Simulating interactive effect of irrigation and nitrogen on crop yield and water productivity in maize–wheat cropping system

Sangeeta Lenka* and A. K. Singh

Water Technology Centre, Indian Agricultural Research Institute, Pusa, New Delhi 110 012, India

In this study the CropSyst model was used to quantify the interactive effects of various irrigation and nitrogen levels on crop water productivity in maize–wheat cropping system. Field experiments were carried out on clay loam soil at the research farm of Indian Agricultural Research Institute, New Delhi, with four consecutive crops (maize–wheat–maize–wheat) taken from July 2002 to April 2004. Three levels of irrigation, namely W1, W2 and W3 referring to limited, medium and maximum irrigation, were applied to each crop depending on seasonal rainfall and critical crop growth stage. The three irrigation levels were used with five nitrogen levels from T1 to T5 (T1, 0% N; T2, 75% N; T3, 100% N; T4, 150% N and T5, 100% N from organic source) in split plot design for the four crops grown in sequence.

Keywords: Crop water productivity, irrigation, maize–wheat system, nitrogen.

CONVENTIONAL methods of analysis in agronomic research usually produce results specific to the sites and seasons in which experiments are conducted. Use of crop growth simulation models has been a more recent and convenient research tool for quantitatively understanding the effect of climatic, edaphic and agronomic management factors and their interaction on crop growth and productivity. CropSyst, as any other model attempting to predict crop responses to the environment, is not a universal model. It requires some field data for calibration so as to represent a particular crop or cultivar of a given location. Based on preliminary validation, CropSyst appears to be a promising tool to analyse best management practices for water and nitrogen[1]. CropSyst model has been validated and tested in several European countries. Bellocchi *et al.*[2] in an evaluation study of the CropSyst model in continuous maize under alternative management options, reported reasonable estimates of crop area index (average modelling efficiency, EF = 0.96), biomass (EF = 0.82) and soil water content (EF = 0.75). The CropSyst model has been used by several other workers, e.g. Donatelli *et al.*[3] for maize, soybean and barley growth; Pala *et al.*[4] and Pannkuk *et al.*[5] in wheat; Badini *et al.*[6] in millets, and Peralta and Stockle[7] in maize, wheat and potato. Under Indian conditions, Jalota *et al.*[8] have also reported that the CropSyst model performed fairly well to simulate biomass production and grain yield in maize–wheat cropping system under varying texture, date of planting and irrigation regimes. However, studies on simulation of interactive effect of water and nitrogen (the two critical inputs of any production system) on crop water productivity in maize–wheat cropping system in the Indo-Gangetic Plains, where the maize–wheat cropping system assumes importance to be an alternative to the rice–wheat cropping system are rare. Hence keeping this necessity in view the CropSyst model was used to study the interactive effect of water and nitrogen on crop yield and water productivity in maize–wheat cropping system.

Methodology

Field study

A field experiment was carried out in a clay loam soil (Typic Haplustept) in the research farm of the Indian Agricultural Research Institute (IARI), New Delhi, with maize and wheat crops grown in sequence for two consecutive cropping seasons from 2002 to 2004. The experimental site is located between 28°37′–28°39′N lat. and 77°90′–77°11′E long. at an altitude of 225.7 m amsl. It is characterized by semi-arid type of climate with mean maximum and minimum temperatures varying from 43.9°C to 45.0°C and 6.0°C to 8.0°C respectively. The mean annual rainfall is about 680 mm, of which 75–80% is received during the monsoon period of July–September. Maize was grown in kharif (July–October) and wheat in rabi (November–April) in both the years. The maize and wheat cultivars sown were KH-101 and HD-2687 respectively. Recommended agronomic practices were carried out for both the crops. The plots were kept weed-free by pre-emergence application of Atrazine in maize and hand-weeding (two times), and in wheat crop by application of 2,4-D and hand-weeding (two times). Also, crops were kept free from insects and pathogen attack. The sowing and harvesting dates of the crops are given in Table 1.

*For correspondence. (e-mail: sangeeta_2@rediffmail.com)

Table 1. Sowing and harvesting dates of maize and wheat crops

Crop	Sowing date	Harvesting date
Maize	04/07/2002	23/10/2002
Wheat	30/11/2002	30/04/2003
Maize	13/08/2003	23/12/2003
Wheat	10/12/2003	13/04/2004

At the start of experiment, soil physical (texture, bulk density, hydraulic conductivity, field capacity and permanent wilting point) and chemical (electrical conductivity (EC), pH, organic carbon (OC), ammoniacal and nitrate nitrogen) properties of the field were determined at 0–15, 15–30, 30–60, 60–90 and 90–120 cm soil depth, following the standard procedures. Initial soil properties of the site are listed in Table 2. The experimental layout was split plot with irrigation levels as the main plot and nitrogen levels as subplot, replicated three times. The treatment details are given in Table 3.

Nitrogen was applied in split, 50% at sowing, 25% at knee-height stage (maize) and maximum tillering (wheat), and the rest 25% at tasseling (maize) and panicle emergence (wheat), P and K were applied as 100% basal. At the time of sowing, *Azotobacter* sp. W5 strain was applied on the seeds as 200 g peat charcoal carrier-based culture per acre containing 10^9 cells g^{-1}.

In all treatments irrigation was given in the entire crop growth season, based on critical crop growth stages, viz. crown root initiation, tillering, flowering and dough in wheat, and knee-height stage and silking in maize. Irrigation was applied by flexible hose and was measured by a water-meter. Depth of irrigation water applied each time was 60 mm. In the water treatments, maximum, medium and minimum irrigation refer to no water shortage, medium water shortage and low water availability respectively, for both the crops.

All important soil properties, soil moisture, nitrogen utilization (soil ammoniacal and nitrate-N, plant N) were monitored periodically at monthly intervals. Biomass and leaf area index (LAI) were also observed at 30 days interval from sowing and at harvest. At maturity, the crop was harvested from the whole plot, excluding border lines. Daily weather data, including rainfall data were taken from the meteorological observatory of IARI, New Delhi, which is about 0.5 km from the experimental plot. For the crops water productivity was computed according to the following formulae.

$$WP_{ET} = \frac{GY}{ET}, \quad (1)$$

where WP_{ET} is the water productivity based on evapotranspiration (kg ha^{-1} mm^{-1}), GY is the grain yield (kg ha^{-1}), and ET is evapotranspiration (mm).

$$WP_{IRF} = \frac{GY}{IRF}, \quad (2)$$

where WP_{IRF} is the water productivity based on irrigation and rainfall (kg ha^{-1} mm^{-1}), and IRF is irrigation plus rainfall (mm).

Simulation study

The CropSyst model was chosen, as it is a process-based, simple, multi-year, multi-crop, daily time-step cropping system simulation model. The model is designed to serve as an analytical tool for studying the effect of cropping system management on crop productivity and environment[9,10]. It simulates the crop growth and development, and soil water budget. Selection of soil, location and building crop rotations with sowing dates and agricultural management practices associated with the crop can construct simulation scenarios. The location parameters include longitude, latitude and weather dataset. Evapotranspiration can be calculated by the Penman–Monteith method (Allen *et al.*[11]) or Priestly and Taylor[12]. Description of other input files and the processes behind them is given in Stockle *et al*.[1].

CropSyst calibration

CropSyst requires several parameters for calibration and validation. These parameters were set based on typical field observations, or taken from the CropSyst manual or from the literature pertaining to site-specific Indian conditions. A few parameters that tend to fluctuate among cultivars were calibrated. The model was initialized each time prior to maize sowing in 2002. Crop parameters used for this simulation are presented in Table 4. The calibrated parameters were adjusted using three points in the dataset (no N/high water, high N/no water and high N/high water, i.e. W3T1, W1T3 and W3T3) for both maize and wheat. The datasets of first year maize 2002 and wheat 2002–03 were used for calibration. These data included grain yield, aboveground biomass, LAI, actual ET, total N uptake. The maize and wheat cultivars simulated were KH-101 and HD 2687, which are varieties largely used in the region.

CropSyst validation and evaluation

After calibration of the model for maize and wheat using W3T1 (maximum water, no nitrogen), W1T3 (no water and maximum nitrogen), and W3T3 (maximum water and maximum nitrogen), it was validated against other nitrogen and irrigation levels in maize and wheat. The model validation was done for grain yield, aboveground biomass, LAI, actual ET, total N uptake and soil moisture of

Table 2. General soil characteristics of the experimental site

Parameter	Depth (cm) 0–15	15–30	30–60	60–90	90–120
Mechanical analysis					
Sand	37.96	31.36	51.06	46.96	51.26
Silt	39.71	38.00	26.70	30.8	28.50
Clay	22.33	30.64	22.24	22.24	20.24
Textural class	Loam	Clay loam	Sandy clay loam	Loam	Loam
Physical properties					
Electrical conductivity (EC; dS m^{-1})	0.31	0.28	0.21	0.15	0.11
pH (1 : 2.5 soil : water)	7.75	7.62	7.46	7.38	7.23
Bulk density (mg m^{-3})	1.52	1.61	1.68	1.71	1.74
Hydraulic conductivity (cm h^{-1})	1.01	0.80	0.70	0.46	0.39
Field capacity (FC, % by vol. basis)	37.9	39	36.4	32.1	34.9
Permanent wilting point (PWP, % by vol. basis)	6.8	9.9	8.1	5.9	6.7
Chemical properties					
Cation exchange capacity (CEC; cmol (P^+) kg^{-1})	13.6	11.5	–	–	–
Organic carbon (OC; %)	0.39	0.25	0.18	0.06	0.01
Soil NH_4^+-N (kg ha^{-1})	19.5	17.8	14.2	12.5	9.1
Soil NO_3^--N (kg ha^{-1})	27.9	19.1	15.2	10.5	8.7
Available K (kg ha^{-1})	199.4	173.5	132.6	113.5	90.5
Available P (kg ha^{-1})	19.8	16.8	10.3	8.6	6.7

Table 3. Details of water and nitrogen management treatments

	No. of irrigations			
	Maize		Wheat	
Treatment details	2002	2003	2002–03	2003–04
Water				
W3 (Maximum irrigation)	3	2	4	4
W2 (Medium irrigation)	2	1	3	3
W1 (Limited irrigation)	1	0	2	2
Nitrogen				
T1 Control (0% N)				
T2 75% N + PK				
T3 100% N + PK*				
T4 150% N + PK				
T5 100% organic source (50% FYM + 25% biofertilizer + 25% crop residue/green manure)				

*100% nitrogen is the recommended dose (120 kg N ha^{-1}).
100% P and K (75 kg P_2O_5 and 45 kg K_2O).

next year maize 2003 and wheat 2003–04. Evaluation of model performance was carried out using statistical tools, viz. mean biased error (MBE), mean absolute error (MAE), root mean square error (RMSE), R^2 (Pearson's correlation coefficient) and *d* (Willmott's index of agreement), according to Willmott[13].

Results and discussion

Field study

Aboveground biomass: Statistically significant difference in biomass accumulation was observed among establishment techniques in both maize and wheat (Table 5). But there was significant difference in the biomass of fully organic (T5) being less than T2 treatment by about 8.65%. There was consistent increase in biomass from the day of sowing, initially at an increasing rate till 60 DAS and at a decreasing rate later on in maize and wheat. In maize 2003, except for 30 DAS and harvest there was no significant difference among three irrigation levels at 60 and 90 DAS. This may be attributed to good amount of rainfall received during these periods (Figure 1), which neglected the effect of irrigation. Because N is often the most limiting nutrient for plant growth and biomass accumulation[14]. At harvest among nitrogen treatments

Table 4. Crop parameters for CropSyst simulation of maize and wheat growth and yield*

Parameter	Maize 2002	Maize 2003	Wheat 2002–03	Wheat 2003–04	Source
Degree-days emergence (°C-day)	150	58	54	97	O
Degree-days peak leaf area index (LAI) (°C-day)	1331	1094	602	484	O
Degree-days flowering (°C-day)	1358	1123	633	503	O
Degree-days maximum grain filling (°C-day)	1465	1207	760	603	O
Degree-days maturity (°C-day)	2135	1507	1642	1418	O
Base temperature (°C)	10	10	6	6	L
Cut-off temperature (°C)	35	35	30	30	L
Optimum mean daily temperature (°C)	27	27	20	20	L
Maximum root depth (m)	1.8	1.8	1.5	1.5	L
Maximum expected LAI	4	4	6	6	O
Specific leaf area (m^2 kg^{-1})	25	25	24	24	C
Stem/leaf partition coefficient	3	3	2.5	2.5	C
Leaf duration (°C-day)	1000	1000	800	800	C
Evapotranspiration crop coefficient	1.05	1.05	0.8	0.8	C
Maximum water uptake rate (mm/day)	16	16	13	13	M
Critical canopy water potential (J kg^{-1})	–1000	–1000	–1600	–1600	C
Wilting canopy water potential (J kg^{-1})	–1800	–1800	–2200	–2200	C
Biomass/transpiration coefficient (kPa)	8.5	8.5	7.5	7.5	C
Light to aboveground biomass conversion (g MJ^{-1})	3	3	3	3	M
Maximum harvest index	0.4	0.4	0.4	0.4	O
N uptake adjustment (0–2)	0.2	0.2	0.2	0.2	O
Maximum nitrogen concentration at emergence (kg kg^{-1})	0.018	0.018	0.02	0.02	O
Maximum nitrogen concentration at maturity (kg kg^{-1})	0.011	0.011	0.011	0.011	O
Minimum nitrogen concentration at maturity (kg kg^{-1})	0.005	0.005	0.009	0.009	O

*Parameters were set as observed from field data (O), extracted from the CropSyst manual (M), site-specific datas from the literature (L), or set by calibration (C).

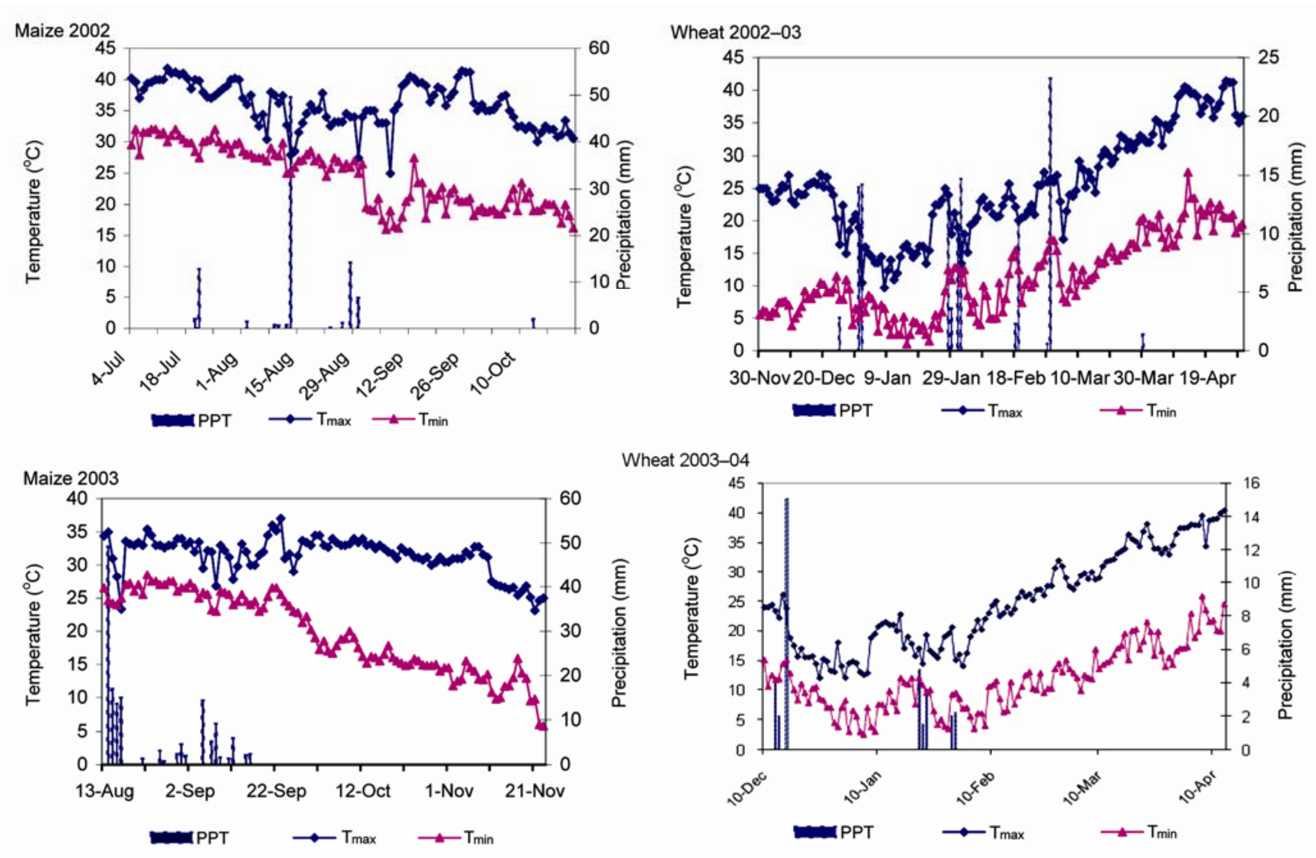

Figure 1. Daily maximum and minimum temperature and precipitation during crop seasons.

Table 5. Aboveground plant biomass (mg ha^{-1}) at different crop growth stages in maize and wheat under various water and nitrogen treatments

	Maize 2002			Maize 2003		
Treatment	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
W1T1	0.814ef*	3.894i	4.954e	0.74e	3.772g	5.017i
W1T2	1.137abcdef	4.957fgh	6.278d	1.44bcd	5.918e	8.642ef
W1T3	1.259abcdef	5.127efg	6.523d	1.62bc	7.019bc	9.127de
W1T4	1.401abcd	5.682cdef	6.857cd	1.69ab	7.594ab	9.690cd
W1T5	0.831def	4.569ghi	5.012e	0.93de	5.610e	8.146fg
W2T1	0.832ef	4.197hi	6.247d	0.92de	3.495g	5.724h
W2T2	1.326abcde	5.234defg	6.418d	1.46bcd	6.193de	8.987e
W2T3	1.413abc	5.861bcde	6.627cd	1.73ab	7.445abc	9.740cd
W2T4	1.429ab	6.589ab	6.918cd	1.99ab	7.728ab	10.18bc
W2T5	0.748f	4.945fgh	6.271d	0.88e	4.864f	7.846g
W3T1	0.855cdef	4.754gh	6.185d	0.95de	3.879g	5.295hi
W3T2	1.524ab	6.121bc	7.417bc	1.68ab	6.190de	8.107fg
W3T3	1.572ab	6.642ab	7.723ab	1.96ab	6.798cd	10.43ab
W3T4	1.616a	7.195a	8.271a	2.18a	7.934a	11.02a
W3T5	1.013bcdef	5.948bcd	6.890cd	1.13cde	4.858f	7.848g

	Wheat 2002–03				Wheat 2003–04		
	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS
W1T1	0.53a	1.76d	3.47h	4.31h	0.21g	0.59g	0.82f
W1T2	0.66a	2.19cd	4.18g	5.97g	0.94def	1.32f	1.95e
W1T3	0.68a	2.28cd	4.78efg	6.75f	1.12cdef	1.40ef	2.04e
W1T4	0.92a	2.52bc	5.52cd	7.45def	1.27bcd	1.69cdef	2.19e
W1T5	0.53a	2.04cd	4.38fg	5.93g	0.79f	1.19f	2.19e
W2T1	0.67a	1.91cd	4.67efg	6.91ef	0.81ef	1.46def	2.28e
W2T2	0.75a	2.26cd	4.99def	7..25ef	1.08cdef	2.18bc	3.96d
W2T3	0.78a	2.29cd	5.27de	7.51def	1.17cde	2.30b	4.76c
W2T4	0.91a	3.03ab	4.17g	8.14cd	1.39abc	3.62a	5.12c
W2T5	0.64a	2.48bc	4.58fg	6.97ef	1.10cdef	2.09bc	3.50d
W3T1	0.63a	2.24cd	5.27de	7.64cde	1.21cd	1.93bcde	2.29e
W3T2	0.80a	2.45bc	6.27b	8.32bc	1.42abc	2.52b	4.92c
W3T3	0.91a	3.26a	6.91a	8.94ab	1.57ab	3.73a	5.93b
W3T4	1.13a	3.53a	7.48a	9.52a	1.69a	4.08a	6.65a
W3T5	0.98a	2.35cd	6.11bc	7.28ef	1.01def	2.02bcd	3.78d

*Means in a column followed by common letters are not significantly different at $P = 0.05$.

across irrigation levels, T4 registered highest yield of more than 25% over T1 for both the crops.

Grain yield: The grain yield for both maize and wheat is presented in Figure 2. During 2002 maize average yield was highest in W3T4 (3.468 mg ha^{-1}). Compared to W3 irrigation regime, yields were significantly reduced by 12% and 26% in W2 and W1 respectively. But the overall effect of T3, T2 and T5 treatments in all the three irrigation levels was at par with each other. However, the yield of fully organic treatment was just less by 4% than T2. Erratic rainfall with prevalent dry period before sowing, and delayed sowing were the main causes behind decline in yield compared to maize 2003. While the yield of maize 2003 ranged from 4.507 to 2.510 mg ha^{-1}, nearly 23% more than the previous year. Similar trends of irrigation and nitrogen were observed as those of maize 2002. But the response of grain yield to different levels of nitrogen was statistically significant. Highest grain yield in T4 compared to T1 is mainly due to higher N uptake and LAI (data not shown). The results are in confirmity with earlier findings[15–17].

In wheat 2002–03, the grain yield varied between 4.708 and 1.641 mg ha^{-1}, with the highest significant effect of T4 in all irrigation levels. There was a greater response of wheat to N levels compared to maize; significant differences among nitrogen treatments were observed. The yield of fully organic treatment was less by 9% than T2 treatment. Though organic manure helps in maintaining the soil health and quality, reduction in yield is probably due to lesser availability of nutrients, especially nitrogen during the active growth period of crops, unlike the results of Rameshwar and Singh[17]. During 2003–04, the wheat yield was lower by 43% compared to 2002–03 due to high temperature (Figure 1) prevalent during flowering and grain-filling. High temperature shortens the grain-filling period[18] and may also induce water stress, leading to slow growth rates and even, some levels of

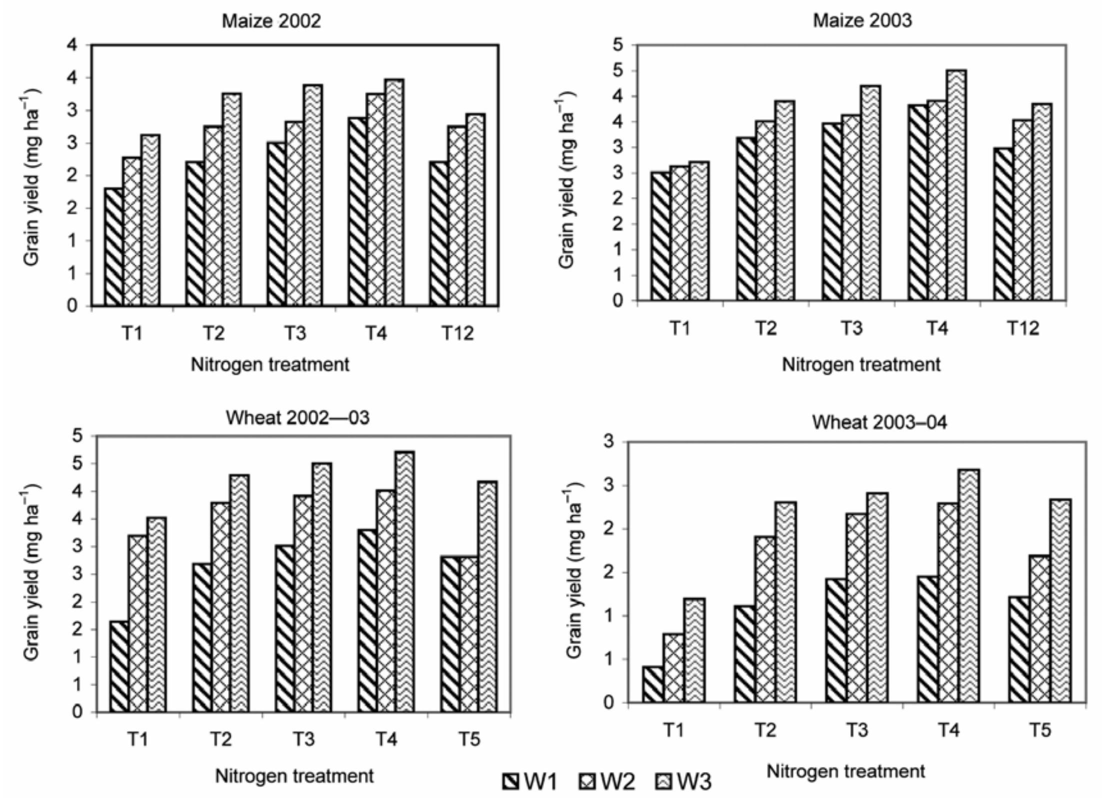

Figure 2. Grain yield (mg ha^{-1}) under various water and nitrogen treatments in maize and wheat.

sterility[19]. The yield ranged from 2.681 to 0.412 mg ha^{-1}. There was also significant reduction in biomass production (Table 5). Despite having similar irrigation levels, the response to nitrogen levels was less, with the effect of T3, T2 and T5 at par with each other. This was further aggravated by delay in sowing due to late harvesting of preceding maize crop. Similar findings of decline in grain yield of wheat due to delay in sowing were also made by several workers[20,21].

Water productivity: In the first year, irrespective of irrigation levels, the water productivity based on ET (WP_{ET}), and irrigation and rainfall (WP_{IRF}) was found to increase with increase in N rate (Table 6). But only statistically comparable data were found among nitrogen treatments. WP_{ET} was highest in W_3T_4 (9.40 kg ha^{-1} mm^{-1}) and lowest in W_1T_1 (7.05 kg ha^{-1} mm^{-1}). But WP_{IRF} was highest in W_1T_4 (18.93 kg ha^{-1} mm^{-1}) and lowest in W_1T_1 (11.84 kg ha^{-1} mm^{-1}). Thus WP_{ET} was highest in W_3 irrigation in both the years. This may be attributed to the linear relationship between grain yield and ET. In maize 2002, there was no significant difference among irrigation levels, however, the effect of W_2 was more followed by W1 and then W3. But water productivity based on total water supply (irrigation and rainfall) was significantly higher for W_1 irrigation level by more than 32% over W_3 during maize 2003.

In the case of wheat, in all irrigation levels, WP_{ET} and WP_{IRF} were found to be highest for T4 treatment among different nitrogen regimes. There was no significant effect of different levels of irrigation treatment on both WP_{ET} and WP_{IRF}. Among the irrigation levels, the effect of W1 was more by 4.3% and 3.6% over W3 and W2 respectively, in wheat 2002–03 for WP_{ET}. For WP_{ET} and WP_{IRF}, the effect of W2 was more than the other two irrigation levels. WP_{ET} in T4 was significantly more than T1 by 26% (wheat 2002–03) and 59% (wheat 2003–04). In wheat, Chaudhary[22] has also reported that water use efficiency (WUE) based on ET ranged between 2.38 and 9.51 kg ha^{-1} mm^{-1} in 1981–82, and between 2.95 and 9.53 kg ha^{-1} mm^{-1} in 1982–83. WUE increased with increase in N rates, as was also reported by several workers in wheat[23,24] and in maize[25–27].

Simulation study

Yield: The calibrated model was validated on independent datasets observed in the years 2002–03 and 2003–04. Comparison of experimental (O) and simulated (P) results with respect to grain yield across irrigations and nitrogen levels is given in Figures 3 and 4. Across irrigation levels the simulated grain yield (mg ha^{-1}) in first-year maize ranged from 2.34 (T1-N_0) to 3.00 (T5-$N_{150\%}$), and from

Table 6. Water productivity under various water and nitrogen regimes in maize (2002, 2003) and wheat 2002–03, 2003–04)

Treatment	Maize 2002 WP$_{ET}$ (kg ha^{-1}mm^{-1})	Maize 2002 WP$_{IRF}$ (kg ha^{-1}mm^{-1})	Maize 2003 WP$_{ET}$ (kg ha^{-1}mm^{-1})	Maize 2003 WP$_{IRF}$ (kg ha^{-1}mm^{-1})
W1T1	7.05c*	11.84e	7.10f	16.55f
W1T2	7.96abc	14.52cde	8.55bcd	20.97c
W1T3	8.97ab	16.44abc	9.21abc	22.81b
W1T4	9.28a	18.93a	9.41ab	25.17a
W1T5	8.16abc	14.51cde	7.84e	19.64cd
W2T1	7.35bc	10.74de	6.53f	12.40h
W2T2	8.49abc	12.96bcd	8.29de	16.55f
W2T3	8.67abc	13.29abcd	8.39cde	17.13ef
W2T4	9.29a	15.31ab	8.90abcd	18.48de
W2T5	8.41abc	12.96bcd	8.37cde	16.66f
W3T1	8.30abc	9.62de	6.37f	9.98i
W3T2	9.06ab	11.94abcd	8.84bcd	14.38g
W3T3	9.26a	12.45abc	9.35ab	15.46fg
W3T4	9.40a	12.74abc	9.76a	16.59f
W3T5	8.64abc	10.81cde	8.40cde	14.16g
	Wheat 2002–03		Wheat 2003–04	
W1T1	8.16f	7.18g	2.57d	3.07d
W1T2	11.81bcd	11.75de	6.66c	8.28c
W1T3	12.89ab	13.20bc	8.26abc	10.59abc
W1T4	13.42a	14.44a	8.13abc	10.82abc
W1T5	11.74bcd	12.31cd	7.17bc	9.05abc
W2T1	11.57cd	11.06e	3.62d	4.07d
W2T2	12.55abc	13.13bc	8.24abc	9.82abc
W2T3	12.70abc	13.56ab	9.32ab	11.20ab
W2T4	12.95ab	13.90ab	9.46a	11.80a
W2T5	10.73de	9.74f	7.23abc	8.70bc
W3T1	10.11e	10.09f	4.58d	4.69d
W3T2	11.88bcd	12.30cd	7.92abc	9.06abc
W3T3	12.16abc	12.92bc	8.17abc	9.48abc
W3T4	12.41abc	13.51ab	8.80abc	10.55abc
W3T5	11.69bcd	11.95de	8.08abc	9.20abc

*Means in a column followed by common letters are not significantly different at $P = 0.05$.

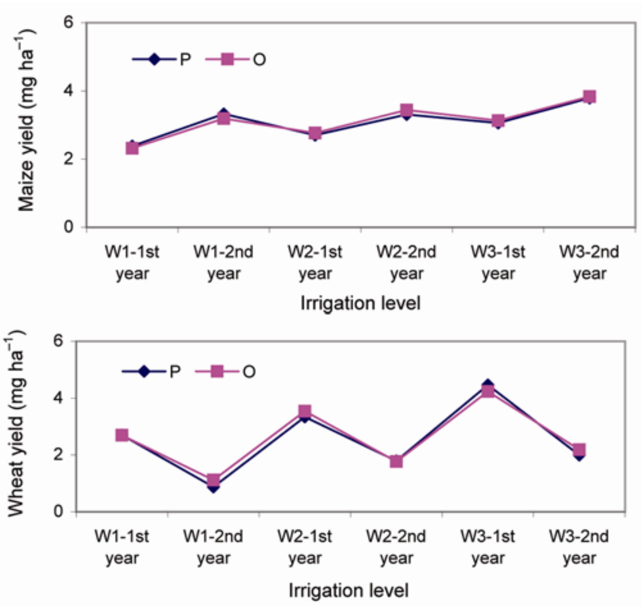

Figure 3. Effect of irrigation level on predicted and observed grain yield (mg ha^{-1}) across nitrogen levels in maize and wheat crops.

3.09 (T1-N$_0$) to 3.69 (T5-N$_{150\%}$) in wheat. The model responded well to different levels of irrigation with significant R^2 values and index of agreement (d) between the observed and predicted data (Table 7). Significant correlation was observed for biomass and grain yield but at higher N-rates; the model underestimated the grain yield. Scatter plot of simulated and observed aboveground biomass is shown in Figure 5. There was good matching between simulated and observed data with higher coefficient of determination (0.81–0.97).

ET and water productivity: Figure 6 gives the observed and predicted ET is given for maize and wheat crops with significant correlation (0.90–0.97). The ET values tend to cluster with increase in N rates in all the three irrigation levels for both maize and wheat yields. This clustering contributed to low R^2 values of linear regression for all the three irrigation levels in both years. Simulated results of crop water productivity (ET and irrigation + rainfall-based) for different irrigations and nitrogen levels are

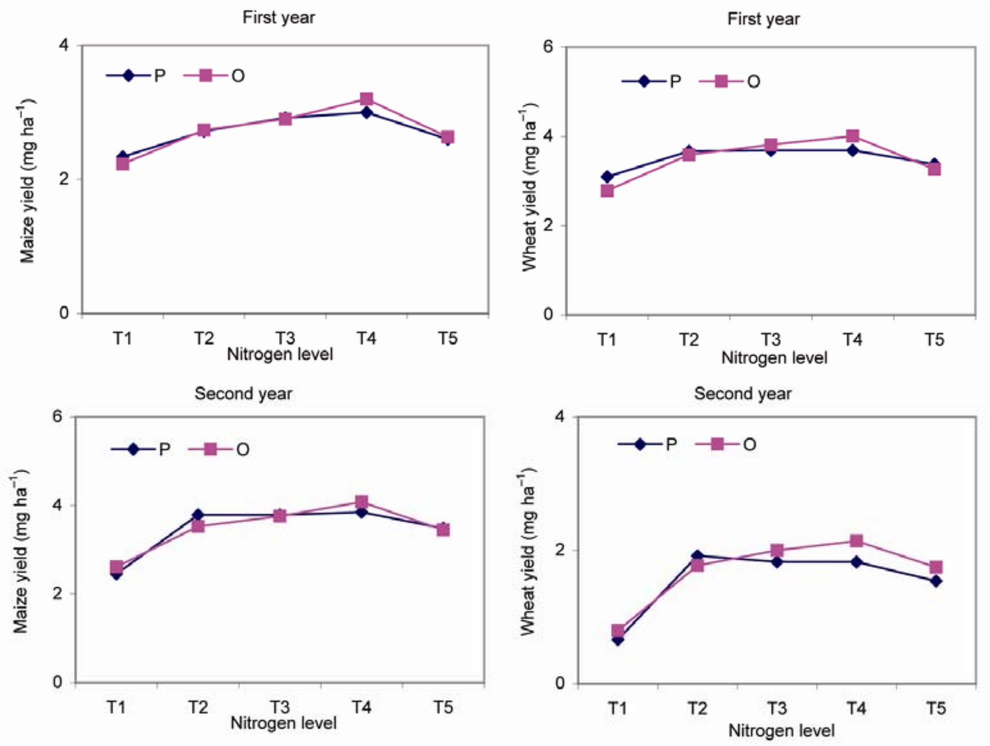

Figure 4. Effect of nitrogen level on predicted and observed grain yield (mg ha^{-1}) across irrigation levels in the first and second year of the cropping sequence.

Table 7. Statistical summary comparing observed data with simulated values using the CropSyst model. The model was initialized prior to sowing of maize – 2002. The statistics represents a combination of two years data

Crop	Parameter	*N*	Observed mean	Predicted mean	*d*	R^2	RMSE	MAE	MBE
Maize	Biomass (mg ha^{-1})	30	8.536	8.408	0.98	0.92	0.520	0.400	–0.128
	Grain (mg ha^{-1})	30	3.114	3.095	0.97	0.88	0.224	0.175	–0.019
	Actual ET (mm)	30	367.27	360.92	0.98	0.95	14.774	11.258	–6.351
	WP_{ET} (kg ha^{-1} mm^{-1})	30	0.85	0.86	0.91	0.73	0.057	0.42	0.014
	WP_{IRF} (kg ha^{-1} mm^{-1})	30	15.20	15.19	0.98	0.92	1.12	0.881	–0.006
Wheat	Biomass (mg ha^{-1})	30	6.472	6.355	0.99	0.97	0.588	0.452	–0.117
	Grain (mg ha^{-1})	30	2.591	2.529	0.98	0.95	0.284	0.227	–0.062
	Actual ET (mm)	30	262.12	269.64	0.99	0.97	13.301	9.446	7.446
	WP_{ET} (kg ha^{-1} mm^{-1})	30	0.95	0.89	0.96	0.90	0.11	0.087	–0.055
	WP_{IRF} (kg ha^{-1} mm^{-1})	30	10.38	9.97	0.95	0.83	1.304	1.013	–0.407

N, No. of observations; *d*, Willmott's index of agreement; R^2, Pearsons's correlation coefficient; RMSE, Root mean square error; MBE, Mean biased error; MAE, Mean absolute error; ET, Evapotranspiration.

given in Tables 6 and 7. The ranges of average WP_{ET} (ET-based) in maize were from 8.48 to 8.71 kg ha^{-1} mm^{-1}, and 6.43 to 11.46 kg ha^{-1} mm^{-1} in wheat. Similarly, WP_{IRF} (irrigation + rainfall-based) varied from 13.22 to 17.17 kg ha^{-1} mm^{-1} in maize, and 7.88 to 12.07 kg ha^{-1} mm^{-1} in wheat. WP_{ET} increased with increase in the number of irrigations. However, there was no significant effect of irrigation on WP_{ET}. WP_{IRF} was found to decrease with increase in the number of irrigations. Further, significant effect of increasing doses of N was found on crop water productivity (ET and irrigation + rainfall-based). This shows that for optimizing crop water productivity, the number of irrigations can be reduced from three to one and four to two in maize and wheat respectively. Thus the best management option for nitrogen and irrigation levels as simulated by the model for the cropping sequence (maize–wheat–maize–wheat) is W1T3 (minimum irrigation and nitrogen-100%). This helps the growers to save the scarce irrigation water.

In maize, WP_{ET} in T5 (N-fully organic) was at par with all the levels of inorganic nitrogen. However, WP_{IRF} in T5 was found to be at par with T2 (N-75%). In W1

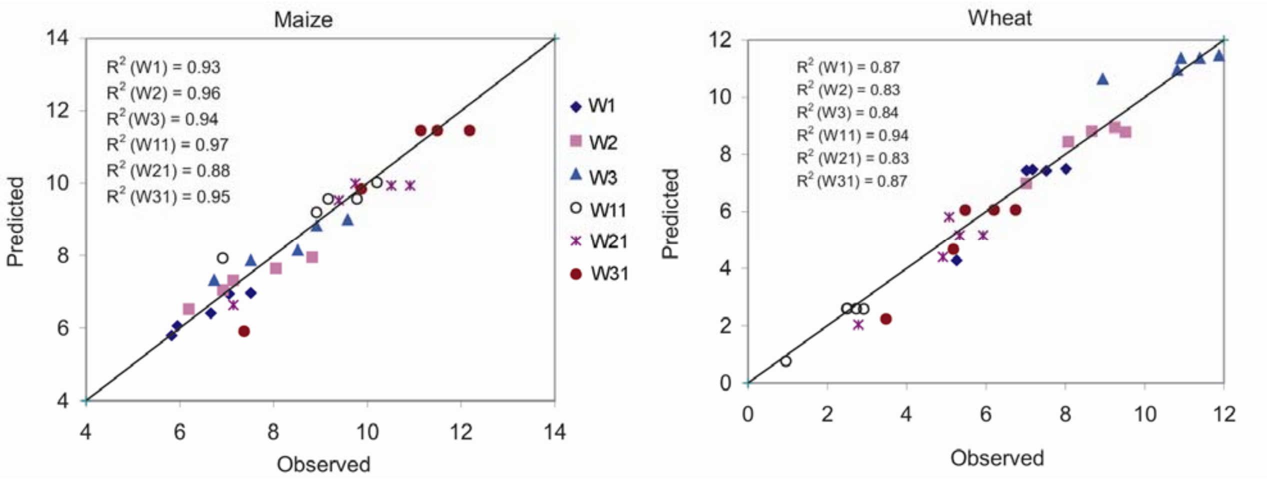

Figure 5. Observed and predicted maize and wheat biomass (mg ha^{-1}) in 2002–03 and 2003–04 under minimum (W1, W11), medium (W2, W21) and maximum irrigation (W3, W31).

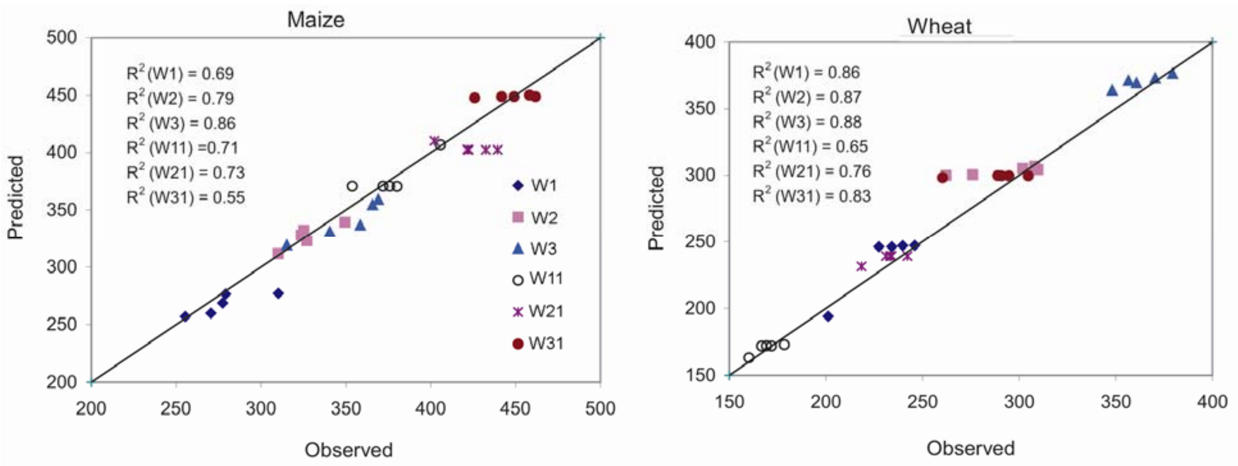

Figure 6. Observed and predicted evapotranspiration (mm) for maize and wheat in 2002–03 and 2003–04 under minimum (W1, W11), medium (W2, W21) and maximum irrigation (W3, W31).

Table 8. Effect of irrigation and nitrogen levels on predicted water productivity based on ET (kg ha^{-1} mm^{-1}) in maize and wheat crops

	First year				Second year			
Treatment	W1	W2	W3	Mean	W1	W2	W3	Mean
Maize								
T1	7.84	7.54	8.30	7.89	7.71	5.89	4.67	6.09
T2	9.04	8.26	8.97	8.76	9.24	8.87	9.75	9.29
T3	9.38	8.58	9.33	9.10	9.24	8.87	9.75	9.29
T4	9.45	8.72	9.54	9.24	8.87	8.87	9.75	9.16
T5	8.68	8.22	8.72	8.54	8.90	8.49	8.32	8.57
Mean	8.88	8.26	8.97	**8.71**	8.79	8.20	8.45	**8.48**
Wheat								
T1	8.69	11.10	11.70	10.50	1.86	3.47	2.96	2.76
T2	11.99	11.51	12.31	11.93	5.93	9.72	8.06	7.90
T3	11.98	11.62	12.19	11.93	5.93	8.57	8.06	7.52
T4	12.03	11.51	12.18	11.91	5.87	8.57	8.06	7.50
T5	12.00	9.29	11.80	11.03	5.92	7.29	6.19	6.47
Mean	11.34	11.01	12.04	**11.46**	5.10	7.52	6.66	**6.43**

Table 9. Effect of irrigation and nitrogen levels on predicted water productivity based on irrigation and rainfall ($kg\ ha^{-1}\ mm^{-1}$) in maize and wheat crops

	First year				Second year			
Treatment	W1	W2	W3	Mean	W1	W2	W3	Mean
Maize								
T1	13.25	11.07	9.74	11.35	18.85	11.42	7.70	12.66
T2	15.98	12.77	11.09	13.28	22.60	16.86	16.11	18.52
T3	17.05	13.44	12.16	14.22	22.60	16.86	16.11	18.52
T4	17.21	13.96	12.58	14.58	23.78	16.86	16.11	18.92
T5	14.83	12.51	10.61	12.65	21.73	16.15	13.78	17.22
Mean	15.66	12.75	11.24	**13.22**	21.91	15.63	13.96	**17.17**
Wheat								
T1	7.38	11.56	12.22	10.39	2.26	4.14	3.47	3.29
T2	12.90	12.17	13.04	12.71	7.61	11.98	9.50	9.69
T3	12.90	12.35	13.05	12.77	7.61	10.56	9.50	9.22
T4	13.01	12.14	13.16	12.77	7.57	10.56	9.50	9.21
T5	12.96	9.66	12.57	11.73	7.61	8.99	7.31	7.97
Mean	11.83	11.58	12.81	**12.07**	6.53	9.24	7.86	**7.88**

irrigation level when there is limited water available for irrigation WP_{ET} and WP_{IRF} in T5 treatment were found to be 12.00 and 12.96 $kg\ ha^{-1}\ mm^{-1}$; 5.92 and 7.61 $kg\ ha^{-1}\ mm^{-1}$ respectively, in the first- and second-year wheat. Thus the water productivity in T5 was higher and comparable with other levels of inorganic N (N-75%, N-100%, N-150%). This indicates that organic source of nitrogen could substitute inorganic-N and even attain the same level of water productivity when there is limited water available for irrigation in wheat.

Statistical analysis

Table 7 includes the statistical analysis for these comparisons in maize and wheat. For both crops the model performed well at lower levels of nitrogen, but the response to higher dose of nitrogen was poor for all the validated parameters, i.e. grain yield, biomass and ET. In the pooled statistical analysis, in spite of lower R^2 values of grain yield and N uptake in maize, the higher *d* values of 0.97 and 0.92 respectively, indicates that it is a better statistical tool for model evaluation than R^2. In maize, the root mean square error for ET was 4% of observed mean, 6% for biomass and 7% for grain yield. The corresponding values for wheat were 5%, 9% and 10% respectively. This indicates that the model is as accurate at predicting ET as yield and biomass. The pooled data analysis showed higher R^2 values because there was a large range of yields and ET when all years are combined because of the variation in precipitation from year to year. Pannkuk *et al.*[5] also reported that the difference in precipitation far outweighed the effect of tillage and residue management when simulations are performed.

Conclusion

Water deficit is an important constraint for maize and wheat production in rainfed, semi-arid, tropical regions of India. The significant finding from this field and simulation study conducted is that scare irrigation water could be saved by reducing the number of irrigations from three to one in maize and four to two in wheat for optimizing crop water productivity in the maize–wheat sequence. Interactive effect of W1T3 (minimum irrigation + N-100%) is significant for optimizing water productivity (ET and irrigation + rainfall-based) in both the crops. In the year of less rainfall with limited water availability for irrigation, nitrogen fertilizer as fully organic (T5) would be the best choice for growers to get maximum water productivity in wheat. Model performance was good on the whole in the semi-arid subtropical regions of India with respect to simulation on grain yield, total biomass and ET. The model responded well to all the levels of water. However, there was no response to higher levels of nitrogen.

1. Stockle, C. O., Martin, S. A. and Campbell, G. S., CropSyst, a cropping systems simulation model: water/nitrogen budgets and crop yields. *Agric. Syst*., 1993, **46**, 335–359.
2. Bellocchi, G., Silvestri, N., Mazzoncini, M. and Menini, S., Using the cropsyst model in continuous rainfed maize under alternative management options. *Ital. J. Agron*., 1996, **6**, 43–56.
3. Donatelli, M., Stockle, C., Ceotto, E. and Rinaldi, M., Evaluation of CropSyst for cropping systems at two locations of northern and southern Italy. *Eur. J. Agron*., 1997, **6**, 35–45.
4. Pala, M., Stockle, C. O. and Harris, H. C., Simulation of durum wheat growth under different water and nitrogen regimes in a Mediterranean environment using CropSyst. *Agric. Syst*., 1996, **51**, 147–163.
5. Pannkuk, C. D., Stockle, C. O. and Papendick, R. I., Evaluating cropsyst simulations of wheat management in a wheat fallow region of the US Pacific northwest. *Agric. Syst*., 1997, **57**, 121–134.
6. Badini, O., Stockle, C. O. and Franz, E. H., Application of crop simulation modeling and GIS to agroclimatic assessment in Burkina Faso. *Agric. Ecosyst. Environ*., 1997, **64**, 233–244.
7. Peralta, J. M. and Stockle, C. O., Dynamics of nitrate leaching under irrigated potato rotation in Washington state: a long term simulation study. *Agric. Ecosyst. Environ*., 2002, **88**, 23–24.

8. Jalota, S. K., Sukhvinder Singh, Chalal, G. B. S., Ray, S. S. and Panigraghy, S., Soil texture, climate and management effects on plant growth, grain yield and water use by rainfed maize–wheat cropping system: Field and simulation study. *Agric. Water Manage*., 2010, **97**, 83–90.
9. Stockle, C. O., Martin, S. A. and Campbell, G. S., CropSyst a cropping system simulation model: water/nitrogen budgets and crop yield. *Agric. Syst*., 1994, **46**, 335–359.
10. Stockle, O. C., Donatelli, M. and Nelson, R., Cropsyst a cropping systems simulation model. *Eup. J. Agron*., 2003, **18**, 289–307.
11. Allen, R. G., Pereira, L. S., Raes, D. and Smith, M., Crop evapotranspiration. Guidelines for computing crop water requirements. FAO. Irrig. Drainage Paper 56, FAO, Rome, 1998.
12. Priestley, C. H. B. and Taylor, R. J., On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Weather Rev., 1972, **100**, 81–92.
13. Willmott, C. J., Some comments on the evaluation of model performance. *Am. Meteorol. Soc*., 1982, **82**, 1309–1313.
14. Keney, D. R. and Nelson, D. W., Nitrogen-inorganic forms. In *Methods of Soil Analysis*. *Part 2* (ed. Page, A. L.), Agron. Monogr. 9, ASA and SSSA, Madison, WI, USA, 1982, 2nd edn, pp. 634–698.
15. Mohiuddin, M. D. and Ghosh, D. C., Response of wheat varieties to nitrogen application in lateritic belt of West Bengal. *Indian J. Agric. Res*., 1998, **32**, 71–74.
16. Muchow, R. C. and Sinclair, T. R., Water deficit effects on maize yields modeled under current and 'greenhouse' climates. *Agron. J*., 1991, **83**, 1052–1059.
17. Rameshwar, R. and Singh, C. M., Effect of FYM and fertilizer on the growth and development of maize and wheat in sequence. *Indian J. Agric. Res*., 1998, **32**, 65–70.
18. Medimore, D. J., Cartwright, P. M. and Fischer, R. A., Wheat in tropical environments. 11, crop growth and grain yield. *Field Crops Res*., 1984, **8**, 207–227.
19. Saini, H. S. and Aspinall, D., Sterility in wheat induced by water deficits or high temperature: possible mediation of abscisic acid. *Aust. J. Plant Physiol*., 1982, **9**, 529–537.
20. Ortiz-Monasterio, J. I., Dhillon, S. S. and Fischer, R. A., Date of sowing effects on grain yield and yield components of irrigated spring wheat cultivars and relationship with radiation and temperature in Ludhiana, India. *Field Crop Res*., 1994, **37**, 169–184.
21. Ahmed, S. M. and Meisner, C. A., Wheat research and development in Bangladesh. Aus. AID/CIMMYT-Bangladesh, Dhaka, Bangladesh,1996, p. 201.
22. Chaudhary, T. N., Response of wheat to irrigation with small amounts of water applied in various ways. *Agric. Water Manage*., 1985, **10**, 357–364.
23. Hussain, G. and AlJaloud, A. A., Effect of irrigation and nitrogen on water use efficiency of wheat in Saudi Arabia. *Agric. Water Manage*., 1995, **27**, 143–153.
24. Sharma, B. D., Cheema, S. S. and Kar, S., Water and nitrogen uptake of wheat as related to nitrogen application rate and irrigation water regime. *Fert. News*, 1990, 31–35.
25. Fernandez, J. E., Moreno, F., Murillo, J. M., Cayuela, J. A., Fernandez-Boy, E. and Cabrera, F., Water use and yield of maize with two levels of nitrogen fertilization in SW Spain. *Agric. Water Manage*., 1996, **29**, 215–233.
26. Arora, V. K. and Gajri, P. R., Performance of simplified water balance models under maize in a subtropical environment. *Agric. Water Manage*., 1996, **31**, 51–64.
27. Jalota, S. K. and Arora, V. K., Model-based assessment of water balance components under different cropping systems in northwest India. *Agric. Water Manage*., 2002, **57**, 75–87.

Received 4 May 2011; accepted 4 November 2011