Journal of the Indian Society of Soil Science, Vol. 63, No. 1, pp 39-52 (2015)
DOI: 10.5958/0974-0228.2015.00006.7

Effects of Phenology-based Irrigation Scheduling and Nitrogen on Light Interception, Water Productivity and Energy Balance of Maize (*Zea mays* L.)

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Maize (*Zea mays* L.) is considered as one of the diversifying options in rice fallows of eastern India. Research was conducted to study intercepted photosynthetically active radiation (IPAR), radiation utilization efficiency (RUE), latent heat flux and water productivity of the crop under different irrigation (120, 180, 240, 300 and 360 mm) and nitrogen (30, 60, 90, 120 and 150 kg N ha^{-1}) levels and relationships were established among biomass, yield, RUE, IPAR and water productivity. The RUE of the crop ranged from 1.01 to 2.16 g MJ^{-1}, the latent heat flux from 8.64 to 18.77 MJ m^{-2} day^{-1} and average water productivity from 0.673 to 0.983 kg m^{-3} under different N and irrigation levels. The difference in LAI, biomass production and yield was not significant between 120 and 150 kg N ha^{-1}, which might be attributed to the fact that these crop attributes were not proportionately increased with the amount of additional N applied. A comparison of water productivity between the treatments receiving irrigation at flowering and milk ripe-grain filling stages and not receiving irrigations at these stages with same amount of irrigation (300 mm) showed that water was more efficiently utilized when irrigation was not skipped at flowering and milk ripe-grain filling stages. The RUE was higher in milk ripe stage (milk to solid conversion of endosperm, but whole kernel content is still milky liquid) and reduced during grain filling stage. This might be attributed to the reduced seed weight and grain number in case of water and N stressed plots, where partitioning of photosynthates towards grain is less that limits the RUE.

Key words: Light interception, radiation use efficiency, maize, water productivity, surface energy balance

Maize (*Zea mays* L.) is third most important food crop in India with the average productivity of 2.89 t ha^{-1}, and it contributes nearly 9% to the national food basket. There is a tremendous need to increase the acreage and productivity of this crop in near future to meet food, feed, and other demands, especially in view of the booming livestock and poultry sectors in the country (Kar *et al.* 2004, 2005). Growth and yield of any grain crop under a particular environment are largely determined by soil moisture, nutrients, radiation interception and the efficiency of conversion of intercepted radiation to dry matter and partitioning of dry matter to grain (Gallaghar and Biscoe 1978; Kar *et al.* 2005; Figuerola and Berliner 2006; Kar *et al.* 2013). The productivity of the crop is constrained in winter season by abiotic stresses like moisture deficit owing to meager and erratic winter rainfall, lack of irrigation facilities and nitrogen (N) stress due to sub-optimal application of N-fertilizers. Deficit irrigation and nutrients create stress in plants and can reduce radiation interception, efficiency of conversion and partitioning of dry matter to grain. As a result, yield components like ear size, number of kernel per year, the kernel weight of the maize and water productivity are reduced (Denmead and Shaw 1960; Nesmith and Ritchie 1992; Bryant *et al.* 1992; Jama and Ottaman 1993; Traore *et al.* 2000; Kar *et al.* 2005). Claassen and Shaw (1970) observed that stress before or during silking and pollination (pre-anthesis period) resulted in reduced kernel number, while stress during or after silking reduced kernel weight.

Nutrient deficiencies also affect both intercepted photosynthetically active radiation (IPAR), radiation utilization efficiency (RUE) and water productivity by reducing crop biomass and grain yield (Quanqi *et al.* 2008). Leaf area index (LAI) was reduced in crops grown under N deficiency (Caviglia and Sadras 2001; Miranzadeh *et al.* 2011). An increase in N concentration at anthesis can result in an increase of LAI by as much as 62% and IPAR by up to 20% (Salvagiotti

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and Miralles 2008). The RUE in wheat has been reported to be reduced when N was limited (Muurinen and Peltonen-Sainio 2006). Dreccer *et al*. (2000) observed that N limitation affected wheat growth *via* reduction of the IPAR. Improved biomass, grain yield and water productivity would depend on the capacity to improve the amount of photosynthetically active radiation (PAR) intercepted by the crop or the efficiency with which the canopy converts that radiation into new biomass (RUE) at different stages of the crop (Tesfaye *et al.* 2006; Acreche and Slafer 2009).

Thus, knowledge of resource capture, particularly, soil moisture, nutrients and radiation by crop species under optimum management can be one of the options in improving the productivity of the crop (Tesfaye *et al.* 2006; Gao *et al.* 2013; Iqbal *et al.* 2013). In addition to the radiation interception, understanding the surface energy balance and latent heat flux will provide information on crop water requirement and can be used as an effective tool for irrigation scheduling for dry season crop (Kar *et al.* 2004; Shen *et al.* 2004; Figuerola and Berliner 2006; Kar and Kumar 2009; Kar *et al.* 2013). Some researchers opined that the management of deficit irrigation is one of the water saving strategies in agriculture. Under deficit irrigation, the amount of biological or economical yield per unit area is less than that of the maximum production, but the crop water productivity (in terms of crop water use, kg m^{-3}) may be increased by proper irrigation scheduling (Toung *et al.* 2000; Bastiaanssen *et al.* 2003; Igbadun *et al.* 2006).

Though some research works have been conducted on radiation interception and RUE of maize in different parts of the world, still there is a paucity of information with regards to the effects of irrigation and N in combination on light interception, RUE, growth and water productivity of the crop. Keeping the importance of those facts in view, research was conducted to study the IPAR and RUE at different growth stages of the crop and to quantify the biomass, LAI, grain yield in terms of IPAR, RUE and water productivity under different irrigation (120, 180, 240, 300 and 360 mm) and N (30, 60, 90, 120 and 150 kg ha^{-1}) levels. Water productivity of the crop was quantified under optimum and deficit irrigation regimes with skipping of irrigations at certain growth stages. Latent heat flux and other components of energy balance were computed to assess the crop water requirements at different stages of the crop under different irrigation levels. Due to limitation in instrumental facilities, computation of surface energy balance was confined to plots with 120, 240, 300 and 360 mm irrigation treatments under 120 kg ha^{-1} N.

Materials and Methods

Study Site

The on-farm experiment was conducted during two winter crop seasons (2007-08 and 2008-09) at Bhuasuni watershed of Dhenkanal district, Orissa (Latitude 28°60′ North and Longitude of 85°57′ East). The height of site is 69 m above mean sea level. The average maximum temperature of the Dhenkanal district varied from 27.0 °C in January to 36.7 °C in May, the minimum temperature ranged between 13.9 °C in December to 21.4 °C in May. Long-term average weather parameters of the district are given in fig.1. The average annual rainfall is 1440 mm, out of which 72% occurs during south-west monsoon period and 30-40% goes off as runoff without any utilization. In winter seasons, rainfall is meager and erratic; cropping is not possible without supplemental irrigations, therefore, the excess water of rainy season can be harvested and utilized to provide supplemental irrigation to the crop of winter/ dry season.

Crop Management and Experimental Treatments Description

Maize composite (cv. Novjyot) was sown on 23rd November, 2007 and 25th November 2008 in split plot

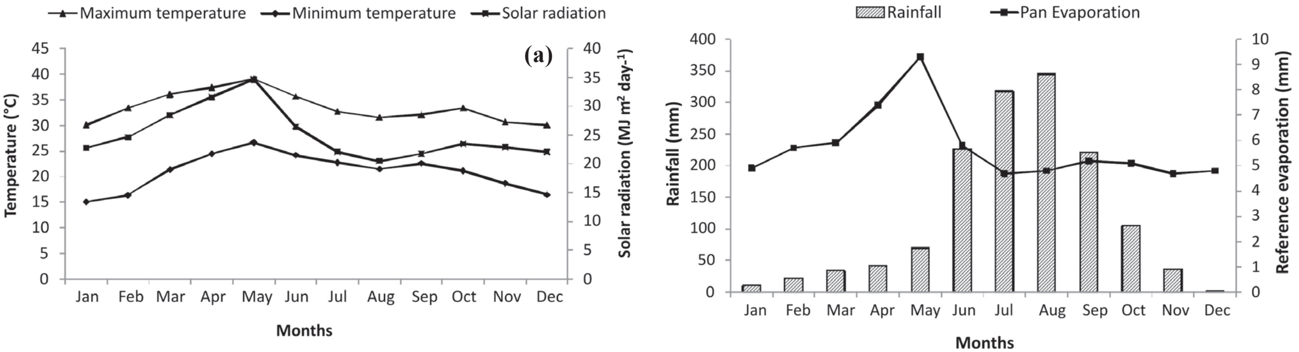

Fig. 1. Average weather conditions of the study area

Table 1. Irrigation treatments for the field experiments during 2007-08 and 2008-09

Stages	Description	Irrigation (mm) treatments					
		I_1	I_2	I_3	I_4	I_5	I_6
Stage 0	Period of germination of seed in the soil	X	X	X	X	X	X
Stage 1	Emergence of coleoptile from the soil and seedling growth up to 3 leaves unfolded	X	X	X	60	60	60
Stage 2	Stem elongation (1): Internodes below 5th, 6th and 7th leaves have begun to elongate	60	60	60	X	X	X
Stage 3	Stem elongation (2): 8 to 11 leaves unfolded, stem elongation rapidly, internodes below 5th and 6th leaves are fully elongated	X	X	X	60	60	6 0
Stage 4	Stem elongation (3): 12 to 15 or more leaves unfolded, stem still elongates, emergence of tassel from the whorl	60	X	60	60	60	6 0
Stage 5	Flowering (start of pollen shedding, 50% pollen shedding, 50% silking, end of flowering)	X	60	60	X	60	6 0
Stage 6	Water ripe stage of caryopsis, start of silk drying	X	60	60	60	60	60
Stage 7	Milk ripe stage (milk to solid conversion of endosperm, but whole kernel content is still milky liquid)	X	X	X	60	X	6 0
Stage 8	Dry ripe stage (kernel is no longer milky, reached physiological maturity)	X	X	X	X	X	X
Stage 9	Ripeness	X	X	X	X	X	X
	Total irrigation during crop growth (mm)	120	180	240	300	300	360

I_1, I_2, I_3, I_4, I_5 and I_6 are irrigations treatments
X = No irrigations were applied

arrangement with six irrigation treatments in main plots and five N treatments in sub-plots. The crop was sown on 0.60 m spaced ridges keeping plant to plant distance of 0.30 m using a seed rate of 25 kg ha^{-1}. The plot sizes were 4 × 3.5 m^2 and were separated by distance of 1.0 m within the blocks. Dyke height of 0.20 m were built around each plot to retain and prevent runoff/spill over the water applied. The six irrigations treatments were phenological based irrigation scheduling (Groot *et al.* 1986) (I_1 = 120 mm at stage 2, stage 4; I_2 = 180 mm at stage 2, stage 5, stage 6, I_3 = 240 mm at stage 2, stage 4, stage 5, stage 6; I_4 = 300 mm at stage 1, stage 3, stage 4, stage 5, stage 6; I_5 = 300 mm at stage 1, stage 3, stage 4, stage 5, stage 6; I_6 = 360 mm at stage 1, stage 3, stage 4, stage 5, stage 6, stage 7) (Table 1). The N treatments were: N_1= 30 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 all cases, N was applied in 3 split doses. The dates of important phenological stages, the LAI, above ground biomass, yield and yield components were recorded under different treatments. The crop was harvested at physiological maturity.

Intercepted Photosynthetically Active Radiation (IPAR) and Radiation Utilization Efficiency (RUE)

The percentage light interception or IPAR (400-700 nm) under different irrigation and N treatments was derived by measuring the incident radiation above the canopy and that transmitted to the ground below the canopy by a 1 m long quantum light bar (Light transmission meter, EMS-7) as per the following relationship:

$$I_i = I_o - I_{rc} - I_t + I_{rg}$$

I_i (%) by the canopy = $(Ii/Io) \times 100$
Ii = Intercepted photosynthetically active radiation (PAR) by the canopy
Io = Incident PAR on the canopy
I_{rc} = Reflected PAR by the canopy
I_t = Transmitted PAR through the canopy
I_{rg} = Reflected PAR from the ground

Measurements of radiation at ground level were taken by placing the linear sensor diagonally across the inter-row space with the ends of the sensor coinciding with the centre-line of the rows. All measurements were performed at 1000 to 1400 h in a clear day at intervals of 7–14 days, depending on weather conditions.

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).

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

where, ε is the radiation use efficiency (RUE) (g MJ^{-1}) (Pitman 2000).

In this study the dry biomass at different stages were measured and corresponding accumulated photosynthetically active radiation (APAR) were computed to estimate RUE using the following relationship:

$$\varepsilon\ (\mathrm{g\ MJ^{-1}}) = \frac{\text{Cumulative biomass (g m}^{-2})}{\text{Cumulative APAR (MJ m}^{-2})}$$

Daily intercepted solar radiation (MJ m^{-2}) by the crops was obtained as the product of daily incident solar radiation, measured at the agro-meteorological station, and the percentage of mid-day light interception. The mean daily values of intercepted photosynthetically active radiation was calculated by multiplying it with 0.48 following Monteith (1972), Yoshida (1972), Kailasanathan and Sinha (1984), Kar *et al*. (2013).

Surface Energy Balance

Bowen ratio (b) energy balance, a micro–meteorological method was used to compute latent heat flux (Shen *et al*. 2004; Kar and Kumar 2007, 2009; Kar *et al*. 2013).

The energy balance equation is:

$$R_n = \lambda E + H + G$$

$$\text{or, } R_n - G = \lambda E(1 + {}^{H}\!/_{\lambda E}) = \lambda E\ (1+\beta)$$

$$\text{or, } \lambda E = {}^{(R_n - G)}\!/_{(1+\beta)}$$

On the other hand, Bowen ratio (β) =

$$\frac{\textit{Sensible heat loss (H)}}{\textit{Evaporative heat loss } (\lambda E)}$$

$$= \frac{c_p P_a}{L\varepsilon}\,\frac{(T_2 - T_1)}{(e_2 - e_1)}$$

where, C_p = specific heat capacity of air (1 J g^{-1} $^{o}C^{-1}$); P_a = atmospheric pressure (101.3 kPa); L = latent heat of vaporization (2449 J g^{-1}); and = ratio of the molecular weight of water to that of air (0.622).

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

where, 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 vapour pressure at height z_1; and e_2 is the vapour pressure at height z_2.

R_n was measured using BABUC M net radiometer. The soil heat flux 'G' was computed with the equation, Gs = 0.4×R_n (Exp(-K×LAI)), where 'K' is the extinction coefficient, LAI = leaf area index (Kar and Kumar 2009).

The sensors to measure temperature, humidity and wind velocity were installed inside the cropped field on a tower at a distance of 0.5 m which measures these parameters at 1 h interval at 3 different heights. The output of all meteorological sensors were recorded with a datalogger and retrieved afterwards with the help of a PC.

Crop water requirements and seasonal crop water use and water productivity

The average actual seasonal crop water use (SCWU) (mm day^{-1}) between two successive soil moisture content sampling was computed using the following relationships.

$$SCWU = IR + ER + \sum_{i=1}^{n} \frac{Mb_i - Me_i}{100} \times A_i \times D_i$$

In which, *SCWU* = seasonal crop water use, mm; *IR* = total irrigation water applied, mm; *ER* = seasonal effective rainfall, mm; Mb_i = moisture percentage at the beginning of the season in the i^{th} layer of the soil; Me_i = moisture percentage at the end of the season in the i^{th} of the soil; A_i = bulk density (Mg m^{-3}) of the i^{th} layer; *Di* = depth of i^{th} layer of the soil within the root zone, mm and *n* = number of soil layers in the root zone, D.

Soil moisture content (m^3 m^{-3}) was monitored at weekly interval throughout the crop growing season using gravimetric method at different soil depth (0.15, 0.30, 0.45, 0.60, 0.90 and 1.20 m). Since limited irrigations were applied, it was assumed that runoff and deep percolation were negligible. The groundwater table is below 4.8 m, thus it is also not contributing to crop water use.

Crop water productivity in terms of seasonal crop water use (SCWU) under different management practices was computed as:

$$\mathrm{CWP_{SCWU}\ (kg\ m^{-3})} = \frac{\text{Crop yield (kg)}}{\text{SCWU (m}^3)}$$

Crop water productivity expressed in economic term was also computed as:

$$\mathrm{CWP_{eco}\ (Rs.\ m^{-3}\ or\ \$\ m^{-3})} = \frac{\text{p} \times \text{Crop yield (kg)}}{\text{SCWU (m}^3)}$$

where, p = selling price of maize (price kg of crop yield), Rs. 10 kg^{-1} = \$ 0.161 kg^{-1} was taken in our study.

Statistical Analysis

The statistical analyses of yield data analysis of variance (ANOVA) and separation of means by the Duncan's Multiple Range Test, were conducted using the SAS 2.0 statistical software.

Table 2. Major weather parameters during crop growth period of two seasons

Weather parameters	Vegetative to tassel initiation	Tassel initiation to silking	Silking to maturity
Maximum temperature (^{O}C)			
2007-08	28.9	26.6	27.8
2008-09	28.1	27.9	28.6
Minimum temperature (^{O}C)			
2007-08	14.4	15.5	16.3
2008-09	14.1	15.2	16.4
Day length (h)			
2007-08	11.5	10.7	11.1
2008-09	11.7	10.9	11.5
Solar radiation (MJ m^{-2})			
2007-08	18.2	20.8	21.9
2008-09	17.4	19.2	20.5
Rainfall (mm)			
2007-08	10.1	2.5	3.9
2008-09	5.5	—	—

Results and Discussion

Weather and Soils

The weather conditions (maximum temperature, minimum temperature, day length, solar radiation) of two crop seasons (2007-08 and 2008-09) at different phenological stages are presented in table 2. The pattern of average temperature was similar in both the years, average maximum temperatures ranged between 26.6 to 28.9 ^{O}C and minimum temperature was 14.1-16.4 ^{O}C during crop growth period. The incoming solar radiation ranged between 17.4 – 21.9 MJ m^{-2} day^{-1} during crop growth period in two crop growth seasons. The average day length ranged from 10.7 to 11.7 h. The rainfall was meager and the total rainfall received during crop growth period of 2007-08 and 2008-09 was only 16.5 and 5.5 mm, respectively. The measured soil profile data of the experimental field are presented in table 3. The soils within the experimental area was found to be relatively homogeneous and soil texture was sandy loam to clay loam in nature where clay content varied from 21.9% at 0.30-0.45 m soil depth to 34.5% at 0.90-1.20 m depth.

Phenological Development and Heat Units

Duration of important phenological stages as influenced by irrigation regimes and N rates is given in table 4. Irrigations had no significant effect on these phenological stages. Averaged over irrigation treatments, it was found that crop took 49-51, 59-60 and 115-117 days to attain tassel initiation, anthesis and physiological maturity under different irrigation treatments. Nitrogen affects duration of phenological stages significantly. The crop took 48 days to appear tassel in N_1 (30 kg N ha^{-1}) to 52 days in N_5 (150 kg ha^{-1}). The higher dose of N (120 kg ha^{-1} and above) also enhanced the duration of anthesis stage by 2-3 days. The crop matured in 113-119 days in different N treatments, took 6-7 more days to mature when higher dose of N (120 kg N ha^{-1} and above) was applied and the difference was statistically significant. Length of the grain-filling period ranged from 43 to 46 days. Thermal time from emergence to anthesis and from anthesis to maturity did not vary significantly among treatments. Thermal units accumulated from emergence to anthesis ranged from 766 to 805 and from 1587 to 1615 during emergence to physiological maturity.

Leaf Area Index as Influenced by Irrigations and Nitrogen

The LAI values steadily increased and reached at maximum value at 65-67 DAS just after anthesis stage; thereafter LAI declined in all the treatments (Fig. 2). Maximum LAI was significantly affected by irrigation levels. Averaged over N rates, peak LAI reached to a value of 3.25, 4.07, 4.32, 5.39, 5.42 and

Table 3. Soil profile data of the experimental site

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	0.098	0.097	0.093	0.098	0.117	0.129
Upper limit, drained (m^3 m^{-3}) of soil moisture	0.265	0.260	0.259	0.276	0.315	0.325
Upper limit, saturated (m^3 m^{-3}) of soil moisture	0.422	0.435	0.418	0.425	0.438	0.468
Root growth factor (0—1)	1.000	1.000	0.512	0.509	0.378	0.245
Saturated hydraulic conductivity, macropore (cm h^{-1})	23.8	13.7	7.98	7.05	4.69	2.65
Bulk density (Mg m^{-3})	1.44	1.46	1.47	1.48	1.50	1.54
Organic carbon (g kg^{-1})	8.6	6.9	5.9	5.8	3.9	4.0
Clay (<0.002 mm) (%)	23.1	25.9	21.9	22.6	23.9	34.5
Silt (0.05—0.002) (%)	11.9	12.9	14.4	13.9	14.4	13.5
pH in water	5.8	5.7	5.9	5.8	6.0	6.7

Table 4. Duration of important phenological stages of maize as influenced by irrigation regimes and nitrogen rates (Pooled data of 2 years)

Factors	Days to emergence	Days to 50% tassel initiation	Days to anthesis	Days to maturity	Grain filling duration (days)
I. Irrigation treatments					
I_1	07(104)	49(686)^{A}	59(779)^{A}	115(1587)^{B}	43^{B}
I_2	08(118)	49(686)^{A}	60(782)^{A}	115(1587)^{B}	44^{B}
I_3	07(104)	49(686)^{A}	59(779)^{A}	115(1587)^{B}	44^{B}
I_4	07(104)	49(686)^{A}	60(792)^{A}	115(1587)^{B}	44^{B}
I_5	07(104)	51(714)^{A}	59(779)^{A}	117(1615)^{A}	46^{A}
I_6	08(118)	51(714)^{A}	60(792)^{A}	117(1615)^{A}	46^{A}
Significance	NS	NS	NS	NS	NS
II. Nitrogen treatments					
N_1	07(104)	48(766)^{B}	58(766)^{B}	113(1559)^{C}	43^{B}
N_2	07(104)	48(672)^{B}	59(779)^{A}	114(1573)^{B}	43^{B}
N_3	07(104)	50(700)^{A}	60(792)^{A}	115(1587)^{B}	44^{B}
N_4	08(118)	51(714)^{A}	60(792)^{A}	118(1628)^{A}	47^{A}
N_5	07(104)	52(728)^{A}	61(805)^{A}	119(1642)^{A}	48^{A}
Significance	NS	NS	NS	**	NS
Interaction					
Irrigation× Nitrogen	NS	NS	NS	NS	NS

**Significant at 5% probability level; NS = Non significant at 5% probability level;

The values in the column followed by same letters are not significant at 5% level of significance based on Duncan's' Multiple Range Test (DMRT); Figures in parenthses indicate growing degree days to attain a particular phenological stage

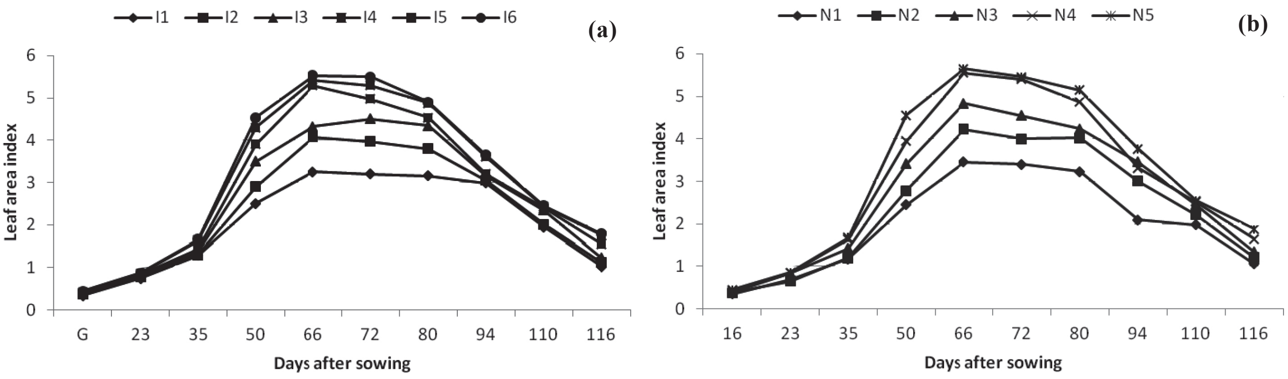

Fig. 2. Leaf area index at different days after sowing as influenced by (a) irrigation regimes and (b) nitrogen rates

5.53 in I_1 (120 mm), I_2 (180 mm), I_3 (240 mm), I_4 (300 mm by skipping irrigation at flowering stage), I_5 (300 mm with irrigation at flowering stage) and I_6 (360 mm) irrigations treatments, respectively (Table 5). Under the same levels of irrigation (I_4 and I_5), timing of irrigation had no role on production of peak LAI, which might be attributed to the fact that vegetative growth was not affected by skipping water at flowering stage. Nitrogen application rate also affected the peak LAI significantly. The lowest peak LAI of 3.45 was obtained with N_1 (30 kg N ha^{-1}) and the highest peak LAI of 5.65 was recorded in N_5 (150 kg N ha^{-1}). Greater leaf expansion in maize was ascribed to higher rate soil moisture and N available for I_4 to I_6 irrigation and N_4 to N_5 treatments.

Dry Biomass Production as Affected by Irrigation and Nitrogen

The dry biomass production at different crop growth stages of the crop are depicted in fig. 3. The highest total above ground biomass was recorded in I_6 treatment which received 360 mm of irrigation water, while the lowest grain yield was recorded in I_1 plots where 120 mm irrigation was applied. An analysis of variance (ANOVA) test showed that the mean difference in dry biomass among the irrigation and N

Table 5. Crop growth and productivity related parameters of maize as influenced by irrigation regimes and nitrogen rates (Pooled data of 2 years)

Factors	Biomass at harvest (kg ha^{-1})	Peak LAI	Grain yield (kg ha^{-1})	HI (%)	Grain No.	1000 grain weigh (g)	Peak IPAR (%)	RUE (g MJ^{-1})
I. Irrigation treatments								
I_1	6393^{E}	3.25	2129^{E}	33.31^{B}	1049^{E}	203^{E}	66.6^{E}	1.07^{E}
I_2	7161^{D}	4.07^{C}	2490^{D}	34.77^{B}	1142^{D}	218^{D}	77.0^{D}	1.18^{D}
I_3	10430^{C}	4.32^{B}	3553^{C}	34.07^{B}	1487^{C}	239^{C}	81.0^{C}	1.72^{C}
I_4	10980^{B}	5.39^{B}	3785^{B}	34.47^{B}	1545^{C}	245^{B}	85.0^{B}	1.83^{B}
I_5	12300^{A}	5.42^{A}	4534^{A}	37.94^{A}	1821^{B}	249^{A}	88.0^{A}	2.01^{A}
I_6	12700^{A}	5.53^{A}	4675^{A}	37.40^{A}	1870^{A}	250^{A}	89.0^{A}	2.05^{A}
Significance	**	**	**	NS			**	**
II. Nitrogen treatments								
N_1	6400^{D}	3.45^{E}	2295^{D}	35.86^{A}	977^{E}	235^{C}	67.8^{D}	1.01^{D}
N_2	7768^{C}	4.22^{D}	2714^{C}	34.94^{B}	1150^{D}	236^{C}	78.1^{C}	1.16^{C}
N_3	10040^{B}	4.83^{C}	3319^{B}	33.06^{B}	1406^{C}	236^{B}	83.3^{B}	1.74^{B}
N_4	12700^{A}	5.55^{A}	4385^{A}	34.53^{B}	1812^{B}	242^{A}	89.9^{A}	2.14^{A}
N_5	13100^{A}	5.65^{A}	4525^{A}	34.54^{B}	1870^{A}	242^{A}	91.2^{A}	2.18^{A}
Significance	**	**	**	NS			**	**
Interaction								
Irrigation × Nitrogen	NS	NS	**	NS				

** Significant at 5% probability level, NS = Non significant at 5% probability level
The values in the column followed by same letters are not significant at 5% level of significance based on Duncan's' Multiple Range Test (DMRT).

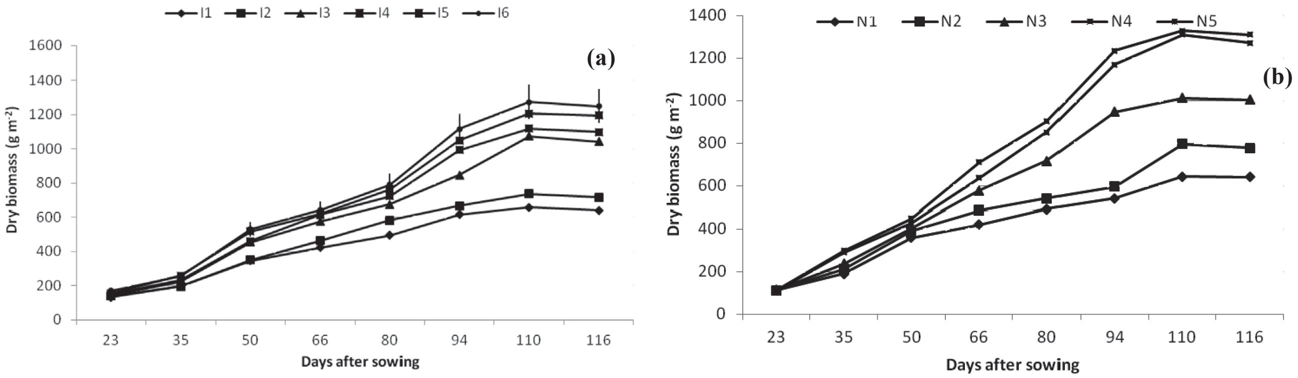

Fig. 3. Dry biomass production at different days after sowing as influenced by (a) irrigation regimes and (b) nitrogen rates

treatments were statistically significant ($P<0.05$) except between I_5 and I_6 and between N_4 and N_5 treatments. Averaged over N rates, maximum total biomass was accumulated in I_6 (12700 kg ha^{-1}) followed by I_5 (12300 kg ha^{-1}), I_4 (10980 kg ha^{-1}), I_3 (10430 kg ha^{-1}), I_2 (7161 kg ha^{-1}) and minimum biomass was found in I_1 (6393 kg ha^{-1}). A comparison of biomass among N treatments revealed that total biomass was also influenced by N application rates. The plants with N_5 (150 kg N ha^{-1}) treatment produced maximum plant height, LAI and ultimately leads to more biomass production. Like LAI, the difference in biomass production was not significant between N_4 (120 kg N ha^{-1}) and N_5 (150 kg N ha^{-1}) treatments, which might be attributed to the fact that the biomass or LAI was not proportionately increased with the amount of additional N applied.

Grain Yield and Yield Components

An analysis of variance (ANOVA) test showed that the mean difference in grain yields among the irrigation and nitrogen treatments were highly significant ($P<0.05$). In I_6, highest yield (4675 kg ha^{-1}) was obtained because in this treatment adequate water was supplied at vegetative, flowering, milk ripe-grain filling stages and the crop satisfied the water requirements fully with the amount of irrigation applied along with rainfall, soil moisture contribution from profile. Averaged over N doses, the grain yield of 2129, 2490, 3553, 3785, 4534 and 4675 kg ha^{-1} was obtained in I_1, I_2, I_3, I_4, I_5 and I_6, respectively. The yield variation occurred mainly due to variation in irrigation and N doses, N and water stress significantly affected the number of grain m^{-2}, 1000 grain weight (Table 5). Among the irrigation treatments, maximum number of effective grains m^{-2} (1870) were produced in I_6 treatment (360 mm), followed by I_5 (1821), I_4 (1545), I_3 (1487), I_2 (1142) and I_1 (1049). Highest 1000 grain weight was found in I_6 (250 g) and minimum 1000 grain weight was recorded in I_1 (203 g). Study also revealed that water stress before or during flowering and pollination resulted in reduced kernel number (I_4), while stress during or after silking reduced kernel weight (I_1 to I_3). Similar findings were also observed by Classen and Shaw (1970). Results also showed that irrigation effects on harvest index (HI) of maize were non-significant among I_1 to I_4 treatments, the crop had an average harvest index of 33.3, 34.7, 34.1, 34.5, 37.9, and 37.4% in I_1, I_2, I_3, I_4, I_5 and I_6, respectively and these variations were statistically non-significant. The non-significant variation of HI among irrigation treatments might be attributed to the fact that this parameter was not influenced by management practices but it is the characteristics of genotypes. In regards to N treatments, grain yield production was significantly affected by N application rates except between N_4 and N_5 (Table 5). Deficit N created N stress and grain yield under deficit N was reduced mainly due to reduction of kernel number and cob size. Like LAI and biomass production, the difference in grain yield was not significant between N_4 (120 kg N ha^{-1}) and N_5 (150 kg N ha^{-1}) treatments, which might be attributed to the fact that the grain was not proportionately increased with the amount of additional N applied.

IPAR under Different Irrigation and Nitrogen Levels

The IPAR at different phenological stages as influenced by irrigations and N rates are presented in fig. 4. The peak values of IPAR with different N and irrigation treatments have also been presented in Table 5. Averaged across the N levels, the lowest peak IPAR of 66.6% was observed for the I_1 which was statistically significant from IPAR of I_2 (77.0%), I_3 (81.0%), I_4 (85.0%), I_5 (88.0%) and I_6 (89.0%) treatments. The I_5 and I_6 recorded peak IPAR was statistically at par. Averaged over irrigation levels, N rates significantly affected the amount of radiation intercepted. The minimum peak IPAR (67.8%) was achieved with N_1 (30 kg N ha^{-1}). The crop with N_5 treatment recorded peak IPAR of 91.2% (Table 5). The increase in IPAR with higher level of irrigations and N rates was due to better crop growth, which gave maximum plant height, LAI and total dry matter. The IPAR was also correlated with LAI and total dry biomass of the crop and are presented in fig. 5, respectively. Study revealed that IPAR was closely related with the LAI and dry biomass in logarithmic relationship with the R^2 value of 0.77 and 0.85, respectively.

RUE under Different Irrigation and Nitrogen Levels

The relationship between total biomass production and APAR was established to derive RUE and showed the linear relationship between total biomass production and APAR (Fig. 6) with the R^2 value of 0.86. Maximum RUE (in terms of total biomass) under different irrigation regimes and N treatments are presented in Table 5. Among irrigation treatments, highest RUE of 2.05 g MJ^{-1} was obtained in case of I_6 but it was statistically at par with I_5 which recorded RUE of 2.01 g MJ^{-1}. Other irrigation treatments were significantly different in respect of RUE (Table 5).

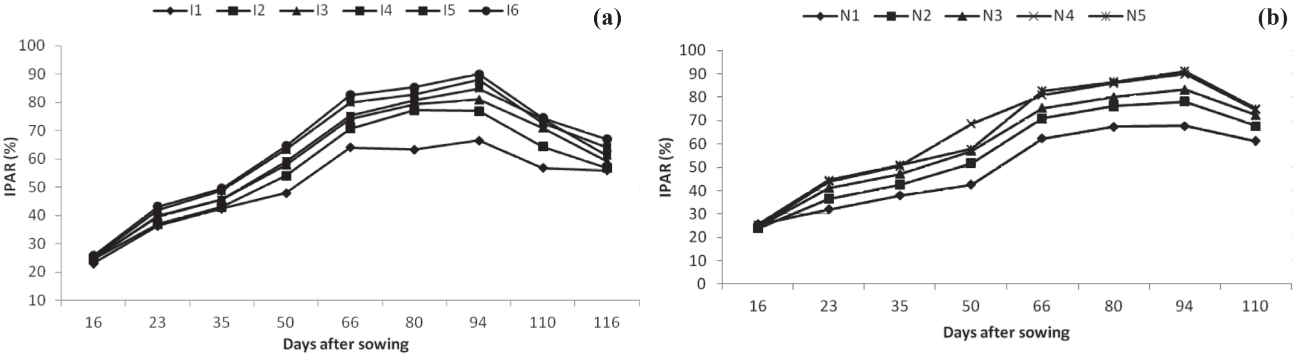

Fig. 4. IPAR (%) at different days after sowing as influenced by (a) irrigation regimes and (b) nitrogen rates

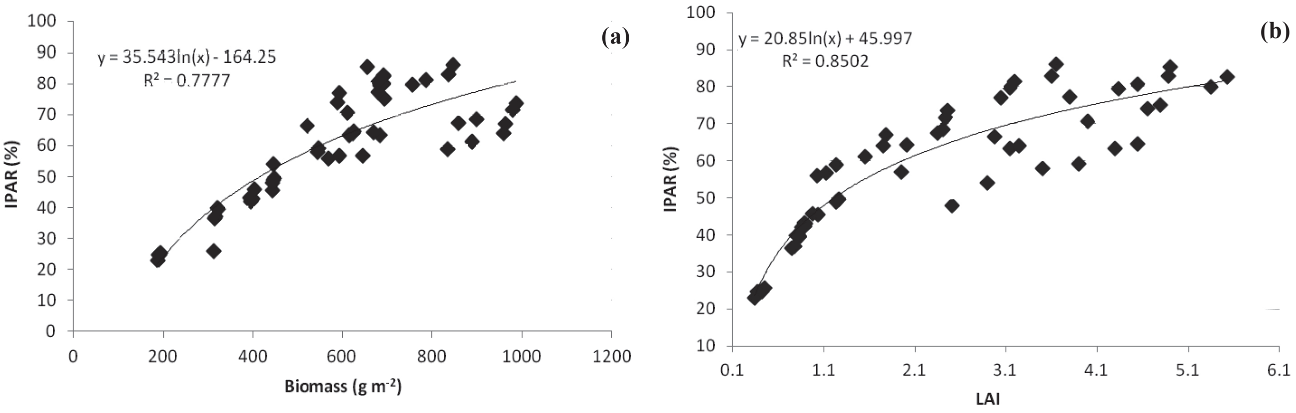

Fig. 5. Relationship between (a) IPAR (%) and dry biomass production; and (b) IPAR (%) and leaf area index

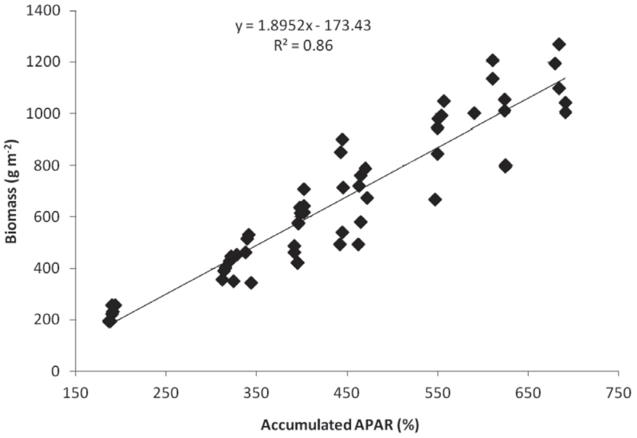

Fig. 6. Relationship between dry biomass and accumulated APAR

Averaged over irrigation treatments, RUE of 1.01, 1.16, 1.74, 2.14 and 2.18 g MJ^{-1} were recorded in N_1, N_2, N_3, N_4 and N_5, respectively, which were statistically significant. Interaction between irrigation and N treatments was found to be non-significant on IPAR and RUE also.

The RUE of different phenological stages were also computed and are presented in fig. 7. The RUE was found to be higher at dry ripe stage (kernel is no longer milky, reached physiological maturity) and did not reduce during seed filling stages in case of non-stressed irrigation and N treatments (I_3, I_4, I_5, I_6 and N_3, N_4 and N_5) but the generality of this phenomenon remains to be tested. On the other hand, in case of in irrigation and N stressed plots (I_1, I_2 and N_1, N_2), RUE was higher in milk ripe stage (milk to solid conversion of endosperm, but whole kernel content is still milky liquid) and reduced during grain filling stage. This might be attributed to the reduced seed weight and grain number in case of water and N stressed plots ((I_1, I_2 and N_1, N_2), where partitioning of photosynthates towards grain is less and limits the RUE. It appears from our study that under optimal growth conditions where assimilate supply is likely maintained approximately equal to its demand, crop growth rate was optimized and RUE did not decline. Similar findings were made by Rajcan and Tollenaar (1999). The study revealed that significant interaction effect of irrigation × N on grain yield was observed but no significant interactions of irrigation × N were observed on phenology, leaf area and biomass, peak IPAR.

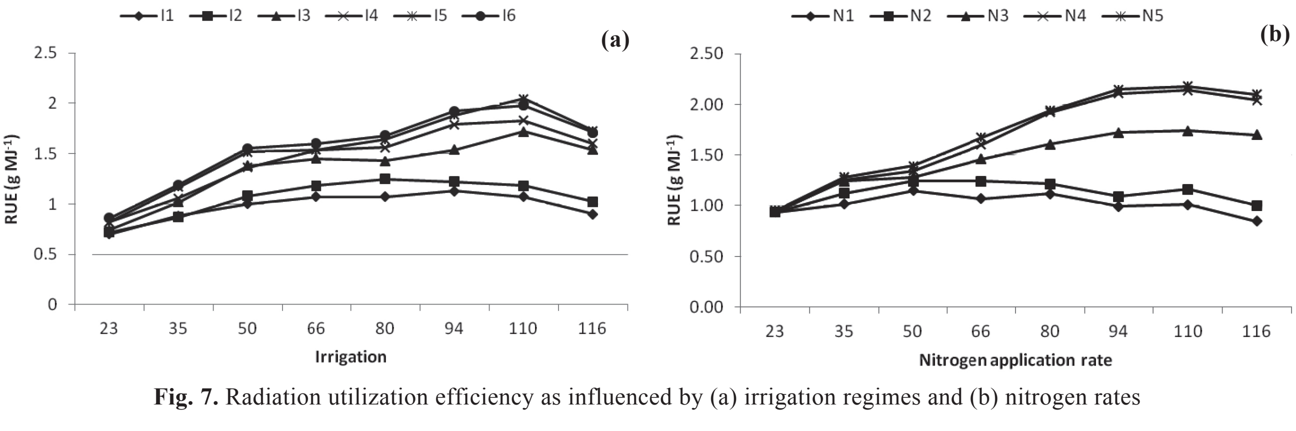

Fig. 7. Radiation utilization efficiency as influenced by (a) irrigation regimes and (b) nitrogen rates

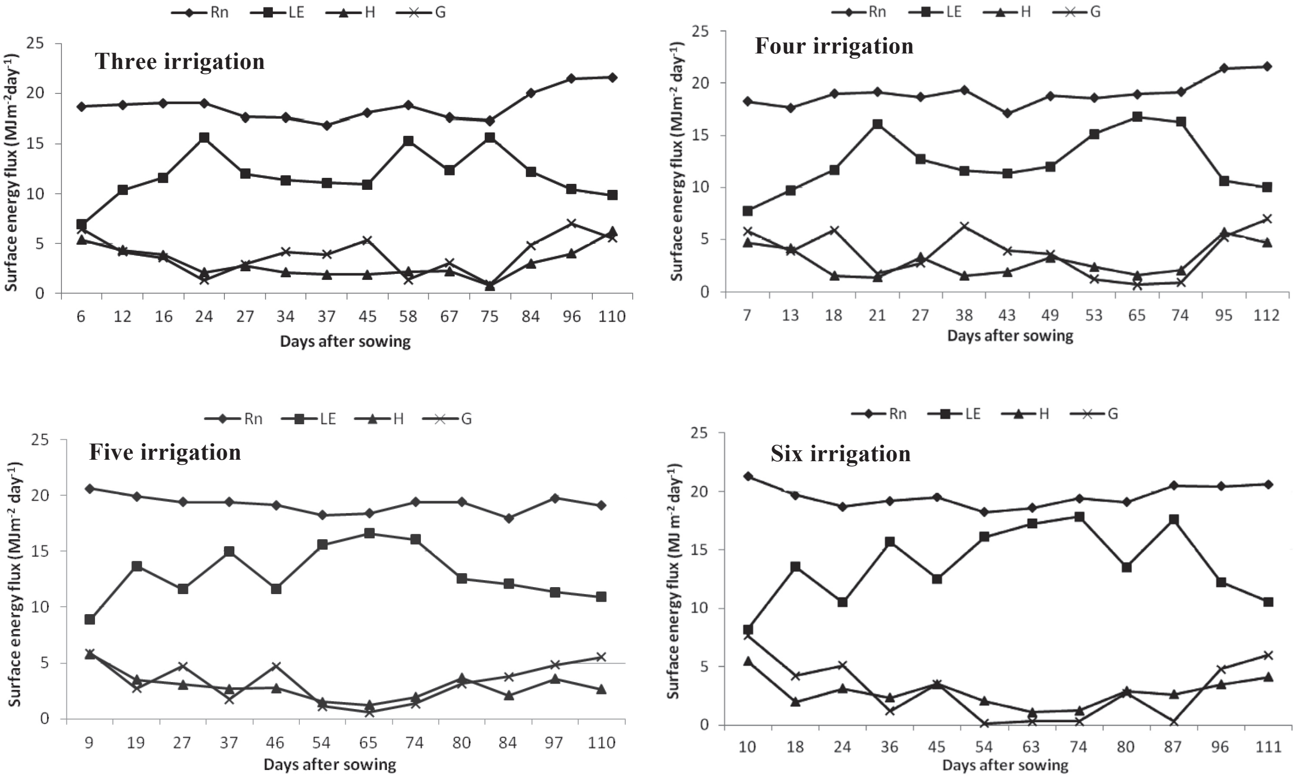

Fig. 8. Surface energy fluxes of maize under different irrigations

Surface Energy Balance

The seasonal variation of surface energy fluxes over maize crop stand during two crop growth seasons (2007-08 and 2008-09) were measured at 7-10 days interval and mid-day average value of 10.00-15.00 hour are depicted in fig. 8. Due to instrumentation limitation, measurements were restricted to I_2, I_3, I_5, I_6 plots under N_5 N treatments only (120 kg N ha^{-1}) to study the variation of surface energy fluxes under different irrigation regimes. Study revealed that average net radiation (R_n), *i.e.* amount of energy available for physical or biological processes over the crop varied from 17.09 to 21.3 MJ m^{-2} day^{-1} in different irrigation treatments during crop growth period.

The latent heat flux (LE) which is most important component of energy balance for irrigation management was largely dependent on development of LAI and soil moisture content and showed peak when LAI was maximum. The mid-day average LE (on clear days) varied from 6.89 to 15.30 MJ m^{-2} day^{-1} at different growth stages in I_2. Whereas, in I_3, LE ranged between 7.76 MJ m^{-2} day^{-1} to 16.77 MJ m^{-2} day^{-1} at different growth stages. In I_5 treatment LE varied from 7.98 to 16.58 MJ m^{-2} day^{-1} and in I_6, LE ranged between 8.19 to 17.86 MJ m^{-2} day^{-1}. The LE variation over the crop stand during different growing periods mainly occurred due to variation of solar radiation, temperature, vapour pressure deficit and soil moisture during the crop seasons. The LE by the crop increased immediately after application of irrigation water because of availability of soil moisture to evapo-transpire. Less LE was recorded when the crop was at early stage and it increased with increasing the LAI of the crop.

The seasonal course of soil heat flux (G) of crop revealed that variation of 'G' during growth seasons clearly reflected the change of crop growth. The 'G' showed peak value during early vegetative and maturity periods when crop coverage was minimum and soil was dry. Afterwards, the course of 'G' was affected by development of crop canopy or LAI. Mid-day averaged 'G' value of crop stand ranged from 0.754 to 8.1 MJ m^{-2} day^{-1} at different growth stages and seasons and 'G' reduced drastically with the application of irrigation water. The ratio of G/R_n from maximum LAI to senescence stage was found to be 6.8-14.8% over the crop. Soil heat flux showed declining trend during peak growth stage which coincided with maximum LAI or maximum IPAR. In general, where water did not limit the transpiration and when soil was wet, LE consumed most of the energy from net radiation. As the soil dried, water became

Table 6. Water productivity of maize under different irrigation and nitrogen levels (pooled data of two years)

Irrigation treatments	GY (kg ha^{-1})	NR (Rs. ha^{-1})	IWA (mm)	ER + (mm) SPC(mm)	SCWU (mm)	WP_{CWU} (kg m^{-3})	WP_{NR} (Rs. m^{-3})	$WP\$_{NR}$ (\$ m^{-3})
I. Irrigation treatments								
I_1	2129^{E}	11661	120	131	251	0.849^{D}	4.65^{D}	0.076
I_2	2490^{D}	14910	180	127	307	0.811^{D}	4.86^{C}	0.080
I_3	3553^{C}	21977	240	118	358	0.993^{B}	6.14^{A}	0.101
I_4	3785^{B}	24065	300	112	412	0.918^{C}	5.84^{B}	0.096
I_5	4534^{A}	25806	300	105	405	1.120^{A}	6.37^{A}	0.104
I_6	4675^{A}	27075	360	99	459	1.019^{B}	5.90^{B}	0.097
II. Nitrogen levels								
N_1	2295^{D}	13155	300	114.8	365	0.629^{D}	3.61^{C}	0.059
N_2	2714^{C}	20526	300	116.8	366	0.742^{C}	5.61^{B}	0.092
N_3	3319^{B}	19871	300	115.6	366	0.908^{B}	5.44^{B}	0.089
N_4	4385^{A}	29465	300	114.5	365	1.203^{A}	8.08^{A}	0.133
N_5	4525^{A}	25725	300	115.5	365	1.239^{A}	7.04^{A}	0.115

GY = Grain yield; NR = Net return; IWA - Irrigation water applied ER = Effective rainfall; SPC = Soil profile contribution; SCWU = Seasonal crop water productivity; WPcwu = Water productivity in terms of crop water use; WP_{NR} = Water productivity in terms of net return in rupees; $WP\$_{NR}$ = Water productivity in terms of net return in US dollar

less available for evapo-transportion and the energy was utilized for heating the soil (soil heat flux) or heating the air (sensible heat flux).

Seasonal Crop Water use and Water Productivity

The grain yield along with the depth of irrigation applied, seasonal water use and water productivity of the crop are given in the table 6. The seasonal crop water use of 251, 307, 358, 412, 405 and 459 mm was determined in I_1, I_2, I_3, I_4, I_5 and I_6 treatments, respectively. From this study it is revealed that for obtaining optimum yield, irrigation at all the stages are required but by applying adequate water at flowering and milk ripe-grain filling stages and deficit water application at vegetative and late reproductive stage, the yield reduction can be minimized. The water productivity in terms of seasonal crop water use (WP_{SCWU}, kg m^{-3}) and net economic return (WP_{eco}, Rs m^{-3} or \$ m^{-3}) were computed and pooled data for both the study years are presented in table 6. Results showed that though yield and net economic returns were the highest in I_6 treatment where 360 mm irrigation water applied but the WP_{CWU} was the highest in I_5 where 300 mm irrigation water was applied (including at flowering stage). This may be attributed to the fact that yield was not achieved proportionately in I_6 treatment with amount of additional water applied. Zwart and Bastiaansen (2004) also concluded that the CWP could be significantly increased if irrigation was reduced and crop water deficit was intentionally induced. In our study water productivity (in terms of seasonal crop water use) of 0.849, 0.811, 0.993, 0.918, 1.120, 1.019 kg m^{-3} was obtained in I_1, I_2, I_3, I_4, I_5 and I_6 irrigations treatments, respectively. These findings imply that 84.9, 81.1, 99.3, 91.8, 112.0, 101.9 kg ha^{-1} maize grain yield was obtained per 100 m^3 of water used by the crop in different irrigation treatments. The highest water productivity in terms of economic value (CWP_{eco}) was obtained in I_5 plots, varied from Rs. 6.37 m^{-3} (\$ 0.104 m^{-3}) because of higher grain yield and net economic returns per unit volume of water utilized. Lowest CWP_{eco} (Rs. 4.65 m^{-3} or \$ 0.076 m^{-3}) was obtained in I_1 plots because of low yield and economic returns per unit volume of water utilized. Nitrogen application rate also significantly affected crop water productivity. The water productivity of 0.629, 0.742, 0.908, 1.203, 1.239 kg m^{-3} was obtained in N_1, N_2, N_3, N_4, N_5 and N_6 treatments, respectively.

A comparison of WP_{SCWU} between the treatments receiving irrigation at flowering and milk ripe-grain filling stages and not receiving irrigations at these stages with same amount of irrigation (I_4 and I_5) showed that water was more efficiently utilized when irrigation was not skipped at flowering and milk ripe-grain filling stages. As for example with the same amount of irrigation (300 mm) in I_4 and I_5, less crop yield was obtained in I_4 because irrigation was skipped at flowering stage of the crop under this treatment. Better water utilization efficiency and higher CWP_{SCWU} in treatment I_5 were obtained which might be associated with adequate water applied during flowering stage. This result implies that the crop growth stage at which deficit irrigations are imposed on the crop is also a determining factor to achieve higher CWP_{SCWU}. The ranges of crop water productivity in our study fall within the range of 0.3 to 2.7 kg

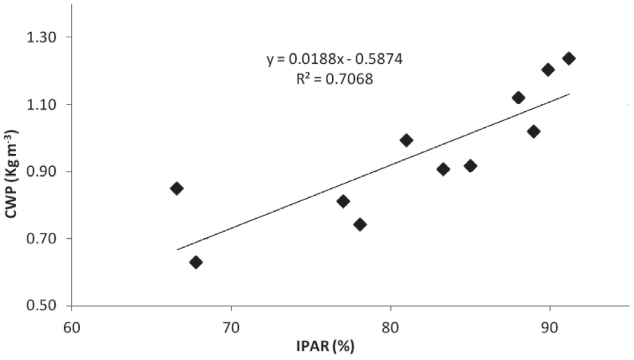

Fig. 9. Relationship between crop water productivity (CWP) and IPAR

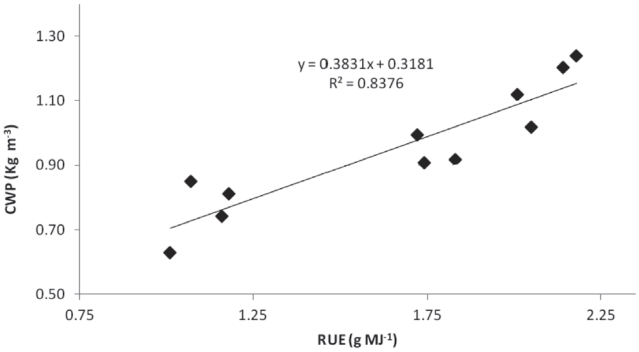

Fig. 10. Relationship between crop water productivity (CWP) and RUE

m^{-3} reported in literature for maize around the world (Bastiaannssen 2000; Bastiaannssen *et al.* 2003). The relationships among IPAR and water productivity (Fig. 9), RUE and water productivity (Fig. 10) were also established and linear relationships were found the best.

Conclusions

A comparison of water productivity between the treatments receiving irrigation at flowering and milk ripe-grain filling stages and not receiving irrigations at these stages with same amount of irrigation (300 mm) showed that water was more efficiently utilized when irrigation was not skipped at flowering and milk ripe-grain filling stages. The RUE was higher in milk ripe stage and reduced during grain filling stage. It appears from our study that, under optimal growth conditions where assimilate supply is likely maintained approximately equal to its demand, crop growth rate was optimized and RUE did not decline. Simulation models that rely on RUE for biomass accumulation can use these relationships for predicting biomass and yield of the crop under different N and irrigation levels. When water did not limit the transpiration and the soil was wet, latent heat flux consumed most of the energy from net radiation. As the soil dried or in water stressed plots less water became available for evapo-transpiration and net radiation was mostly utilized for heating the soil (soil heat flux) or heating the air (sensible heat flux). Crop water productivity (CWP) was maximized by withholding irrigation at certain stages under limited irrigation availability. It is important, however, to mention that the objectives of farmers many times is not to maximize CWP, but to maximize profits. Therefore, there could be very good justifications for applying deficit irrigation other than trying to increase CWP. Under the condition of water scarcity in eastern India, deficit irrigation combined with proper fertility and plant population may be a viable alternative to improve biomass and crop water productivity of maize.

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Revised received 1 August 2014; Accepted 4 December 2014