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Radiation utilization efficiency, latent heat flux, and crop growth simulation in irrigated rice during post-flood period in east coast of India

Gouranga Kar · Ashwani Kumar · Narayan Sahoo · Sucharita Mohapatra

Abstract   To study the radiation utilization efficiency, latent heat flux, and simulate growth of rice during post-flood period in eastern coast of India, on-farm trial was conducted with three water regimes in main plots (W_1 = continuous flooding of 5 cm, W_2 = irrigation after 2 days of water disappearance, and W_3 = irrigation after 5 days of water disappearance) and five nitrogen levels in subplots (N_1 = 0 kg N ha^{-1}, N_2 = 60 kg N ha^{-1}, N_3 = 90 kg N ha^{-1}, N_4 = 120 kg N ha^{-1}, and N_5 = 150 kg N ha^{-1}) on a rice cultivar, 'Lalat'. Average maximum radiation utilization efficiency (RUE) in terms of above ground dry biomass of 2.09 (±0.05), 2.10 (±0.02), and 1.9 (±0.08) g MJ^{-1} were computed under W_1, W_2, and W_3, respectively. Nitrogen increased the RUE significantly, mean RUE values were computed as 1.60 (±0.07), 1.78 (±0.02), 2.060 (±0.08), 2.30 (±0.07), and 2.34 (±0.08) g MJ^{-1} when the crop was grown with 0, 60, 90, 120, and 150 kg ha^{-1} nitrogen, respectively. Midday average latent heat flux (on clear days) varied from 7.4 to 14.9 and 8 to 13.6 MJ m^{-2} day^{-1} under W_2 and W_3 treatments, respectively, at different growth stages of the crop in different seasons. The DSSAT 4.5 model was used to simulate phenology, growth, and yield which predicted fairly well under higher dose of nitrogen (90 kg and above), but the model performance was found to be poor under low-nitrogen dose.

Keywords   Crop modeling · Grain yield · Rice · Nitrogen · Radiation use efficiency

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Introduction

Rice is the staple food in Asia which accounts for 40–46 % of the irrigated area of all the crops. In seasonal flood prone areas of east coast of India, rice is grown under irrigated conditions during post-flood period (dry season), but water availability during that season is the major constraint for successful rice cultivation. Since rice requires huge quantity of water, any water saving in rice cultivation will be significant for optimum management and utilization of water (Tabbal et al. 2002; Belder et al. 2004). Also optimum nitrogen rates for sustainable rice production are still promising management recommendations in order to increase profit for low-income farmers of the region (Frageria et al. 1997).

Growth and yield of any grain crop again is largely determined by radiation interception, the efficiency of conversion of intercepted radiation to dry matter and partitioning of dry matter to grain (Monteith 1972; Gallaghar and Biscoe 1978; Kar 2005; Figuerola and Berlinger 2006). In addition to radiation interception, understanding the latent heat flux will be useful for making effective irrigation scheduling and water budgeting (Tsai et al. 2007; Alberto et al. 2009; Maruyama and Kuwagata 2010). These radiation interception and energy balance characteristics of grain crops were well established in different parts of the world from unstressed field experiments for wheat (Kiniry et al. 1989; Gregory et al. 1992), maize (Sivakumar and Viramani 1984), barley (Gallaghar and Biscoe 1978), pigeonpea (Hughes and Keatinge 1983; Robertson et al. 2001), and sunflower (Conner et al. 1985). For rice crop of eastern coast of India, still there is a paucity of such type of information where farmers are heavily dependent on irrigated rice cultivation during post-flood/dry season. In rainy/wet season, farmers of the region struggle to grow rice because of seasonal flood.

Crop simulation model is one of the important tools to predict crop growth and productivity as a function of local weather, soil conditions, and crop management. (Ritchie et al. 1998; Jones et al. 2003; Bouman et al. 2007; Swain et al. 2007). CERES-Rice model was used to predict yield and productivity in many tropical and sub-tropical locations in Asia and Australia by many authors under different management practices (Alociljha and Ritchie 1991; Godwin et al. 1994; Jintrawat 1995; Ritchie et al. 1998; Hoogenboom et al. 2004; Sarkar and Kar 2006). But limited scientific information is available regarding the application of simulation model predicting crop growth and yield under two management factors like water and nitrogen management in post-flood period of coastal region of eastern India.

Keeping the importance of above points in view, in this investigation, attempt was made to study the variation of observed phenological events, crop growth (LAI and dry biomass), grain yield, radiation utilization efficiency, and latent heat flux under different water and nitrogen management practices. DSSAT 4.5 model was calibrated and validated to explore the possibility of predicting crop growth and yield of rice in the region during post-flood period under different nitrogen rate and water management practices.

Materials and methods

Study site

Two years on-farm experiments were conducted during post-flood period (December to March of 2007–08 and 2008–09) in a representative seasonal flood prone region of east coast of India (Alisha, Sattyabadi block, Puri, Odisha, India). The region receives 1,500 mm average annual rainfall, but 80 % of it occurs during rainy season (June–October) when flood occurs in the region. The saucer shaped land form, high rainfall due to southwest monsoon (June–September), and poor drainage condition make the region waterlogging during rainy season. During that period, farmers cannot cultivate rice successfully, as a result they depend on rice cultivation during post-flood dry season. After receding flood, the land remains dry from January to May because rainfall during post-flood period is meager and as a result successful crop cultivation is not possible without irrigation. In the region, mean maximum temperature ranges from 37 °C in May to 26 °C in December–January.

Crop management

A medium duration (120 days), high-yielding rice variety 'Lalat' was grown following standard package of practices in split plot design with three replications during two growing seasons. On 23rd December, and 20th December in 2007–08 and 2008–09, respectively, 21 days old seedlings were transplanted in hills spaced by 20 cm × 15 cm. The size of the individual plot being 4 m × 3 m. The treatments consisted of three water management practices viz., W_1 = continuously submerged of 5 cm depth, W_2 = intermittent submergence of 5 cm and irrigation after 2 days of disappearance of water from soil surface, and W_3 = intermittent submergence of 5 cm and irrigation after 5 days of water disappearance from the soil surface in main plots and five N fertilizer application rates, viz., N_1 = 0 kg N ha^{-1}, N_2 = 60 kg N ha^{-1}, N_3 = 90 kg N ha^{-1}, N_4 = 120 kg N ha^{-1}, and N_5 = 150 kg N ha^{-1} in sub-plots. Irrigation was necessary every 3 days under W_1 whereas it was required every 5–6 days under W_2 and every 8–9 days under W_3. The plots were isolated by ditches of 2.5 m to avoid lateral movement of water. The leaf length–width measurement technique with a correction factor was used to measure leaf area following the procedure of Yoshida 1981.

$$\text{Leaf area} = K \times \text{length (cm)} \times \text{width (cm)} \tag{1}$$

K correction factor ranges from 0.67 to 0.80 depending upon variety and growth stages of rice crop. After calibrating the values measured in the field using graph paper, the correction factor was fixed as 0.75 for measuring leaf area at active tillering, pancie initiation, and flowering stages of the crop. A sub-sample of green leaves and branches were oven dried to a constant weight at 80 °C for determining dry biomass.

Radiation utilization efficiency (RUE) and intercepted photosynthetically active radiation (IPAR)

The rate of increase of biomass density, B (g m^{-2}), is proportional to the absorbed photosynthetically active radiation, APAR (MJ m^{-2} d^{-1}) (Monteith 1977).

$$\frac{dB}{dT} = \varepsilon \text{ APAR} \tag{2}$$

where ε is the radiation use efficiency (RUE) (g MJ^{-1}). Hence, the cumulative biomass can be obtained by integrating equation (2):

$$B = B_0 + \varepsilon \text{ APAR} \tag{3}$$

where APAR is the cumulative absorbed PAR flux density and B_0 is the biomass density at time zero. Regression of B versus APAR should a linear regression line of slope ε and intercept zero, if no biomass is present prior to the start of photosynthesis (Pitman 2000). In this study, the dry biomass at different stages were measured and corresponding accumulated photosynthetically active radiation (APAR) were computed to estimate radiation utilization efficiency (RUE) using the following relationship:

$$\varepsilon \left(g \, M \, J^{-1}\right) = \frac{\sum B(g \, m - 2)}{\sum APAR(M \, J \, m - 2)} \qquad (4)$$

The mean daily values of solar radiation received above the crop canopy during different weeks of the crop growth were estimated using Penman (1948) formula and the photosynthetically active radiation (PAR) was calculated by multiplying it with 0.48 following Monteih (1972), Kailasanathan and Sinha (1984), Kar (2005). The calculations are as follows:

$$R_i = R_a \left(I - \alpha\right) \left(a + b \times n/N\right) \, cal \, cm^{-2} \, day^{-1} \qquad (5)$$

where, R_i incoming solar radiation, cal cm^{-2}, R_a radiation received at the top of atmospheric, cal cm^{-2}, A reflection coefficient (0.25 has been used for green crops), N maximum possible sunshine hours, a, b are constants, N actual bright sunshine hours.

The unit of APAR in cal cm^{-2} day^{-1} was converted into MJ m^{-2} s^{-1} as per the following relationships
1 cal m^{-2} min^{-1} = 697 J m^{-2} s^{-1},
1 kJ m^{-2} s^{-1} = 1.43 cal cm^{-2} min^{-1}

The intercepted PAR (IPAR) was measured using light transmission meter (EMS-7) as per the following relationship.

IPAR = incident radiation on the canopy − reflected radiation by the canopy − transmitted radiation through the canopy + reflected radiation from the ground.

IPAR (%) at any canopy height
$$= \frac{PAR \, received \, at \, any \, height \, of \, the \, canopy}{PAR \, incident \, above \, the \, crop \, canopy} \times 100 \qquad (6)$$

The PAR measurement was done in sunny days at different phenological stages at 11.30 am when disturbances due to leaf curling were minimum.

Latent heat flux and surface energy balance

Seasonal variation of main components of the energy balance equation viz., net radiation (R_n), latent heat flux (λE), sensible heat flux (H), and soil heat flux (G) were computed at periodic interval and measurement was confined to the plots fertilized with 120 kg N ha^{-1} and grown under two water management practices (W_2 and W_3) because of limitation in measurement. Bowen ratio (β) energy balance method was used to compute latent heat flux (Kar and Kumar 2007, 2009).

$$R_n = \lambda E + H + G \qquad (7)$$

$$\Rightarrow R_n - G = \lambda E \left(1 + \frac{H}{\lambda E}\right) = \lambda E \left(1 + \beta\right) \qquad (8)$$

Since,
$$\beta = \frac{Sensible \, heat \, flux \, (H)}{Latent \, heat \, flux \, (\lambda E)}$$

$$\lambda E = \frac{(R_n - G)}{(1 + \beta)} \qquad (9)$$

On the other hand,

$$Bowen \, ratio \, (\beta) = \frac{Sensible \, heat \, flux \, (H)}{Latent \, heat \, flux \, (\lambda E)} \qquad (10)$$

$$\beta = \frac{C_p P_a}{L\varepsilon} \frac{(T_2 - T_1)}{(e_2 - e_1)} \qquad (11)$$

where,
C_p: specific heat capacity of air (1 J g^{-1} °C^{-1})
P_a: Atmospheric pressure (101.3 kPa)
L: Latent heat of vaporization (2,449 J g^{-1})
ε: ratio of the molecular weight of water to that of air (0.622)

$$\beta = \frac{(1 \times 101.3)}{(2449 \times 0.622)} \frac{(T_2 - T_1)/z_2 - z_1}{(e_2 - e_1)/z_2 - z_1} = 0.067 \frac{(\delta T/\delta z)}{(\delta e/\delta z)} \qquad (12)$$

$R_n - G$ = available energy, T_1 is the temperature at height, z_1, T_2 is the temperature at height, z_2, e_1 is the vapor pressure at height, z_1, e_2 is the vapor pressure at height, z_2.

R_n was measured using BABUC M net radiometer where the hemispherical polyethylene windshield domes protect the net radiometer sensor devices. G was computed with the equation, $G = 0.4 \times R_n(Exp(-K_e \times LAI))$, where '$K_e$' is the extinction coefficient, LAI = leaf area index (Kar and Kumar 2007). Experiments show that the value of K_e ranged between 0.45 and 0.65 which was nearly equal to the extinction coefficient reported by (Uchijima 1976) within a rice canopy. The temperature, wind velocity, and humidity sensors (Weather Meter, Kestrel 2500) were installed inside the cropped field on a tower at a distance of 0.5 m which measures temperature, relative humidity, and wind velocity at 1-h interval at three different heights. The recorded output of all the sensors were downloaded with the help of a PC and analyzed.

Crop growth simulation using DSSAT model

The DSSAT 4.5 model was calibrated with the observed crop growth and yield data set of 2007–08, obtained from plots fertilized with 120 kg N ha^{-1}. The model performed good in simulation of growth, phenology, grain yield, and biomass during calibration process. To select the most suitable set of coefficients, an iterative approach proposed by Hunt et al. (1993) was used. A detailed description of the cultivar coefficients used for final calibration of the model 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 nitrogen treatments. The experimental data collected in 2008–09

season were used for independent model evaluation for predicting data for anthesis, maturity, grain yield, leaf area index, and total biomass.

Statistical analysis

The statistical analysis of the data was carried out using standard statistical techniques (Gomez and Gomez 1984). The analysis of variance (ANOVA) study of crop and instrumental observations was done using SAS 9.2 package. The significant differences between treatments were determined using Fisher's unrestricted least significant difference at $p = 0.05$.

Result

Soil profile information used for simulation

The measured soil profile data of the experimental field utilized as input for DSSAT model are presented in Table 2. The soil within the experimental area was found to be relatively homogeneous and soil texture is clayey in nature where clay content varied from 41.6 % (0.15–0.30 m) to 63.5 % (0.30-0.45 m). The bulk density was 1.45 Mg m^{-3} at 0–0.15 layer and it increased with soil depth, at 0.90–1.20 m layer, it was 1.63 Mg m^{-3}. The pH was slight to moderately acidic and no salt problem was detected in the soil. The organic carbon content was relatively higher (6.11 g kg^{-1}) at upper layer (0–15 cm) while at deeper layer it was 3.12 g kg^{-1}. The water content at field capacity was 0.452 m^3 m^{-3} at 0–0.15 m layer and the highest water content was 0.555 m^3 m^{-3} at 0.45–0.60 m soil depth.

Table 1 Genotype coefficients of rice variety 'Lalat' used for calibration

Genetic coefficients	Values
P1: time period in growing degree days (base 9 °C) from emergence to end of juvenile phase	565
P2R: photoperiod sensitivity (degree day delay per hour increase in day length)	118
P5: degree days (base 9 °C) from beginning of grain-filling (3–4 days after flowering) to physiological maturity	430
P2O: critical photo period (h)	10.5
G1: potential spikelet number coefficient as estimated from number of spikelets per g main culm + spike dry weight at anthesis (g)	63
G2: single dry grain weight (g)	0.028
G3: tillering coefficient	1
G4: temperature tolerance coefficient	1

Observed phenological development, crop, growth, and yield attributes

The effect of treatments on number of days to active tillering, panicle initiation, flowering/anthesis, and maturity are presented in Table 3. Water management effects were nonsignificant on days to active tillering, panicle initiation, days to flowering/anthesis and to maturity, but effect of nitrogen on these phenophases were found highly significant. Statistically minimum days to flowering (89.5 days) and maturity (118.9 days) were taken by plants when no nitrogen was applied (N_1). Average numbers of days to maturity were more in N_4 and N_5 with the duration being 125.6 and 126.5 days, respectively.

Observed growth and productivity of the crop as influenced by water management and irrigation regimes are also analyzed and are presented in Table 4. Water management effect on above ground dry biomass (AGDB) accumulation was non-significant between W_1 and W_2, but AGDM under W_3 was significantly reduced. On the other hand, AGDB production responded positively to nitrogen application. Averaged over sowing dates, maximum AGDB at maturity to value of 14,757 kg ha^{-1} was achieved in N_5 followed by in N_4 (14,561 kg ha^{-1}), N_3 (11,694 kg ha^{-1}), and N_2 (9,092 kg ha^{-1}) treatment which were statistically significant. The treatments N_4 and N_5 produced maximum plant height, LAI, and ultimately produced more biomass. Lowest LAI and AGDB were recorded when no nitrogen was applied (N_1).

No significant difference was observed between W_1 and W_2 in case of leaf area development, but in W_3 LAI was reduced significantly. Nitrogen application dose significantly affects maximum LAI for all the three stages studied (active tillering, panicle initiation, and flowering stages). At flowering time, averaged over years and water management practices, LAI reached to a value of 5.57 in the N_5 treatment followed by N_4 (5.34), N_3 (5.0), N_2 (3.91), and N_1 (2.59) treatments. Greater leaf expansion in rice was ascribed in N_4 and N_5 treatments due to higher growth rate and rapid leaf area development.

No significant yield difference was also achieved between W_1 and W_2 water management treatments, but under W_3 treatment yield was reduced significantly. Nitrogen dose significantly influenced grain yield. Highest grain yield (5,331 kg ha^{-1}) was obtained under N_5 nitrogen treatment which was statistically at par with N_4 (5,297 kg ha^{-1}). Results also showed that with increased nitrogen levels from 0 to 120 kg ha^{-1}, grain yield was increased significantly. Plots with 0 kg N ha^{-1} (N_1) produced significantly less grain yield (2,667 kg ha^{-1}) as compared to plots fertilized with 60 kg N ha^{-1} and above. Under N_2 (60 kg ha^{-1}) and N_3 (90 kg ha^{-1}), grain yield of 3,723 and 4,696 kg ha^{-1} were obtained, respectively.

Table 2 Measured soil profile data of the experimental field utilized as input of DSSAT 4.5 model for calibration and validation

Soil parameters	Soil profile depth (m)					
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	0.60–0.90	0.90–1.20
Lower limit ($m^3 m^{-3}$) of soil moisture	0.193	0.232	0.254	0.235	0.211	0.223
Upper limit, drained ($m^3 m^{-3}$) of soil moisture	0.452	0.532	0.555	0.472	0.488	0.448
Upper limit, saturated ($m^3 m^{-3}$) of soil moisture	0.586	0.637	0.641	0.594	0.592	0.554
Root growth factor (0–1)	1.000	1.000	0.607	0.497	0.368	0.172
Sat. hydraulic conductivity, macropore ($cm h^{-1}$)	39.3	3.24	7.87	1.63	1.63	1.63
Bulk density ($Mg m^{-3}$)	1.45	1.54	1.59	1.54	1.57	1.61
Organic carbon ($g kg^{-1}$)	6.11	5.01	5.25	4.95	3.85	3.12
Clay (<0.002 mm) (%)	41.6	61.6	63.5	51.2	49.2	47.2
Silt (0.05–0.002) (%)	25.4	17.1	11.3	21.2	23.3	21.2
pH in water	6.8	6.8	6.2	6.3	6.4	6.5

Table 3 Duration of important phenological stages as influenced by water management and irrigation regimes

Factors	Days to active tillering	Days to panicle initiation	Days to flowering/anthesis	Days to maturity
Water management (W)				
W_1	42.2[a]	59.1[a]	93.2[a]	122.1[a]
W_2	43.3[a]	59.2[a]	93.8[a]	123.4[a]
W_3	43.3[a]	59.5[a]	92.8[a]	122.8[a]
Significance	NS	NS	NS	NS
Nitrogen levels (N)				
N_1	40.0[d]	56.7[d]	89.5[e]	118.9[d]
N_2	42.1[c]	57.8[c]	91.3[d]	121.3[c]
N_3	43.2[b]	59.2[b]	94.2[c]	123.6[b]
N_4	44.7[a]	62.6[a]	95.6[b]	125.6[a]
N_5	44.7[a]	62.5[a]	97.6[a]	126.5[a]
Significance	**	**	**	**
$W \times N$	NS	NS	NS	NS

The values in the column followed by same letters are not significant at 5 % level of significance

S significant, NS not significant, W_1 continuous flooding of 5 cm, W_2 irrigation after 2 days of water disappearance, W_3 irrigation after 5 days of water disappearance, N_1 0 kg N ha^{-1}, N_2 60 kg N ha^{-1}, N_3 90 kg N ha^{-1}, N_4 20 kg N ha^{-1}, N_5 150 kg N ha^{-1}

* Significant at 1 % level of significance; ** significant at 5 % level of significance

Intercepted photosynthetically active radiation (IPAR)

The IPAR was measured at different phenological stages and peak values of it as influenced by water management and nitrogen application are depicted in Figs. 1 and 2, respectively. Study revealed that IPAR (%) was higher in boot leaf stage (coincided with maximum leaf area index) followed by flowering stage. In regard to water management practices, peak intercepted PAR were 83.9 and 82.6 % for W_1 and W_2, respectively, which was significantly different from W_3. But the differences were found to be non-significant between W_1 and W_2 water management treatments.

Nitrogen levels significantly affected the amount of peak radiation intercepted. Averaged over years and water

management practices, mean peak IPAR was 92.4 % when plots were fertilized with 150 kg N ha^{-1} (N_5) followed by N_4 plots (90.8 %) which were not significantly different. The IPAR of 69.3, 73.5, and 69.3 % was recorded with 0, 60 and 90 kg N ha^{-1}. The increase in IPAR (%) with higher level of nitrogen was due to better crop growth, which produced maximum plant height, LAI, and total dry matter.

Radiation utilization efficiency in terms of total biomass

The Radiation Utilization Efficiency (RUE) in terms of total above ground dry biomass was computed as per the procedure mentioned in materials and methods and RUE as

Table 4 Crop growth and productivity of rice (cv Lalat) as influenced by water management and irrigation regimes

Factors	LAI$_{AT}$	LAI$_{PI}$	LAI$_{FL}$	BDB$_{AT}$ (kg ha^{-1})	ABDB$_{PI}$ (kg ha^{-1})	ABDB$_{FL}$ (kg ha^{-1})	ABDBM$_{AT}$ (kg ha^{-1})	Grain yield (kg ha^{-1})
Water management (W)								
W_1	1.37[a]	4.26[a]	4.72[a]	563[a]	3617[a]	7182[a]	11577[a]	4524[a]
W_2	1.34[a]	4.21[a]	4.73[a]	556[a]	3584[a]	7112[a]	11520[a]	4440[a]
W_3	1.11[b]	3.55[b]	3.83[b]	475[b]	3271[b]	6218[b]	10092[b]	4064[b]
Significance	*	**	*	*	**	**	**	**
Nitrogen levels (N)								
N_1	0.514[d]	2.21[d]	2.59[d]	390[d]	2050[d]	4775[d]	7228[d]	2667[d]
N_2	0.928[c]	3.07[c]	3.91[c]	495[c]	2953[c]	5368[c]	9092[c]	3723[c]
N_3	1.61[b]	4.67[b]	5.0[b]	539[b]	3268[b]	7195[b]	11694[b]	4696[b]
N_4	1.65[a]	5.01[a]	5.34[a]	615[a]	4566[a]	8438[a]	13561[a]	5297[a]
N_5	1.69[a]	5.26[a]	5.57[a]	622[a]	4614[a]	8510[a]	13757[a]	5331[a]
Significance	**	**	**	**	**	**	**	**
Interaction: $W \times N$	NS	NS	NS	NS	NS	NS	NS	NS

The values in the column followed by same letters are not significant at 5 % level of significance

S significant, *NS* not significant, *LAI$_{AT}$* LAI at active tillering stage, *LAI$_{PI}$* LAI at panicle initiation stage, *LAI$_{FL}$* LAI at flowering stage, *ABDB$_{AT}$* above ground biomass at active tillering stage, *ABDB$_{PI}$* above ground biomass at panicle initiation stage, *ABDB$_{FL}$* above ground biomass at flowering stage, *ABDBM$_{AT}$* above ground biomass at maturity stage

* Significant at 1 % level of significance; ** significant at 5 % level of significance
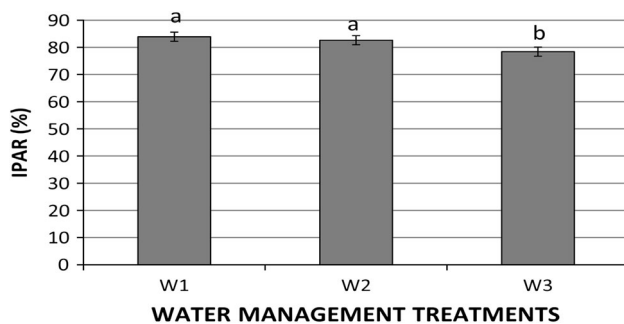

Fig. 1 Peak values of intercepted photosynthetically active radiation (IPAR) as influenced by water management treatments (pooled data of 2 years). The column followed by same letters are not significant at 5% level of significance
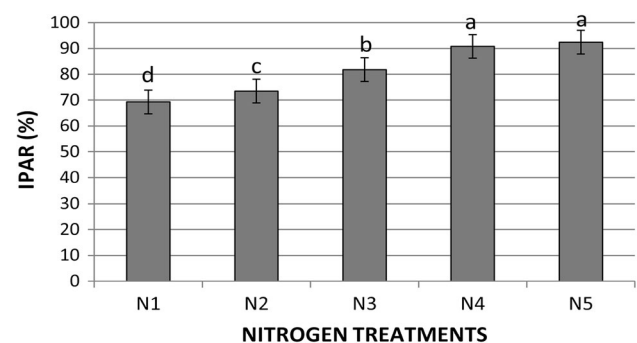

Fig. 2 Peak values of intercepted photosynthetically active radiation (IPAR) as influenced by nitrogen treatments (pooled data of 2 years). The column followed by same letters are not significant at 5% level of significance

influenced by water management and nitrogen applications are presented in Figs. 3 and 4, respectively. Among water management practices, W_3 plots registered lower RUE of 1.90 g MJ^{-1} for AGDM accumulation as compared to other W_1 (2.09 g MJ^{-1}) and W_2 (2.10 g MJ^{-1}). Significant differences were found in RUE among N treatments. High dose of *N* increased RUE significantly, mean RUE vales were computed as 1.60, 1.78, 2.06, 2.30, and 2.34 g MJ^{-1} for N_1 (0 kg N ha^{-1}), N_2 (60 kg N ha^{-1}), N_3 (90 kg N ha^{-1}), N_4 (120 kg N ha^{-1}), and N_5 (150 kg N ha^{-1}) treatments, respectively. The lower values of mean RUE was registered from plots fertilized with 0 and 60 kg N ha^{-1} (N_1 and N_2), which might be attributed to less biomass and grain yield in those plots. Interaction

between water management practices and nitrogen rate were found to be non-significant.

Radiation utilization efficiency in terms of grain yield

The effects of water management and nitrogen treatments on radiation use efficiency for grain yield (RUEgy) are presented in Figs. 5 and 6, respectively. Similar trend was observed in this case also like radiation utilization efficiency in terms of above ground dry biomass. The values of RUEgy recorded were 0.69, 0.68, and 64 g MJ^{-1} in W_1, W_2, and W_3, respectively, which indicated that RUEgy between W_1 and W_2 are not significantly different. Nitrogen application doses also significantly affect radiation
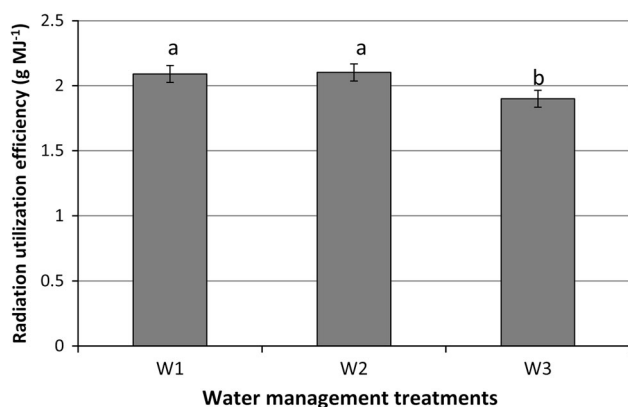
Fig. 3 Radiation utilization efficiency of rice (cv. LaIat) in terms of total above ground dry biomass as influenced by water management treatments (pooled data of 2 years). The column followed by same letters are not significant at 5% level of significance
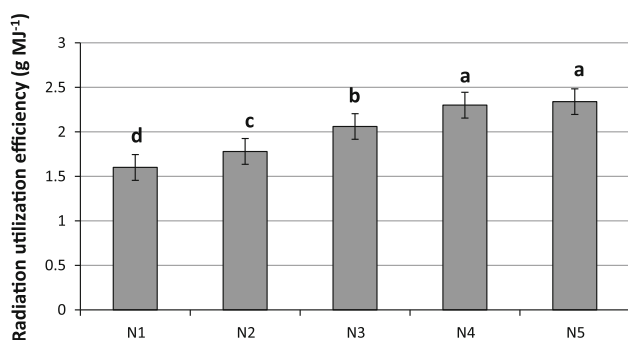

Fig. 4 Radiation utilization efficiency of rice (cv. Lalat) in terms of total above ground dry biomass as influenced by nitrogen treatments (pooled data of 2 years). The column followed by same letters are not significant at 5% level of significance
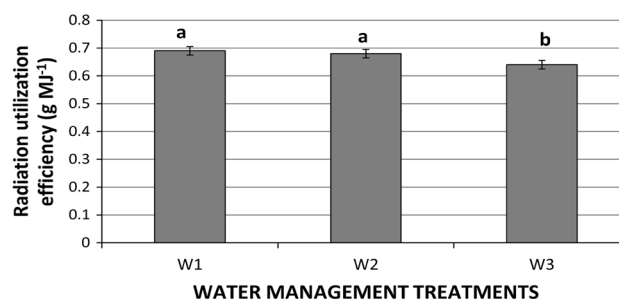

Fig. 5 Radiation utilization efficiency of rice (cv. LaIat) in terms of grain yield as influenced by water management treatments (pooled data of 2 years). The column followed by same letters are not significant at 5% level of significance
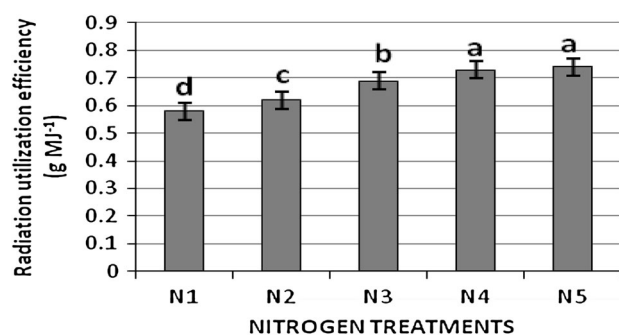

Fig. 6 Radiation utilization efficiency of rice (cv. LaIat) in terms of grain yield as influenced by nitrogen treatments (pooled data of 2 years). The column followed by same letters are not significant at 5% level of significance

utilization efficiency in terms of grain yield. Averaged over years and water management treatments, maximum RUEgy was recorded by N5 treatment (0.74 g MJ^{-1} RUEgy). The radiation use efficiency for grain yield (RUEgy) was computed as 0.58, 0.62, 0.69, and 0.73, g MJ^{-1} for N_1, N_2, N_3, and N_4 treatments, respectively, which were significantly different.

Crop evapo-transpiration and water use efficiency

Water-use efficiency (WUE) is a common expression of plant productivity. It may represent the ratio of total above ground dry biomass or dry seed weight to the seasonal evapotranspiration (ET). With this approach, different cultural practices can be assessed to determine optimum use of limited irrigation water. Based on latent heat flux evapotranspiration of the crop grown with 120 kg N ha^{-1}

under W_2 and W_3, water management treatments were computed and results are depicted in Figs. 7 and 8 for the year 2007–08 and 2008–09, respectively. Crop evapo-transpiration (ETc) was found to be the highest at boot leaf stage which ranged from 5.95 mm day^{-1} under W_3 to 6.08 mm day^{-1} under W_3 in 2007–08. In 2008–09, the ETc ranged from 5.75 mm day^{-1} under W_3 to 6.44 mm day^{-1} under W_2. Total crop ETc was computed as 622 and 598 mm under W_2 and W_3, respectively, in 2007–08 and in 2008–09 total crop ETc were 632 and 608 mm under W_2 and W_3, respectively. Crop water-use efficiency (pooled data of 2 years) was computed in terms of both total biomass and grain yield and are presented in Figs 9 and 10, respectively. Crop water use efficiencies of 8.67 and 8.07 kg ha^{-1} mm^{-1} (in terms of grain yield) were obtained under W_2 and W_3 water management treatments, respectively, when the crop was grown with 120 kg N ha^{-1}. Whereas, crop water use efficiencies of 22.6 and 22.1 kg ha^{-1} mm^{-1} (in terms of total biomass) were obtained under W_2 and W_3 water management treatments, respectively, with same nitrogen treatment.

Fig. 7 Crop evapo-transpiration of rice during 2007–08 under W_2 and W_3 water management with 120 kg N ha^{-1}
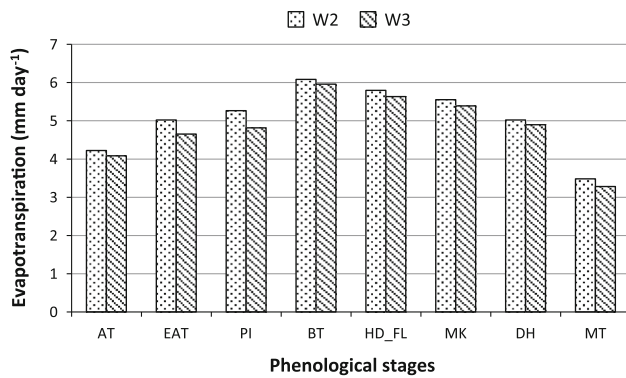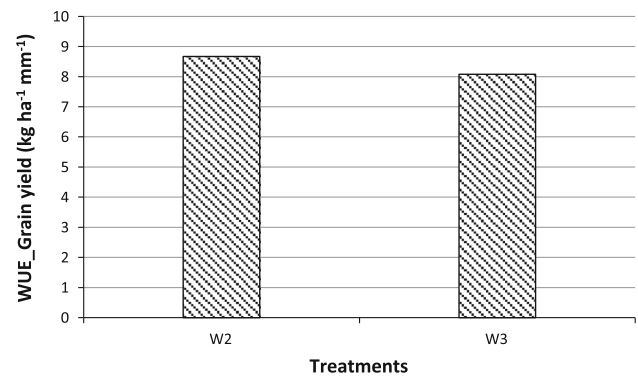

Fig. 8 Crop evapo-transpiration of rice during 2008–09 under W_2 and W_3 water management with 120 kg N ha^{-1}

Fig. 9 Crop water use efficiency of rice (cv. Lalat) in terms of grain yield with 120 kg N ha^{-1} under W_2 and W_3 water management treatments

Latent heat flux and surface energy balance

The seasonal variation of surface energy flux over rice stand grown with 120 kg ha^{-1} during two seasons (2007–08 and 2008–09) were measured at periodic intervals under W_2 and W_3 plots and mid day average values of 10.00–15.00 h are depicted in Figs. 11, 12, 13, and 14.

Fig. 10 Crop water use efficiency of rice (cv. Lalat) in terms of total above ground biomass with 120 kg N ha^{-1} under W_2 and W_3 water management treatments
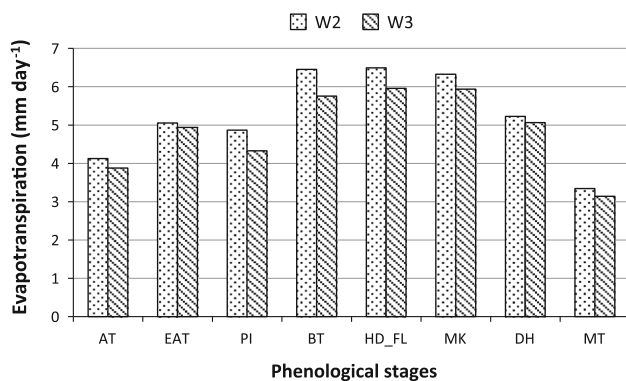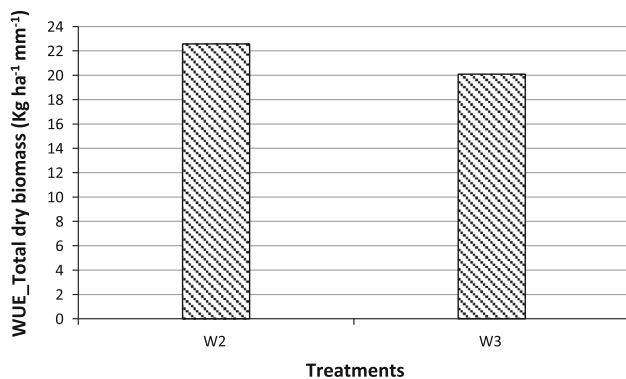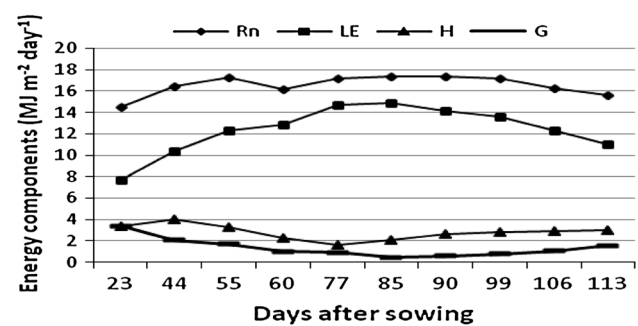

Fig. 11 Latent heat flux and surface energy balance of rice (cv. LaIat) under W_2 water management during 2007–08
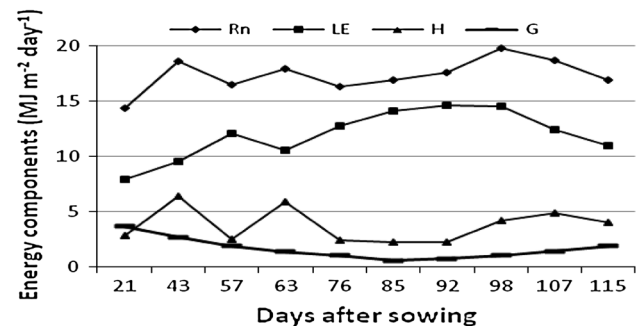

Fig. 12 Latent heat flux and surface energy balance of rice (cv. LaIat) under W_3 water management during 2007–08

Study revealed that during growing period, net radiation (R_n) varied from 14.5 to 17.4 MJ m^{-2} day^{-1} in 2007–08. In 2008–09, the net radiation varied from 14.4 to 18.7 MJ m^{-2} day^{-1}.

The latent heat flux (LE) was largely found to be varied with leaf area index (LAI) which showed peak when LAI was maximum. In 2007–08, under W_2 treatment, the mid-day average latent heat flux (on clear days) varied from 7.7 MJ m^{-2} day^{-1} (during transplanting stage) to
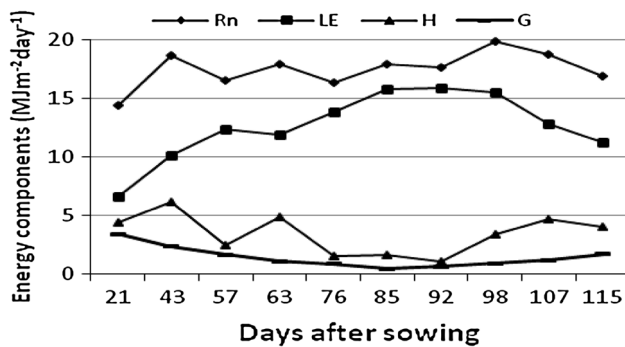
Fig. 13 Latent heat flux and surface energy balance of rice (cv. LaIat) under W_2 water management during 2008–09
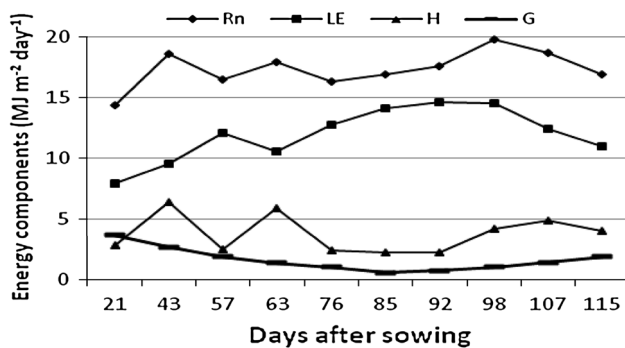

Fig. 14 Latent heat flux and surface energy balance of rice (cv. LaIat) under W_3 water management during 2008–09

14.8 MJ m^{-2} day^{-1} (during boot leaf stage to flowering stage). Whereas in W_3 treatment, it varied from 8.0 to 13.6 MJ m^{-2} day^{-1} in different rice growth stages. In 2008–09, the LE ranged from 6.6 to 15.9 MJ m^{-2} day^{-1} in different growth stages of the crop under W_2 water management treatment and 7.9 to 14.3 MJ m^{-2}day^{-1} under W_3 treatment.

The variation of soil heat flux (G) of the crop during growth seasons clearly reflects the change of crop growth. The 'G' showed peak value during early vegetative and maturity growth stages when crop coverage was minimum and soil was dry. Afterward, the course of 'G' was affected by development of crop canopy or leaf area index. Midday average 'G' value of the crop ranged from 0.46 to 3.4 MJ m^{-2} day^{-1} in 2008–09 and 0.45 to 3.39 MJ m^{-2} day^{-1} in 2007–08 under W_2 treatment. Whereas, in W_3, it ranged from 0.60 to 3.59 MJ m^{-2} day^{-1} in 2007–08 and varied from 0.56 to 3.65 MJ m^{-2} day^{-1} in 2008–09. The 'G' reduced drastically with the increasing canopy cover and growth. The ratio of G/R_n from maximum LAI to senescence stage was found to be 7–13.5 % over the crop. Soil heat flux showed declining trend during the peak growth stage which coincided with maximum leaf area index (LAI).

Crop growth modeling

Cultivar genetic coefficients and calibration of the model

Calibration results showed that model predicted number of days to flowering with the error of 1.05, 2.10, and 3.19 % for W_1, W_2, and W_3 water management treatments, respectively. Only 1–3 days difference was recorded between observed and simulated days to flowering under different water management practices. The model simulated number of days from planting to physiological maturity with error of −0.80, 0.79, and 1.58 % under W_1, W_2, and W_3 treatments, respectively. In calibrating leaf area index, the model under estimated the maximum LAI and simulated with the larger errors of −6.51, −9.01, and −6.25 % under W_1, W_2, and W_3 treatments, respectively. There was a good agreement between observed and simulated above ground biomass at harvest with the error ranging from −0.52 % for W_1, −0.62 % for W_2, and −1.63 % for W_3. The simulation of grain yield was also well correlated with the error of −0.37, 0.62, and 1.91, among simulated and observed values under W_1, W_2, and W_3 treatments, respectively.

Model evaluation

Accuracy of the model simulations and performance of genetic coefficients were assessed by running the model with data sets of 2007–08 against nitrogen treatments 0, 60, 90, and 150 kg ha^{-1}. Study revealed that the time for flowering/anthesis was delayed by 1–5 days with increase in N level under different water management treatments. At higher N rate (150 kg N ha^{-1}), days to anthesis were closely predicted with the error of 0 to −1.07 %. At low N levels (0 and 60 kg ha^{-1}), there were greater differences between predicted and observed values and the error between simulated and observed values were 4.44 to 5.68 %. This showed that days to anthesis were affected by N rates, but the model is not able to predict the days to anthesis closely under N stress conditions because DSSAT model might assume optimum N conditions in predicting crop phenology. Similar trend was observed in simulation of days to maturity, yield, dry biomass, and leaf area index also. In general, error between simulated and observed values were closer at higher nitrogen levels (90 kg N ha^{-1} and above) as compared to lower applied dose (0 and 60 kg N ha^{-1}). Among different plant attributes, larger percentage of errors was observed in predicting the maximum leaf area index.

Further, validity of DSSAT model was evaluated by comparing simulated and observed data collected during year 2008–09 under five nitrogen rates viz., 0, 60, 90, 120, and 150 kg N ha^{-1}. The corresponding simulation results of grain yield are shown in Table 5. There was good

Table 5 Comparison of simulated and observed crop parameters with 0, 60, 90, 120, and 150 kg N ha^{-1} in 2008–09

Nitrogen (kg ha^{-1})	W_1			W_2			W_3		
	OBS	SIM	Error (%)	OBS	SIM	Error (%)	OBS	SIM	Error (%)
Comparison of simulated and observe days to anthesis at different nitrogen levels									
0	89	96	5.61	90	94	4.44	89	94	4.49
60	92	95	3.22	91	95	4.39	90	94	4.44
90	94	95	1.06	94	95	1.06	93	93	0
120	95	96	1.05	96	97	1.04	95	96	1.05
150	97	97	0	98	97	−1.02	97	98	1.03
Comparison of simulated and observe days to maturity at different nitrogen levels									
0	118	124	5.08	120	115	−4.10	120	125	5.04
60	120	124	3.83	121	125	3.31	120	124	4.16
90	124	125	0.83	124	125	1.61	124	123	−0.81
120	126	127	0.79	126	125	−0.79	126	125	−0.79
150	127	127	−0.78	127	127	0	126	126	0
Comparison of simulated and observe maximum leaf area index at different nitrogen levels									
0	2.75	2.53	−3.63	2.75	2.80	9.45	2.23	2.50	4.03
60	3.88	3.45	−11.08	4.11	4.35	−13.62	2.89	3.45	10.57
90	5.10	4.90	−3.92	5.20	5.45	4.80	4.43	4.50	1.58
120	5.82	5.55	−4.63	5.86	5.89	0.511	4.60	4.63	0.65
150	5.97	5.65	−5.36	5.99	5.95	−0.66	4.73	4.75	0.42
Comparison of simulated and observe mean total biomass (kg/ha) at different nitrogen levels									
0	7,453	7,055	−5.34	7,850	7,454	−5.04	6,369	6,100	−4.22
60	9,405	8,935	−4.99	9,299	8,922	−4.01	8,551	8,035	−6.03
90	12,305	12,102	−1.64	11,911	11,850	−0.51	10,816	10,750	−0.61
120	14,325	13,459	−6.04	14,209	14,120	−0.62	12,133	12,247	0.93
150	14,357	14,120	−1.65	14,334	14,160	−1.21	12,563	12,500	−0.50
Comparison of simulated and observe mean total grain yield (kg/ha) at different nitrogen levels									
0	2,840	2,545	−10.38	2,717	2,477	8.83	2,461	2,655	7.88
60	3,819	3,515	−7.91	3,775	3,546	6.06	3,530	3,750	6.23
90	4,853	4,800	−1.09	4,758	4,705	1.11	4,418	4,346	−1.62
120	5,385	5,312	−1.35	5,450	5,422	0.51	4,910	5,023	2.30
150	5,458	5,400	−1.06	5,458	5,512	0.68	4,953	5,074	2.44

agreement between observed and simulated grain yield under 90 N kg ha^{-1} and above nitrogen levels.

These results showed the model was able to predict the rice phenology accurately at higher N levels, but under N stress conditions, there could be greater deviations in model predictions. For accurate phenology and crop growth predictions in N-deficient tropical soils, a N stress factor needs to be incorporated into the model for farmers and researchers to be able to use it with confidence. Similar recommendations were given by Kiniry (1991) in maize crop.

Discussion

Rice (*Oryza sativa* L.) is a major food grain crop of India and in eastern coast of India there are many factors responsible for low yield of rice such as plant density, sowing time, imbalanced fertilizer application water deficit, etc. Among various factors, the growth and yield of a crop can be adversely affected by deficient nitrogen because it plays a central role in plant growth as an essential constituent of cell components. The crop matured early (119 days) when no nitrogen was applied, whereas, higher doses of nitrogen (90 kg ha^{-1} and above) delayed the crop maturity period by 5–8 days. The probable reason could be that nitrogen had enhanced vegetative growth, which delayed reproductive stage. Nitrogen significantly influenced the performance of crop growth parameters like leaf area index, biomass, etc. Greater LAI could be attributed to significant increases in leaf expansion i.e., length and breadth due to high N levels. Greater leaf expansion due to more nitrogen was ascribed to higher rate

of cell division and cell enlargement by Wright (1982). Total dry matter (TDM) production increased steadily after crop establishment until maturity in all the treatments. The increase in TDM with higher level of nitrogen was due to better crop growth, which gave maximum plant height, LAI, and ultimately produced more biological yield. Increased plant height in rice with the increasing levels of *N* fertilizer may be attributed to greater supply of nitrogen resulting in increased nitrogen metabolism. Nitrogen stress in plots fertilized with lesser levels of nitrogen might be the cause of less LAI that leads to lower radiation interception, growth rate, radiation utilization efficiency, and therefore, grain number and yield. This appeared to increase the length of internodes resulting in higher plant height when nitrogen was optimally used and less plant height was observed at lower levels of nitrogen (Schinir et al. 1990; Dingkuhn et al. 1990).

Declining water quality and quantity are also major concerns for sustainability of irrigated rice-based production system in Aisa. Our study revealed that continuous flooding of 5-cm depth (W_1) and irrigation after 2 days of disappearance of water (W_2) produced biomass, leaf area and yield satistically at par, but irrigation after 5 days of disappearance of water (W_3) resulted significant reduction in dry biomass and yield. Under W_3 conditions, water availability might not matched with the water required for satisfying the outflows (seepage, S, and percolation, P) to the surroundings and depletions to the atmosphere (evaporation, E, and transpiration, T) (De Datta 1981; Tuong et al. 1996; Tuong 1999). Working in different parts of India, similar findings also reported by many earlier workers (Sandu et al. 1980; Tripathi et al. 1986; Mishra et al. 1997; Singh et al. 2001). Tabbal et al. (2002) reported that in transplanted and wet seeded rice, keeping the soil continuously around saturation reduced yields on an average by 5 % and water inputs by 35 % and increased water use efficiency by 45 % compared with flooded conditions.

It was observed that during mid-growth stage when canopy is fully developed and water does not limit transpiration (soil is wet), latent heat flux consumes most of the energy from net radiation. As the soil dries toward the maturity period, water becomes less available for evapotranspiration. At the beginning, when the crop was not developed fully, the sensible heat flux or soil heat flux was higher and these values were decreased with the increase of canopy growth. Similar observations were reported by Perez et al. (1999), Mo and Liu (2001), Figuerola and Berliner (2006).

Another prerequisite for high yields is a high production of total dry matter (TDM) per unit area that can be attained through optimizing the assimilate area i.e., leaf area index (LAI) to intercept more PAR and improving the radiation use efficiency. In this study, average maximum radiation utilization efficiency (RUE) in terms of above ground dry biomass of 2.09 ($\pm$0.05), 2.10 ($\pm$0.02), and 1.9 ($\pm$0.08) g MJ^{-1} were computed under W_1, W_2, and W_3, respectively. Higher dose of nitrogen increased the RUE significantly, mean RUE values were computed as 1.60 ($\pm$0.07), 1.78 ($\pm$0.02), 2.060 ($\pm$0.08), 2.30 ($\pm$0.07), and 2.34 ($\pm$0.08) g MJ^{-1} when the crop was grown with 0, 60, 90, 120, and 150 kg ha^{-1} nitrogen, respectively. RUE in terms of above ground dry biomass was found to be smaller in nitrogen and water stressed plots. Averaged over year and water management practices, peak intercepted photosynthetically active radiation (IPAR) of 69.3, 73.5, 81.8, 90.8, and 92.4 % was measured under 0, 60, 90, 120, and 150 kg ha^{-1} nitrogen, respectively. The RUE of C_3 crops were computed within the range of 1.2–1.93 g MJ^{-1} for different parts of the world, example (1.2–2.93 g MJ^{-1}) for wheat (Kiniry et al. 1989; Siddique et al. 1989; Gregory and Eastham 1996). Reported RUE for pea ranged from 0.91 to 2.50 g MJ^{-1} (Martin et al. 1994; Jannink et al. 1996; Thomson and Siddique 1997). Siddique et al. (1989) found that RUE (based on above ground biomass) was smaller for a given biomass if a greater proportion of biomass is partitioned to roots. Hamblin et al. (1990) and Jamieson et al. (1995) suggested that often more successful environments have higher root–shoot ratios that lead to lower RUE estimates based on above ground dry biomass. Investigation of crop root–shoot dynamic would permit determination of the partitioning factor for biomass/PAR relations.

CERES-Rice has been evaluated for many tropical and sub-tropical locations across Asia and in temperate climates in Japan and Australia. In this study over the data sets examined for validating phenology, crop growth and yield, the of CERES-Rice embedded DSSAT 4.5 model predicted fairly well at higher dose of nitrogen, but model performance was poor under conditions of low nitrogen. The model also underestimated leaf area index under all conditions. Under the conditions of Philippines, Alociljha and Ritchie (1991) reported good agreement between observed and predicted number of days to anthesis and maturity, with RMSE of 4 and 3 %, respectively. Tongyai (1994) concluded that the number of days to physiological maturity was overestimated by 9–12 days in Bangkok. Jintrawat (1995), however, reported accurate predictions of phenology for both photoperiod sensitive and insensitive cultivars, but the heading dates were underestimated for a photo-sensitive cultivar, especially for early planting dates. The capability to simulate photoperiod effects has since been included in CERES-Rice. At temperate and subtropical locations in Japan (Seino 1995), the model predicted days to physiological maturity of unspecified cultivars quite well, with normalized RMSE = 2 % and D-index = 1.0. In sub-tropical northwest India (Timsina et al. 1995), the absolute RMSE for both anthesis and maturity was 6 days, but D-index was 0.72 for anthesis and

0.96 for maturity, indicating less satisfactory performance of the model. In south India (Saseendran et al. 1998a, b), prediction of anthesis was less accurate with RMSEs of Jaya and IR8 of 4.4 and 4.2 days, and D-index = 0.65 and 0.84, respectively. Mall and Aggarwal (2002) compared the performance of CERES-Rice and ORYZA1N at 11 locations from north to south India, including four in northwest India. Predicted values were within 15 % of observations for both models, with similar RMSE of 4.5 days (CERES-Rice) and 4.8 days (ORYZA1N).

Conclusion

The crop matured early (119 days) when no nitrogen was applied, whereas, higher doses of nitrogen (90 kg ha^{-1} and above) delayed the crop maturity period by 5–8 days. The probable reason could be that nitrogen had enhanced vegetative growth, which delayed reproductive stage. Nitrogen significantly influenced the performance of crop growth parameters like leaf area index, biomass, etc. Greater LAI could be attributed to significant increases in leaf expansion i.e., length and breadth due to high N levels. Greater leaf expansion due to more nitrogen was ascribed to higher rate of cell division and cell enlargement. The increase in RUE and IPAR with higher level of nitrogen was due to better crop growth, which produced maximum plant height, LAI, and total dry matter. No significant difference in crop growth and development was achieved between W_1 (continuous flooding of 5 cm) and W_2 (irrigation after 2 days of water disappearance), but significant difference was obtained in biomass and yield production when the crop was grown under W_3 (irrigation after 5 days of water disappearance).

References

Alberto MCR, Wassmann R, Hirano T, Miyata A, Kumar A, Padre A, Amante M (2009) CO_2/heat fluxes in rice fields: comparative assessment of flooded and non-flooded fields in the Philippines. Agric For Meteorol 149:1737–1750

Alociljha EC, Ritchie JT (1991) A model for the phenology of rice. In: Hodges T (ed) Predicting crop phenology. CRC Press, Boca Raton, pp 181–189

Belder P, Bouman BAM, Cabangon R, Lu G, Quilang EJP, Li Y, Spiertz JHJ, Tuong TP (2004) Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. Agric Water Manag 65:193–210

Bouman BAM, Feng L, Tuong TP, Lu G, Wang H, Feng Y (2007) Exploring options to grow rice under water-short conditions in Northern China using a modeling approach. II: quantifying yield, water balance components and water productivity. Agric Water Manag 88:23–33

Conner DJ, Jones TR, Palla JA (1985) Response of sunflower to strategies of irrigation. I. Growth, yield and efficiency of water use. Field Crop Res 10:15–36

De Datta SK (1981) Principles and practices of rice production. International Rice Research Institute, Los Baños, p 618

Dingkuhn M, Penning de Vries FWT, De Datta SK, Van Laar HH (1990) Concepts for a new plant type for direct seeded flooded tropical rice. In: Direct seeded flodded rice in the tropics. International Rice Resaerch Institute, Los Banos, Philippines, pp 17–38

Fageria NK, Baligar VC, Jones CA (1997) Growth and mineral nutrition of field crops, 2nd edn. Marcel Dekker, New York

Figuerola PI, Berlinger PR (2006) Characterization of the surface layer above a row crop in the presence of local advection. Atmosfera 19:75–108

Gallaghar JN, Biscoe PV (1978) Radiation absorption, growth and yield of cereals. J Agric Sci Camb 91:47–60

Godwin DC, Meyer WS, Singh U (1994) Simulation of the effect of chilling injury and nitrogen supply on floret fertility and yield in rice. Aust J Exp Agric 34:921–926

Gomez KA, Gomez AA (1984) Statistical procedures for agricultural research with spatial emphasis on rice. International Rice research, Philippines

Gregory PJ, Estham J (1996) Growth of shoot and roots, and interception of radiation by wheat and lupin crops on a shallow, duplex soil in response to time of sowing. Aust J Agric Res 47:427–447

Gregory PJ, Tennant D, Belford RK (1992) Root and shoot growth and water and light use efficiency of barley and wheat crop grown on a shallow duplex soil in Mediterranean—type environment. Aust J Agric Res 43:555–573

Hamblin A, Tennant D, Perry MW (1990) The coast of stress: dry matter partitioning changes with seasonal supply of water and nitrogen to dry land wheat. Plant Soil 122:47–58

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Batchelor WD, Hunt LA, Boote KJ, Singh U, Uryasev O, Bowen WT, Gijsman AJ, du Toit A, White JW, Tsuji GY (2004) Decision support system for agrotechnology transfer version 4.0 [CD-ROM]. University of Hawaii, Honolulu

Hughes G, Keatinge JDH (1983) Solar radiation interception, dry matter production and yield in pigeonpea (Cajanus cajan (L.) Millspaugh). Field Crop Res 6:171–178

Hunt LA, Pararajasingham S, Jones JW, Hoogenboom G, Imamura DT, Ogoshi RM (1993) GENCALC: software to facilitate the use of crop models for analyzing field experiments. Agron J 85:1090–1094

Jamieson PD, Martin RJ, Francis GS, Wilson DR (1995) Drought effects on biomass production and radiation use efficiency in barley. Field Crop Res 43:77–86

Jannink JL, Liebman M, Merrick LC (1996) Biomass production and nitrogen accumulation in pea, oat and vetch green manure mixture. Agron J 88:231–240

Jintrawat A (1995) A decision support system for rapid assessment of lowland rice-based cropping alternatives in Thailand. Agric Syst 47:245–258

Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT (2003) DSSAT cropping system model. Eur J Agron 18:235–265

Kailashnathan K, Sinha SK (1984) Radiation, productivity potential and actual biology yield at Delhi. Proc Indian Nat Sci Acad B 46(5):688–693

Kar G (2005) Radiation interception, rainwater and radiation utilization efficiency study of legume based intercropping in

rainfed upland rice area of eastern India. J Agrometeorol 7(1):84–89

Kar G, Kumar A (2007) Surface energy fluxes and crop water stress index in groundnut under irrigated ecosystems. Agric For Meteorol 146(1–2):94–106

Kar G, Kumar Ashwani (2009) Energy balance and crop water stress in winter maize under phenology-based irrigation scheduling. Irrigation Sci 28:211–220

Kiniry JR (1991) Maize phasic development. In: Hanks J, Ritchie JT (eds) Modeling plant and soil systems. Agronomy monograph no. 31. ASA, CSSA, and SSSA, Madison, pp 55–70

Kiniry JR, Jonnes CA, O'Toole JC, Blanchet R, Cabelguenne M, Spanel DA (1989) Radiation—use efficiency in biomass accumulation prior to grain—filling for five grain crop spices. Field Crop Res 20:51–54

Mall RK, Aggarwal PK (2002) Climate change and rice yields in diverse agro-environments of India.I. Evaluation of impact assessment models. Clim Change 52:315–330

Martin GB, Frary A, Wu T, Brommonschenkel SH, Earle ED, Tanksley SD (1994) A member of the tomato *Pto* gene family confers sensitivity to fenthion resulting in rapid cell death. Plant Cell 6:1543–1552

Maruyama A, Kuwagata T (2010) Coupling land surface and crop models to estimate the effects of changes in the growing season on energy balance and water use of rice paddies. Agric For Meteorol 150:919–930

Mishra HS, Rathore TR, Pant RC (1997) Root growth, water potential, and yield of irrigated rice. Irrigation Sci 17(2):69–75

Mo X, Liu S (2001) Simulating evapotranspiration and photosynthesis of winter wheat over the growing season. Agric For Meteorol 109:203–222

Monteith JL (1972) Solar radiation and productivity in tropical ecosystem. J Appl Ecol 9:747–766

Monteith JL (1977) Climate and efficiency of crop production in Britain. Philos Trans of R Soc Lond B 281:277–294

Perez PJ, Castelly IF, Ibanez M, Russel J (1999) Assessment of reliability of Bowen method for partitioning fluxes. Agric For Meteorol 97:141–150

Pitman JI (2000) Absorption of photo-synthetically active radiation, radiation use efficiency and spectral reflectance of bracken [*Pteridium aquilinum* (L.) Kuhn] canopies, Ann Bot 85 (Supplement B):101–111

Ritchie JT, Singh U, Godwin DC, Bowen WT (1998) Cereal growth, development and yield. In: Tsuji GY, Hoogenboom G, Thornton PK (eds) Understanding options for agricultural production. Kluwer Academic, Dordrecht, pp 79–98

Robertson MG, Silim S, Chauhan YS, Ranganathan R (2001) Predicting growth and development of pigeonpea: biomass accumulation and partitioning. Field Crop Res 70:89–100

Sandhu BS, Khera KL, Prihar SS, Singh B (1980) Irrigation needs and yield of rice on a sandy-loam soil as affected by continuous and intermittent submergence. Indian J Agric Sci 50(6):492–496

Sarkar R, Kar S (2006) Evaluation of management strategies for sustainable rice-wheat cropping system, using DSSAT seasonal analysis. J Agric Sci 144:421–434

Saseendran SA, Hubbard KG, Singh KK, Mendiratta N, Rathore LS, Singh SV (1998a) Optimum transplanting dates for rice in Kerala, India, determined using both CERES v3.0 and Clim Prob. Agron J 90:185–190

Saseendran SA, Singh KK, Rathore LS, Rao GSLHVP, Mendiratta N, Lakshmi Narayan K, Singh SV (1998b) Evaluation of the CERES-Rice v. 3.0 model for the climate conditions of the state of Kerala, India. Meterol Appl 5:385–392

Schinir HF, Dingkuhn M, DeDatta SK, Mengal K, Faronilo JE (1990) Nitrogen fertilization of direct seeded vs transplanted rice. I. Nitrogen uptake photosynthesis, growth and yield. Crop Sci 30:1276–1284

Seino H (1995) The impacts of climatic warming on cereal crop production in Japan. J Agric Meteor 51:131–138

Siddique KHM, Belford RK, Perry MW, Tennant D (1989) Growth, development and light interception of old and modern wheat cultivars in a Mediterranean-type environment. Aust J Agric Res 40:473–487

Singh KB, Gajri PR, Arora VK (2001) Modelling the effects of soil and water management practices on the water balance and performance of rice. Agric Water Manag 49(2):77–95

Sivakumar MKV, Viramani SM (1984) Crop productivity in relation to interception of photosynthetically active radiation. Agric For Meteorol 31:131–141

Swain DK, Herath S, Bhaskar BC, Krishna P, Rao KS, Nayak SK, Dash RN (2007). Developing ORYZA1 N for medium and long duration rice. Agron J 99(2):438–440

Tabbal DF, Bouman BAM, Bhuiyan SI, Sibayan EB, Sattar MA (2002) On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. Agric Water Manag 56(2):93–112

Thomson BD, Siddique KHM (1997) Grain legume species in low rainfall Mediterranean-type environments. Light interception and utilization of four grain legumes 307 II. Canopy development, radiation-use efficiency and dry matter production. Field Crop Res 54:189–199

Timsina J, Singh U, Singh Y, Lansigan FP (1995) Addressing sustainability of RW systems: testing and applications of CERES and SUCROS models. In: Proceedings of the international rice research conference, IRRI, Los Banos, Philippines, 13–17 Feb 1995 pp 633–656

Tongyai C (1994) Impact of climate change on simulated rice production in Thailand. In: Rosenzweig C, Iglesias A (eds) Implications of Climate Change for International Agriculture: Crop Modelling Study. US Environmental Protection Agency, Washington, DC

Toung TP (1999) Productive water use in rice production opportunities and limitations. J Crop Prod 2:241–264

Toung TP, Cabangon R, Wopereis MCS (1996) Quantifying flow processes during land soaking of cracked rice soils. Soc Soil Sci Am J 60(3):872–879

Tripathi RP, Kushwaha HS, Mishra RK (1986) Irrigation requirements of rice under shallow water table conditions. Agric Water Manag 12(1–2):127–136

Tsai J, Tsuang B, Lu P, Yao M, Shen Y (2007) Surface energy components and land characteristics of a rice paddy. J Appl Meteorol Climatol 46:1879–1900

Uchijima Z (1976) Maize and rice. In: Monteith JL (ed) Vegetation and the atmosphere, vol 2., Case StudiesAcademic Press, London, pp 33–64

Wright JL (1982) New evapotranspiration crop coefficients. J Irrigation Drainage Div ASCE 108:57–74

Yoshida S (1981) Fundamentals of rice crop science. The International Rice Research Institute, Los Banos, p 268