83 ± 0.44	0.76	1.92	13.2	1.09
AR-180 N-M-120 N	7.70 ± 0.34	6.86 ± 0.49	0.92	1.95	14.6	1.22
AR-180 N-M-90 N	7.65 ± 0.34	6.86 ± 0.49	0.91	1.97	14.5	1.21
FR-120 N-M-120 N	6.23 ± 0.14	6.85 ± 0.47	0.45	1.89	13.1	0.74
FR-120 N-M-90 N	6.20 ± 0.15	6.84 ± 0.47	0.44	1.90	13.0	0.74
FR-180 N-M-120 N	8.03 ± 0.25	6.85 ± 0.47	0.56	1.91	14.9	0.83
FR-180 N-M-90 N	8.01 ± 0.23	6.85 ± 0.47	0.56	1.94	14.9	0.83

AR—aerobic rice; FR—flooded rice; WP: water productivity.

Table 11
Simulated water applied, drainage and seasonal ET of the aerobic and flooded rice–maize crop rotation.

Treatment	Water applied I + R (mm)		Drainage (mm)		ET (mm)	
	Rice	Maize	Rice	Maize	Rice	Maize
AR-120 N-M-120 N	882 ± 157	363 ± 33	364 ± 142	26 ± 14	462 ± 27	391 ± 22
AR-120 N-M-90 N	882 ± 159	357 ± 29	361 ± 144	25 ± 12	461 ± 27	390 ± 22
AR-180 N-M-120 N	861 ± 158	354 ± 30	340 ± 143	23 ± 12	463 ± 27	388 ± 21
AR-180 N-M-90 N	864 ± 158	350 ± 30	343 ± 144	23 ± 12	463 + 27	388 ± 21
FR-120 N-M-120 N	1405 ± 91	365 ± 33	505 ± 10	18 ± 12	455 ± 27	393 ± 22
FR-120 N-M-90 N	1406 ± 91	363 ± 33	505 ± 10	18 ± 12	455 ± 27	393 ± 22
FR-180 N-M-120 N	1429 ± 93	361 ± 33	522 ± 10	20 ± 14	461 ± 23	389 ± 21
FR-180 N-M-90 N	1428 ± 95	357 ± 36	521 ± 10	20 ± 14	461 ± 22	389 ± 21

AR—aerobic rice; FR—flooded rice; ET—evapotranspiration.

AR resulted in the highest yield, this treatment may have some potential environmental risks because of higher nitrate leaching losses (annual average of 66 kg N ha^{-1} $crop^{-1}$) compared to 120 kg N application (annual N loss average of 43 kg N ha^{-1} $crop^{-1}$). Water productivity (WP, g grain kg of $water^{-1}$, averaged over all AR treatments) as estimated from the grain yield and amount of water used (irrigation + rainfall) was higher with AR (0.84) and aerobic R–M system (1.15) compared to FR (0.50) and flooded R–M system (0.79).

3.4.2. Water balance components of rice–maize system

Water balance components were simulated under different rice establishment methods to assess the impact of AR on water use. Significant differences were found among various water balance components between the aerobic and FR systems. On an average, AR averaged 872 mm of water per year over the 25 years as compared to 1417 mm in FR, resulting in 38.4% savings. It was found that irrigated water in FR was lost mostly through deep percolation since the seasonal evapotranspiration was similar under both the systems (Table 11). Irrigation requirements and water balance components of maize followed by rice crop were not influenced by the rice establishment method.

3.4.3. Nitrogen balance components of rice–maize system

Even though we have not calibrated and validated the N balance components due to lack of experimental data on various N losses, we still used the simulated outputs on N balance components to identify best irrigation and nitrogen management options due the fact that CERES-Rice and -Maize models able to predict the N uptake and yield components accurately. We assume that these models can predict the N balance components reasonably as well. Crop establishment methods such as AR will have a strong influence on N dynamics in rice since the crop is grown under oxic conditions compared to traditional anaerobic, FR. In order to study the influence of the aerobic method, the N balance components were simulated under varying N rates in both the systems. Fertilizer application played a major role in increasing rice yields under both systems and N output primarily occurred during crop harvest. The rice crop sometimes obtains a majority of its N requirements (60–80%) from the organic N pool of the soil (Broadbent, 1979) and therefore the amount of N mineralized during the crop season may also important for achieving higher yields. In flooded soils, soil organic matter decomposition occurs at a slower potential rate due to anaerobic conditions. This was also clearly indicated by the simulated results on mineralized N, which showed that on an average 78% N was mineralized and available to the crop in AR compared to flooded system. On the other hand, most of the N lost in FR was mainly through denitrification and, to a small extent, volatilization and leaching (Table 12). It was also observed in other studies the CERES-Rice model predicted higher denitrification and lower ammonia volatilization losses, for urea applied at 120 kg N ha^{-1}, compared to observed losses (Pathak et al., 2004) indicating the need for model improvement in simulating nitrogen balance components for flooded rice. The differences in various N components were mainly due to the system of rice cultivation, as in AR nitrate-N is the dominant form and can be easily leached from the system if it is not taken up by the crop. Nitrogen losses in rice-fallow-maize were not influenced greatly by rice establishment methods. Immobilization of fertilizer N in soil organic matter that mineralizes very slow (Ichir et al., 2003) might be the reason that resulted in suppressed utilization of residual N from the previously applied N in both aerobic and flooded system resulting in similar nitrogen losses in succeeding maize. However, increased N rates in rice led to increased N losses in maize grown subsequently in the same fields. Leaching losses of N were more in maize grown after AR than in maize grown after FR, mainly due to higher mineralization rates in AR-maize systems. The simulation results were found to be in agreement with the experimental results, wherein we observed that the recovery of ^{15}N in the subsequent crops was very low (4.2–6.0%). Most of the residual N fertilizer recovery occurred in the maize crop grown after immediately following rice (3–4.5%), and decreased to 1% or less in the subsequent growing seasons, indicating poor utilization of residual N. Further, no significant difference was observed in the subsequent crop (maize)

Table 12
Simulated average N balances in the aerobic and flooded rice–maize crop rotation.

Treatment	N uptake ($kg\,ha^{-1}$)		N leached ($kg\,ha^{-1}$)		N mineralized ($kg\,ha^{-1}$)		N denitrified ($kg\,ha^{-1}$)		N volatilized ($kg\,ha^{-1}$)		Total N loss ($kg\,ha^{-1}$)	
	Rice	Maize	Rice	Maize	Rice	Maize	Rice	Maize	Rice	Maize	Rice	Maize
AR-120 N-M-120 N	146 ± 17	177 ± 5	44.8 ± 18	2.1 ± 1	75 ± 7	74 ± 7	1.9 ± 1	0.08 ± 0.1	0.0 ± 0.0	0.0 ± 0	46.7	2.2
AR-120 N-M-90 N	144 ± 17	148 ± 6	41.7 ± 17	2.0 ± 1	74 ± 7	73 ± 7	1.8 ± 1	0.07 ± 0.0	0.0 ± 0.0	0.0 ± 0	43.5	2.1
AR-180 N-M-120 N	192 ± 9	192 ± 8	70.5 ± 32	3.4 ± 2	116 ± 12	105 ± 8	3.0 ± 2	0.12 ± 0.1	0.0 ± 0.0	0.0 ± 0	73.5	3.5
AR-180 N-M-90 N	189 ± 9	178 ± 10	61.1 ± 26	3.1 ± 2	113 ± 12	104 ± 9	2.7 ± 2	0.12 ± 0.1	0.0 ± 0.0	0.0 ± 0	63.8	3.2
FR-120 N-M-120 N	134 ± 3	174 ± 4	10.5 ± 2	0.3 ± 0.5	44 ± 4	67 ± 6	40.4 ± 9	0.10 ± 0.0	2.5 ± 0.4	0.0 ± 0	53.4	0.4
FR-120 N-M-90 N	133 ± 3	145 ± 4	9.5 ± 2	0.3 ± 0.5	43 ± 3	65 ± 5	36.8 ± 9	0.09 ± 0.0	2.5 ± 0.3	0.0 ± 0	48.8	0.4
FR-180 N-M-120 N	193 ± 4	184 ± 7	12.2 ± 3	0.4 ± 0.5	63 ± 9	92 ± 10	50.3 ± 13	0.11 ± 1.0	4.4 ± 0.6	0.0 ± 0	66.9	0.5
FR-180 N-M-90 N	192 ± 4	159 ± 8	11.1 ± 2	0.4 ± 0.5	62 ± 9	91 ± 11	46.2 ± 12	0.10 ± 0.0	4.4 ± 0.6	0.0 ± 0	61.7	0.5

AR—aerobic rice; FR—flooded.

Table 13
Stability parameters of rice–maize crop rotation.

Cropping system	Yield ($t\,ha^{-1}$)	CV (%)	Rank	S_i^2	Rank	β_i	Rank	W_i^2	Rank	Overall
AR-120 N-M-120 N	13.3	4.7	7	0.39	7	2.57	7	0.97	5	26
AR-120 N-M-90 N	13.2	4.9	8	0.42	8	2.88	8	0.96	6	30
AR-180 N-M-120 N	14.6	4.2	6	0.37	6	1.13	1	1.06	3	16
AR-180 N-M-90 N	14.5	4.2	5	0.37	5	1.15	2	1.05	4	16
FR-120 N-M-120 N	13.1	3.9	3	0.26	1	2.25	4	0.95	7	15
FR-120 N-M-90 N	13.0	3.9	4	0.26	2	2.23	3	0.95	8	17
FR-180 N-M-120 N	14.9	3.8	2	0.31	4	2.38	5	1.08	1	12
FR-180 N-M-90 N	14.9	3.7	1	0.31	3	2.43	6	1.08	2	12

CV—coefficient of variation; S_i^2—variance across environments; β_i—regression coefficient; W_i^2—ecovalance parameter; AR—aerobic rice; FR—flooded rice.

recoveries between aerobic and flooded rice system (Kadiyala et al., 2011).

3.5. Stability analysis of rice–maize system

Yield stability of cropping systems may be more important than yield maximization. Stability indicates the variability of cropping systems across different environments, and in this study, different years are used to simulate different environments in the 25-year long cropping sequence. The cropping systems with minimum variability are regarded as the most stable systems. Various stability indices were used to identify the best cropping system. In this study, FR with 120 kg N ha^{-1} followed by maize with 120 kg N ha^{-1} was found to be the most stable with smallest variance. Wrickie's Ecovalance (W_i^2) given by Eq. (7) considers the interaction mean-squares for the cropping system-year parameters for stability analysis. Smaller W_i^2 values indicate a more stable system and vice versa. According to this criterion, the AR with 180 kg N ha^{-1} followed by maize with 120 kg N ha^{-1} was found to be the most stable cropping system.

The observed yields of the cropping systems were also regressed with an environmental index, defined as the difference between the marginal mean yield of the environments and the overall mean, in order to estimate the regression coefficient (β_i). The β_i for each cropping system was considered as a measure of stability with the β_i values ≥1 considered as stable systems. According to this criterion, the FR with 180 kg N ha^{-1} followed by maize with 120 kg N ha^{-1} was found to be the best system. The coefficient of variation (CV%) indicated that the FR with 180 N ha^{-1} followed by maize with 90 kg N $ha^{-1}$was the most stable system. Even though different parameters suggested different results, the overall rank sum indicated that the FR with 180 kg N followed by maize either with 120 kg N ha^{-1} or 90 kg N ha^{-1} was found to be the stable cropping systems (Table 13). Among the AR systems, AR with 180 kg N followed by maize with either 120 kg N or 90 kg N ha^{-1} systems were the most stable systems. Overall, the sequence analysis and stability indices indicated that in both aerobic and FR systems, application of 180 kg N ha^{-1} to rice followed by 120 kg N ha^{-1} to maize were the most stable systems.

4. Conclusions

The DSSAT CSM- CERES-Rice and -Maize models were utilized as tools to explore possible water and N management options so as to develop nitrogen and water efficient BMPs for rice–maize cropping system in semi-arid tropics. This study clearly demonstrated that the yield level of AR can be improved almost to the yield level of the flooded rice system, even while saving substantial amounts of water by employing careful water and nitrogen management strategies. However, if the N application rates exceed actual crop requirements, it may result in high N leaching as shown by the model simulations. Based on the simulation analysis, it can be concluded that application of 180 kg N ha^{-1} in four split applications and irrigation at 60% ASW was the best management option for AR. Highest yield of maize can be obtained with the application of 120 kg N ha^{-1} and an irrigation threshold at 40% ASW. Further, the DSSAT analysis showed that careful maneuvering of irrigation and N inputs by changing the irrigation threshold and increasing the split applications of N can improve the AR yields on par with FR. Long term simulations of rice–maize cropping system analysis revealed that that long-term stable productivity in the rice–maize system can be attained by applying 180 kg N ha^{-1} in rice followed by 120 kg N ha^{-1} in maize under both aerobic and FR systems. Thus, the CERES-Rice and -Maize models provided suitable, reliable and economical ways to obtain useful information on the interaction between water and N management strategies for long-term experiments, especially in developing countries. However, it should be noted that crop simulation models will have certain typical associated uncertainties with inputs and model parameters, which may affect the model predictions to some degree. Furthermore, it should also be noted that the crop simulation models used for this study do not account for the influence of weeds, pest and diseases on crop growth and development.

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