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ORIGINAL PAPER

Effect of irrigation and nitrogen application methods on input use efficiency of wheat under limited water supply in a Vertisol of Central India

**K. K. Bandyopadhyay · A. K. Misra ·
P. K. Ghosh · K. M. Hati · K. G. Mandal ·
M. Moahnty**

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Abstract Field experiments were conducted in a deep Vertisol at the Indian Institute of Soil Science, Bhopal during the years 2001–2005 to assess the effect of five different irrigation strategies through combinations of sprinkler and flood irrigation and two N application methods on yield and water use efficiency of wheat (cv WH 147). The amount of irrigation applied each year differed according to the availability of water in the water harvesting pond to simulate the actual water crisis faced by the farmers in this region during these years due to monsoon failure. Results indicated that when wheat was grown only with 8-cm irrigation at sowing or 14 cm up to the crown root initiation stage, dry sowing of wheat immediately followed by sprinkler and subsequent irrigation through flooding produced the highest yield and water and nitrogen use efficiencies. However, when 20-cm irrigation was supplied up to the flowering stage or 14-cm irrigation was supplied up to tillering stage through sprinkler in 4 and 3 splits, respectively, at critical growth stages, maximized the grain yield and water and nitrogen use efficiencies. Across the years, the crop yield and water and nitrogen use efficiencies increased with increase in water supply.

Introduction

In India, monsoon rains have a significant bearing on agricultural productivity. Other than meeting the water requirement of the rainy season crops, the monsoon rains also determine the recharge of groundwater and harvesting of water in ponds for subsequent use for irrigating the post-rainy season crops. In Vertisols, water harvested in the ponds does not last long enough to provide irrigation for the entire growth period of post-rainy season crops because of losses by seepage through cracks and evaporation. Thus, limited availability of irrigation water is one of the major constraints to higher productivity of wheat in the Vertisols of Central India. The erratic distribution of rainfall in this region further aggravates the problem. Thus, there is a need for developing strategies for efficient utilization of water for higher crop yield.

In Vertisols, irrigation applied through surface flooding results in non-uniform distribution of water and fertilizer in the seed-zone because of preferential flow of water and the dissolved fertilizer through shrinkage cracks causing leaching loss of fertilizers (Smalling and Bouma 1992), which not only reduces the fertilizer use efficiency and crop yield but also leads to environmental pollution due to ground water contamination. Sprinkler irrigation may be a viable alternative to flood irrigation (Chen et al. 2002; Home et al. 2002) to address this water management problem. Beneficial effect of sprinkler irrigation over flood irrigation with respect to water saving and increase in water use efficiency has been reported by many workers (Verma and Shrivastava 1992; Home et al. 2002; Pawar et al. 2002). However, sprinkler irrigation is an energy intensive process because of low discharge rate than the flood irrigation, which requires the pump to run for longer period to apply a given amount of water. Furthermore, the resource-poor

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K. K. Bandyopadhyay · A. K. Misra · P. K. Ghosh ·
K. M. Hati · K. G. Mandal · M. Moahnty
Indian Institute of Soil Science, Nabibagh, Berasia Road,
Bhopal 462 038, Madhya Pradesh, India

K. K. Bandyopadhyay (✉)
Central Institute for Cotton Research Regional Station,
Coimbatore 641003, India
e-mail: kk.bandyopadhyay@gmail.com

farmers of the third world countries cannot afford to own the sprinkler system, rather they can hire it from other farmers having this system. So, strategically, there is novel effort for combined use of irrigation methods (Manjunatha et al. 2000). Honglu et al. (1998) reported that an irrigation system with sprinkler in the early stages of maize and wheat and surface irrigation at the later stage was economically feasible and water efficient.

Yield of wheat under irrigated condition is a function of evapo-transpiration, which is usually reflected in the water use efficiency and water use pattern of the crop (Van Keulen 1975; Fischer 1979). The relationship between crop yield and seasonal evapo-transpiration in the form of evapo-transpiration production function (ETPF) has been reported as linear by some workers (Singh et al. 1979; Steiner et al. 1985; Hunsaker and Bucks 1987; Musick and Porter 1990; Hati et al. 2001). However, others have reported curvilinear ETPF (Ehlig and Le Mert 1976; Sharratt et al. 1980; Bandyopadhyay et al. 2004). Although yield–ET relationships have been widely used for irrigation management purpose in water-limited areas, they did not account for nutrient management and these are mostly based on conventional flood irrigation method. Therefore, there is need for a thorough understanding of the effect of irrigation methods on relationships between crop yield and evapo-transpiration and water use efficiency by wheat.

There is a significant interaction between nitrogen and water supply for their effect on wheat yield (Gajri et al. 1993; Hussain and Al-Jalaud 1995). However, the response of yield to N supply is strongly influenced by environmental conditions, especially the quantity and timing of water available to the crop (Hauck 1984). So there is a need for developing strategies for optimum utilization of water for achieving higher nitrogen use efficiency and crop yield. Nitrogen use efficiency by wheat is less in Vertisols due to losses of N by ammonia volatilization under high soil pH, leaching and denitrification. Efforts have been made by different workers to improve the nitrogen use efficiency in wheat through modified nitrogenous fertilizers, nitrification, urease inhibitors etc. Manipulation of timing of fertilizer application and method of irrigation may help in improving nitrogen use efficiency of wheat (Abourached et al. 2008). A number of experiments in winter cereals have shown that adjusting fertilizer rate and splitting of N fertilizer application are strategies to improve nitrogen use efficiency (Dilz 1988; Alcoz et al. 1993; Delogu et al. 1998; Lopez Bellido et al. 2005). Besides timing, placement of fertilizer N also influences the nitrogen use efficiency (Mahler et al. 1994). It has been reported that application of nitrogenous fertilizer before irrigation transports it to subsurface layer and results in higher nitrogen use efficiency and crop yield. However, in Vertisols, because of crack formation, farmers usually prefer to apply nitrogen fertilizers after irrigation to avoid the leaching loss of N through the cracks.

In this backdrop, the objective of the present investigation was to study the effect of different combinations of sprinkler and surface flooding on root growth, soil water extraction, crop yield, evapo-transpiration production functions and water and nitrogen use efficiency of wheat under limited water supply.

Materials and methods

Soil and climate

Field experiments were conducted during 2001–2005 in a Vertisol at the research farm of the Indian Institute of Soil Science, Bhopal (23°18′N, 77°24′E and 485 m above mean sea level), Madhya Pradesh, India. The region has a hot and subhumid climate with mean annual rainfall of 1,083 mm and mean annual potential evapo-transpiration of 1,400 mm. Much (88%) of the rainfall occurs during the four rainy months (June to September), but the distribution is quite erratic. The rainfall received during the last 3 years (827 mm in 2001, 761 mm in 2002, 863 mm in 2004) was much less than the mean annual rainfall of this region (1,083 mm), whereas there was 1,113 mm rainfall in 2003. Farmers in this region experienced water stress in the low rainfall years (2001, 2002 and 2004). The monthly rainfall for the five cropping years along with the 28 years average monthly

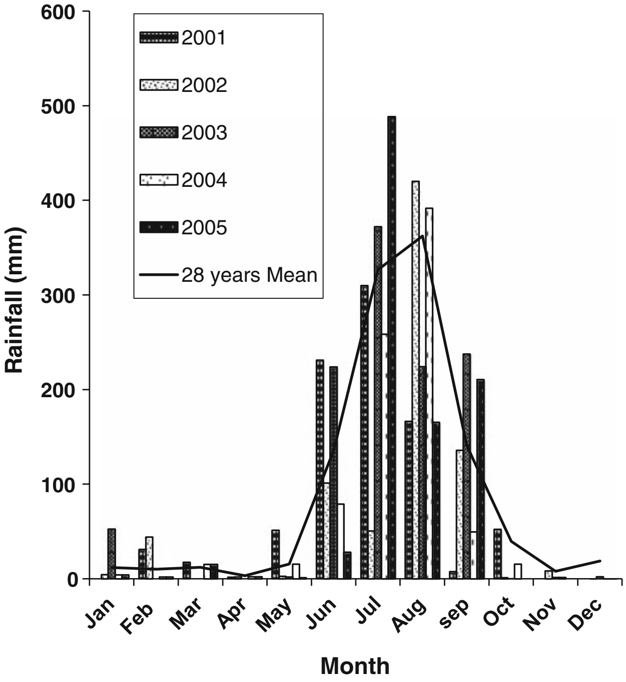

Fig. 1 Distribution monthly rainfall during the years 2001–2005

Table 1 Description of the treatments used for the experiment

Irrigation methods	Pre-/postsowing	1st irrigation (CRI)	2nd irrigation (tillering)	3rd irrigation (flowering)
Main plot: irrigation method				
I_1	4 cm Presowing (sprinkler)	5 cm (Sprinkler)	5 cm (Sprinkler)	6 cm (Sprinkler)
I_2	8 cm Presowing (sprinkler)	6 cm (Sprinkler)	–	6 cm (Sprinkler)
I_3	8 cm Presowing (sprinkler)	6 cm (Flooding)	–	6 cm (Flooding)
I_4	8 cm Postsowing (sprinkler)	6 cm (Flooding)	–	6 cm (Flooding)
I_5	8 cm Presowing (flooding)	6 cm (Flooding)	–	6 cm (Flooding)
Subplot: N application methods				
N_1	100% N as basal before presowing irrigation			
N_2	50% N as basal after presowing irrigation + 50% N topdressing after 1st irrigation			

rainfall have been depicted in Fig. 1. The soil of the experimental site was a deep Vertisol (Typic Haplustert) with clayey texture (52% clay) and bulk density of 1.34 Mg m^{-3} at 0.27 g g^{-1} soil water content. The moisture retentions at 0.033 and 1.5 Mpa were 40.6 and 25.6%, respectively, in the surface (0–15 cm) layer. The pH of the surface soil (1:2 soil/water ratio) was 7.5 with 5.2 g kg^{-1} soil organic carbon (Walkley and Black 1934), 0.3 dS m^{-1} electrical conductivity (1:2 soil/water ratio) and 46 cmol (p+) kg^{-1} cation exchange capacity. The soil was low in available N (Alkaline $KMnO_4$ oxidizable N as per Subbiah and Asija 1956) (112 mg kg^{-1}), exchangeable NH_4-N being 15.5 kg ha^{-1} and exchangeable NO_3-N being 25.3 kg ha^{-1} (Keeney and Nelson 1982) and available P (0.5 M NaHCO3 extractable P as per Olsen et al. 1954) (2.6 mg kg^{-1}) and high in available K (1 M ammonium acetate extractable K as per Knudsen et al. 1982) (227 mg kg^{-1}).

Experimental details

The treatment consisted of five irrigation strategies with different combinations of sprinkler and flood irrigation at critical growth stages as main plot factors and two N application methods as subplot factors (Table 1). The factorial combination of treatments was laid out in a split plot design with four replications. The subplot size was 6 m × 6 m. Surface flood irrigation was supplied through HDPE pipes, while sprinkler irrigation was supplied through aluminum pipes with riser pipes (20 mm × 75 cm). The size of sprinkler nozzle was 3.17 mm × 2.38 mm (RIL 10, M/S Rungta Irrigations Ltd, Jabalpur, India) with a discharge rate of 3.6 lpm at a pressure of 0.35 kg cm^{-2}. The diameter of spray was 9.5 m with precipitation rate of 5.6 mm h^{-1} at an area of 6 m × 6 m. The sprinkler spacing was maintained at 6 m × 6 m and

Table 2 Year-wise application of irrigation water

Irrigation methods	Critical stage up to which irrigation was supplied			
	2001–2002 (Sowing)	2002–2003 (CRI)	2003–2004 (Flowering)	2004–2005 (Tillering)
I_1	4 cm (PS)-Sp	4 cm (PS)-Sp + 5 cm (CRI)-Sp	4 cm (PS)-Sp + 5 cm (CRI)-Sp + 5 cm (Till)-Sp + 6 cm (F)-Sp	4 cm (PS)-Sp + 5 cm (CRI)-Sp + 5 cm (Till)-Sp
I_2	8 cm (PS)-Sp	8 cm (PS)-Sp + 6 cm (CRI)-Sp	8 cm (PS)-Sp + 6 cm (CRI)-Sp + 6 cm (F)-Sp	8 cm (PS)-Sp + 6 cm (CRI)-Sp
I_3	8 cm (PS)-Sp	8 cm (PS)-Sp + 6 cm (CRI)-Fl	8 cm (PS)-Sp + 6 cm (CRI)-Fl + 6 cm (F)-Fl	8 cm (PS)-Sp + 6 cm (CRI)-Fl
I_4	8 cm (PoS)-Sp	8 cm (PoS)-Sp + 6 cm (CRI)-Fl	8 cm (PoS)-Sp + 6 cm (CRI)-Fl + 6 cm (F)-Fl	8 cm (PoS)-Sp + 6 cm (CRI)-Fl
I_5	8 cm (PS)-Fl	8 cm (PS)-Fl + 6 cm (CRI)-Fl	8 cm (PS)-Fl + 6 cm (CRI)-Fl + 6 cm (F)-Fl	8 cm (PS)-Fl + 6 cm (CRI)-Fl

NB: *PS* presowing, *PoS* postsowing, *CRI* crown root initiation, *Till* tillering, *F* flowering, *Sp* sprinkler, *Fl* surface flooding irrigation was applied with 50% overlapping for uniform distribution of water in the plot. Sufficient buffer strip (6 m width) was left between the irrigation strips to avoid any error during water application.

Although initially it was planned to apply 20 cm of water (Table 1), the amount of irrigation applied differed from year to year (Table 2) depending on the availability of water in the water harvesting pond to simulate the actual water crisis faced by the farmers of this region in these 4 years. In the 1st year (2001–2002), only 8-cm irrigation was supplied once before sowing, in the 2nd year (2002–2003), 14-cm irrigation was supplied up to the crown root initiation (CRI) stage, only in the 3rd year (2003–2004), 20-cm irrigation was supplied up to flowering stage, whereas in the 4th year (2004–2005), 14-cm irrigation was supplied up to maximum tillering stage as per the treatment (Table 1). All the plots received recommended basal dose of phosphorus and potassium (26.2 kg P ha^{-1} as single super phosphate and 33.3 kg K ha^{-1} as muriate of potash). Nitrogen was applied at 120 kg N ha^{-1} as urea as per treatment (Table 1).

Estimation of soil water storage, evapo-transpiration and water use efficiency

Soil water content in the profile was measured gravimetrically at regular intervals up to a depth of 90 cm at 15-cm increment. Seasonal evapo-transpiration (ET) was estimated using water balance approach,

$$\mathrm{ET} = P + I + \mathrm{Cp} - \mathrm{Dp} - \mathrm{Rf} - \Delta \mathrm{S} \quad (1)$$

where P, precipitation; I, irrigation; Cp, contribution through capillary rise from groundwater; Dp, deep percolation; Rf, runoff; $\Delta \mathrm{S} = \mathrm{Sf} - \mathrm{Si}$, change in the soil water storage in the profile; where Si, soil water storage in the profile at sowing and Sf, soil water storage in the profile at harvest.

Since the depth of groundwater was very low (6–8 m), Cp was assumed negligible. Dp was considered negligible beyond 90 cm because of negligible changes in the soil moisture storage below 90 cm soil depth. There was no runoff (Rf) from the field as all the plots were provided with bunds. Thus,

$$\mathrm{ET} = P + I - \Delta \mathrm{S}. \quad (2)$$

Evapo-transpiration production function (ETPF), the linear relation between yield (Y) and seasonal evapo-transpiration was derived as

$$Y = a + b \times \mathrm{ET} \quad (3)$$

where a is the intercept and b is the slope of the ETPF.

Water use efficiency (WUE) was computed as

$$\mathrm{WUE} = \frac{Y}{\mathrm{ET}} \quad (4)$$

where Y is the grain yield of wheat. Thus,

$$\mathrm{WUE} = b + \frac{a}{\mathrm{ET}}. \quad (5)$$

Marginal water use efficiency (WUEm), the differentiation of the ETPF with respect to ET i.e., (dY/dET), was computed using the following formula (Liu et al. 2002)

$$\mathrm{WUEm} = \mathrm{d}Y/\mathrm{dET} = b \quad (6)$$

where b is the intercept of the WUE vs. 1/ET equation (Eq. 5).

The elasticity of water production function (Ewp) was computed using the following formulae (Liu et al. 2002)

$$\mathrm{Ewp} = \frac{\mathrm{d}Y/Y}{\mathrm{dET}/\mathrm{ET}} = \frac{\mathrm{d}Y/\mathrm{dET}}{Y/\mathrm{ET}} = \frac{\mathrm{WUEm}}{\mathrm{WUE}} = \frac{b \times \mathrm{ET}}{a + b \times \mathrm{ET}} \quad (7)$$

WUE will increase with ET if $a < 0$, decrease with increasing ET if $a > 0$, and equal to WUEm if $a = 0$.

According to Liu et al. (2002), when ET is equal to maximum ET (ETm)

$$\mathrm{Ewp} = \mathrm{Ky} \quad (8)$$

where Ky = Yield response factor of Doorenbos and Kassam (1979) equation

$$1 - \frac{Y}{Y_{\mathrm{m}}} = \mathrm{Ky}\left(1 - \frac{\mathrm{ET}}{\mathrm{ETm}}\right). \quad (9)$$

Table 3 Effect of methods and scheduling of irrigation on seedling emergence parameters of wheat

Irrigation	2002–2003			2003–2004			2004–2005		
	Population m^{-2}	MED	ERI	Population m^{-2}	MED	ERI	Population m^{-2}	MED	ERI
I_1	166b*	5.65	29.4	293a	10.2	28.7	219a	6.6	33.0
I_2	156bc	5.45	28.6	269b	9.0	30.0	209a	6.4	32.5
I_3	138c	6.08	22.7	264b	9.0	29.5	179ab	7.8	22.8
I_4	225a	5.22	43.1	187c	5.1	36.9	206a	9.3	22.2
I_5	104d	6.01	17.2	171c	9.7	17.7	128b	6.5	19.7

MED mean emergence day, *ERI* emergence rate index

* Means followed by the same letter in a column are not statistically different at $P < 0.05$ as per DMRT (Duncan's multiple range test)

Soil water extraction from different soil layers was computed as

$$\mathrm{SWE}_i = \sum_{j=1}^{k} \Delta w_{ij} \times \rho_i \times z_i \qquad (10)$$

where SWE_i, soil water extraction from ith layer; Δwij, change in the gravimetric water content of the ith layer at jth sampling interval; ρ_i, bulk density of the ith layer; z_i, depth of ith layer; and k, number of sampling intervals.

Total soil water extraction from the profile was computed as

$$\mathrm{SWE} = \sum_{i=1}^{n} \mathrm{SWE}_i \qquad (11)$$

where n is the number of layers in the profile.

Estimation of nitrogen use efficiency

After leaving the border rows of 1 m from all the four sides of the plot, the net plot was harvested manually. Then, representative plant samples were collected for N analysis. After processing, the grain and straw samples were analyzed for total N content using Kjeldhal method A.O.A.C (1970). Using the biomass and N concentration, the N uptake by grain and straw was estimated. These data were utilized to compute different nitrogen use efficiency parameters as follows:

$$\text{N uptake}\left(\text{kg ha}^{-1}\right) = \text{N concentration}\ (\%) \times \text{Biomass}\left(\text{kg ha}^{-1}\right) \qquad (12)$$

$$\text{N Harvest Index (NHI)} = \frac{\text{N uptake by grain}\left(\text{kg ha}^{-1}\right)}{\text{Total N uptake by grain and straw}\left(\text{kg ha}^{-1}\right)} \qquad (13)$$

$$\text{N requirement}\left(\text{NR, kg N uptake 100 kg}^{-1}\text{ grain}\right) = 100 \times \frac{\text{Total N uptake}\left(\text{kgha}^{-1}\right)}{\text{Grain yield}\left(\text{kg ha}^{-1}\right)} \qquad (14)$$

$$\text{Partial factor productivity of N (PFPN)} = \frac{\text{Grain yield}\left(\text{kg ha}^{-1}\right)}{\text{Total N applied}\left(\text{kg ha}^{-1}\right)} \qquad (15)$$

$$\text{N utilization efficiency}\left(\text{NUtE, kg kg}^{-1}\right) = \frac{\text{Grain yield}\left(\text{kg ha}^{-1}\right)}{\text{Total N uptake}\left(\text{kg ha}^{-1}\right)}. \qquad (16)$$

Root studies

Root samples were collected at the flowering stage of wheat using root sampling cores (6 cm height, 8.6 cm diameter) up to a depth of 30 cm. After thorough washing in the root washing system and staining with methylene blue staining agent, the root length was determined with a Delta T scanner and image analysis system (Delta-T Devices Ltd., Burwell, Cambridge, England).

The root length density (RLD) of a given layer was computed as

$$\mathrm{RLD}_i = L_i/V \qquad (17)$$

where L_i, length of roots collected from ith layer, V, volume of the sampling core.

The root mass density (RMD) of a given layer was computed using the oven dry weight of the root mass collected in the core samplers using the following formulae

$$\mathrm{RMD}_i = M_i/V \qquad (18)$$

where M_i, mass of roots collected from ith layer, V, volume of the sampling core.

Seedling emergence study

Seedling emergence parameters were determined by daily counting of the number of emerged seedlings in 1 m^2 area with three replications until a constant value was attained.

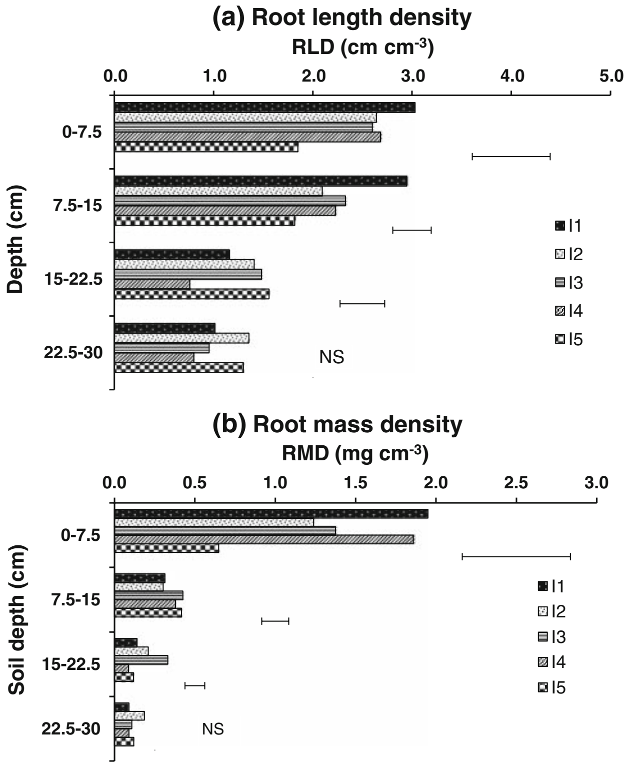

Fig. 2 **a** Root length density and **b** Root mass density of wheat at peak flowering stage during the year 2004–2005 as influenced by methods of irrigation. *The error bars* wherever present indicate the least significant difference at $P < 0.05$

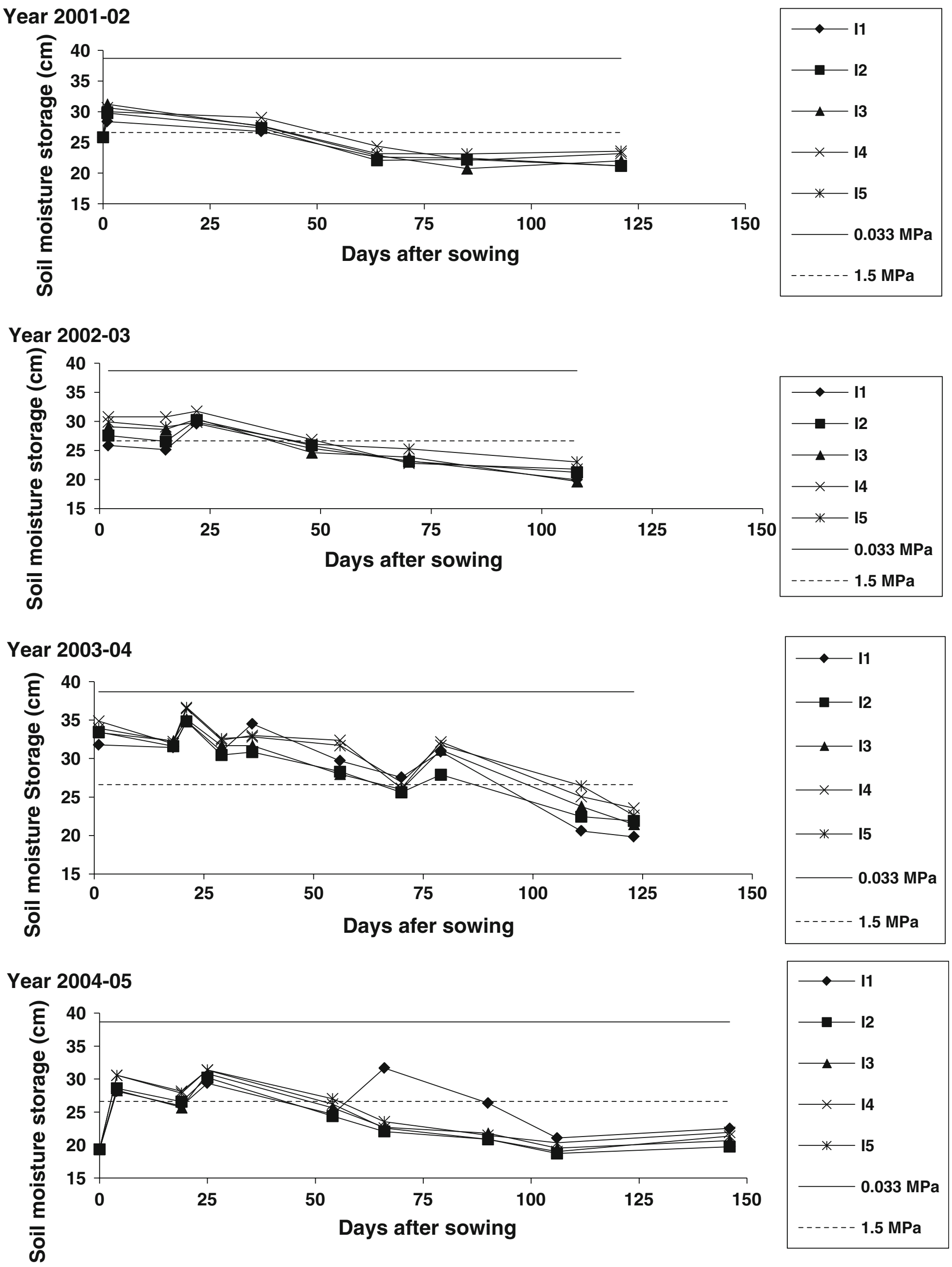

Fig. 3 Temporal variation in the soil water storage in the profile (0–90 cm) during wheat growth in different years as influenced by the methods of irrigation

The emergence rate index (ERI) was estimated following Bilbro and Wanjura (1982)

$$\text{ERI} = (\text{No. of emerged plants}/m)/\text{Mean emergence day (MED)} \quad (21)$$

where

$$\text{MED} = \sum_{i}^{n} NiDi \Big/ \sum_{i}^{n} Ni \quad (20)$$

N_i is the number of plants emerged in any particular day (Di), and Di is the number of days after sowing.

Statistical analysis

All the data were statistically analyzed using analysis of variance (ANOVA) as applicable to split plot design (Gomez and Gomez 1984). The significance of the treatment effects was determined using *F*-test, and the difference between the means was estimated by using least significance difference and Duncan's multiple range test at 5% probability level. Regression analyses were determined using the data analysis tool pack of MS excel.

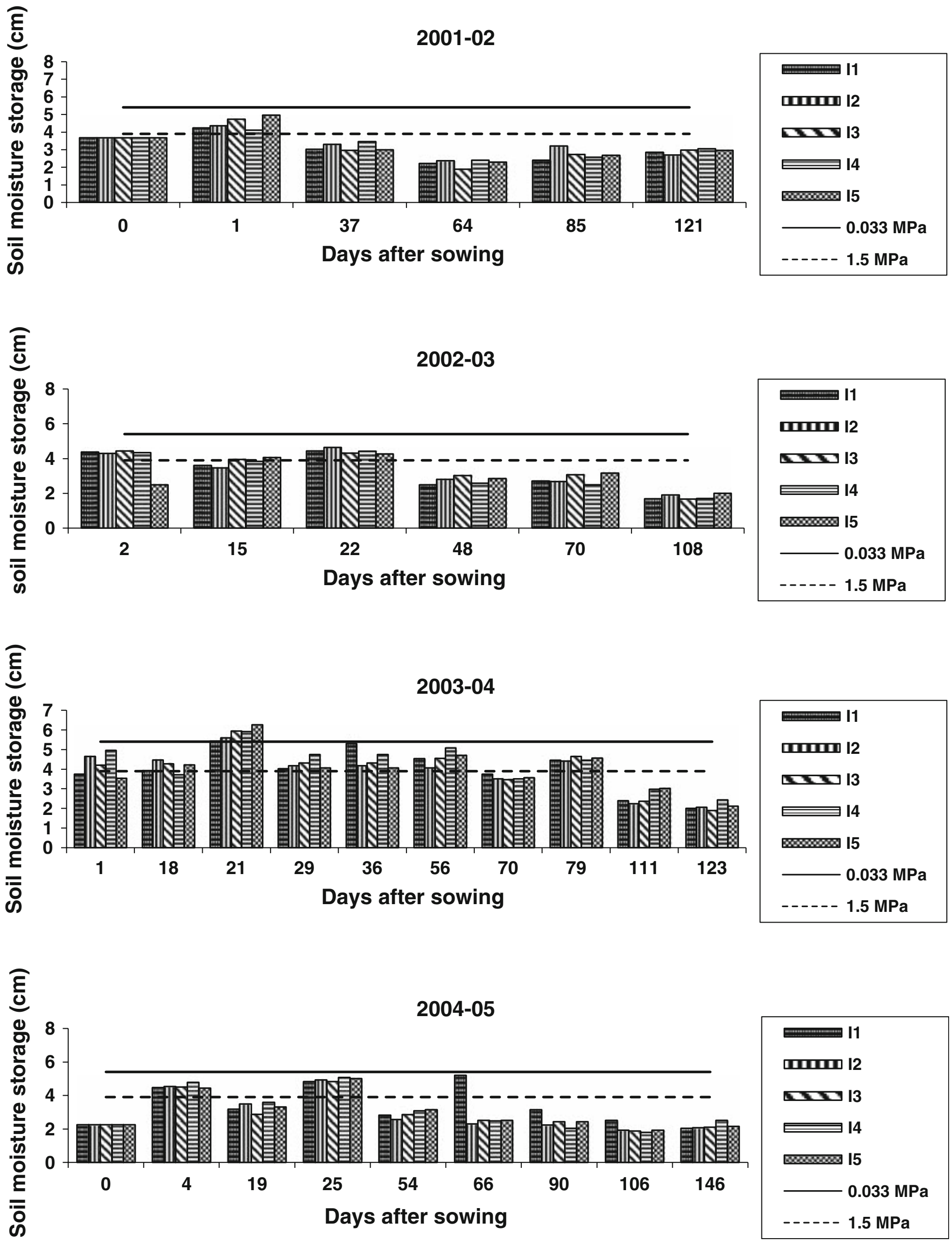

Fig. 4 Temporal variation in the soil water storage in the plough layer (0–15 cm) during wheat growth in different years as influenced by the methods of irrigation

Results and discussion

Seedling emergence under different methods of irrigation

Flood-irrigated plots (I_5) had lower plant population and emergence rate index than sprinkler-irrigated plots (Table 3). This may be attributed to uniform wetting of seed zone under sprinkler irrigation, whereas under flood irrigation, there was chance of non-uniform wetting of seed zone due to preferential flow of water through shrinkage cracks (Smalling and Bouma 1992). Mean emergence day (MED), the time taken for complete emergence, was lowest in I_4 during 2002–2003 and 2003–2004 and in I_2 during 2004–2005. The emergence rate index (ERI) was highest in I_4 during 2002–2003 and 2003–2004, whereas during the year 2004–2005, the highest ERI was recorded in I_1. However, in all the years of study, the lowest ERI was recorded in I_5. There was no significant difference among the nitrogen treatments with respect to seedling emergence.

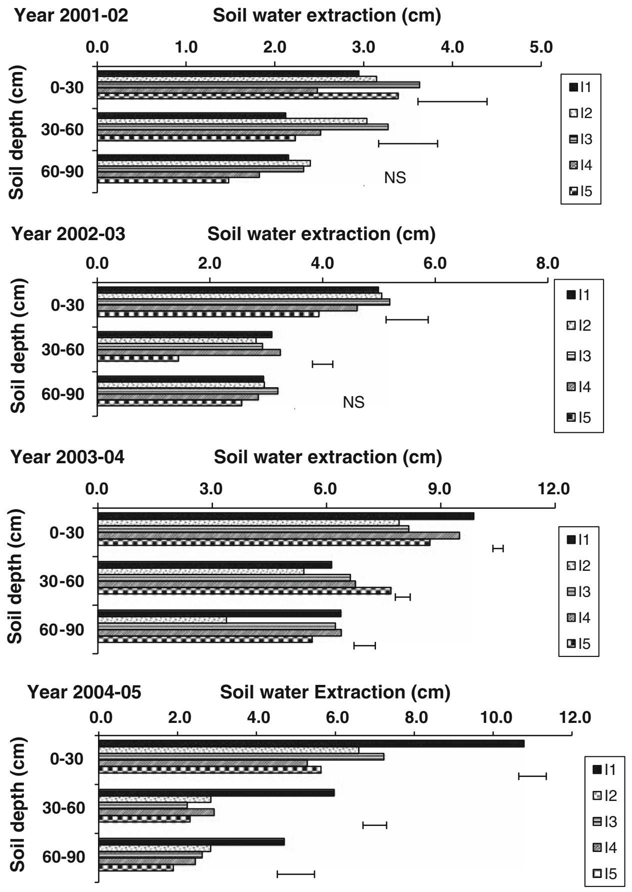

Fig. 5 Soil water extraction by wheat in different years as influenced by different methods of irrigation. *The error bars* wherever present indicate least significant difference at $P < 0.05$

Root growth under different methods of irrigation

Irrespective of the treatments, the maximum root length density (RLD) and root mass density (RMD) of wheat occurred in the 0–15 cm soil layer, and there was decline in the RLD and RMD with depth (Fig. 2a, b). The reduction in the RLD with depth was less than that in RMD. This implies that the length/mass ratio of wheat roots increased more in lower soil layers than in upper layers. Hence, mostly finer roots were found in the lower soil layers. The RLD and RMD of wheat under sprinkler irrigation were higher than that of flood irrigation (I_5) treatment. In the plough layer (0–15 cm), the maximum RLD and RMD were recorded under I_1. This may be attributed to frequent and light irrigation under this treatment, which resulted in higher soil moisture storage for longer period of time.

Soil water dynamics and soil water extraction

Temporal variations in the soil water storage in the profile (0–90 cm) for the 4 years (2001–2005) are presented in Fig. 3. The numbers of irrigations are reflected in terms of numbers of peaks in soil moisture storage observed during the crop growth period. The difference in soil water storage in the profile due to irrigation was not significant for the same amount and frequency of irrigation. However, when soil water storage of the surface layer (0–15 cm) was compared, relatively higher storage was recorded in I_4 (Fig. 4). This was attributed to the fact that unlike other treatments, the soil was not ploughed for sowing following irrigation in I4 treatment as irrigation was supplied immediately after dry sowing. So the evaporation loss of water was expected to be low in this treatment than other irrigation treatments.

The maximum soil water extraction by wheat occurred in the 0–30 cm soil depth, irrespective of the method of irrigation (Fig. 5). Below this depth, the soil water extraction gradually decreased. Increased surface evaporation, shallow root density and more water uptake by the

Table 4 Grain and straw yield of wheat as influenced by irrigation schedule and N application methods under limited water supply

Treatment	Critical growth stage up to which irrigation was supplied							
	Presowing (2001–2002)		CRI (2002–2003)		Flowering (2003–2004)		Tillering (2004–2005)	
	Grain yield (kg/ha)	Straw yield (kg/ha)	Grain yield (kg/ha)	Straw yield (kg/ha)	Grain yield (kg/ha)	Straw yield (kg/ha)	Grain yield (kg/ha)	Straw yield (kg/ha)
Irrigation								
I_1	1196c*	1993a	1373c	1736d	5051a	5810a	3008a	3850a
I_2	1362b	1956a	1883b	2227c	4616bc	4708bc	2155bc	2718bc
I_3	1332b	1818b	2044b	2752ab	4756ab	5011b	2069bc	2536bc
I_4	1468a	1752b	2484a	2938a	4296c	4446bc	2360b	2910b
I_5	777d	926c	1855b	2360bc	4244c	4361c	1908c	2304c
Nitrogen								
N_1	1238a	1719a	1948a	2515a	4615a	4985a	2286a	2857a
N_2	1219a	1658a	1908a	2290a	4570a	4749a	2314a	2871a

* Means in a column followed by the same letter are not statistically different at $P < 0.05$ as per DMRT (Duncan's multiple range test)

Table 5 Effect of irrigation scheduling and N application methods on harvest index of wheat under limited water supply

Treatment	Critical growth stage up to which irrigation was supplied (harvest index)			
	Presowing (2001–2002)	CRI (2002–2003)	Flowering (2003–2004)	Tillering (2004–2005)
Irrigation				
I_1	0.456a	0.441a	0.494a	0.450a
I_2	0.408c	0.467a	0.496a	0.441a
I_3	0.431b	0.426a	0.488ab	0.451a
I_4	0.426b	0.459a	0.493a	0.446a
I_5	0.410c	0.449a	0.467b	0.437a
Nitrogen				
N_1	0.424b	0.441a	0.483b	0.443a
N_2	0.428a	0.456a	0.492a	0.447a

* The means followed by the same letter in a column are not statistically different at $P < 0.05$ as per DMRT (Duncan's multiple range test)

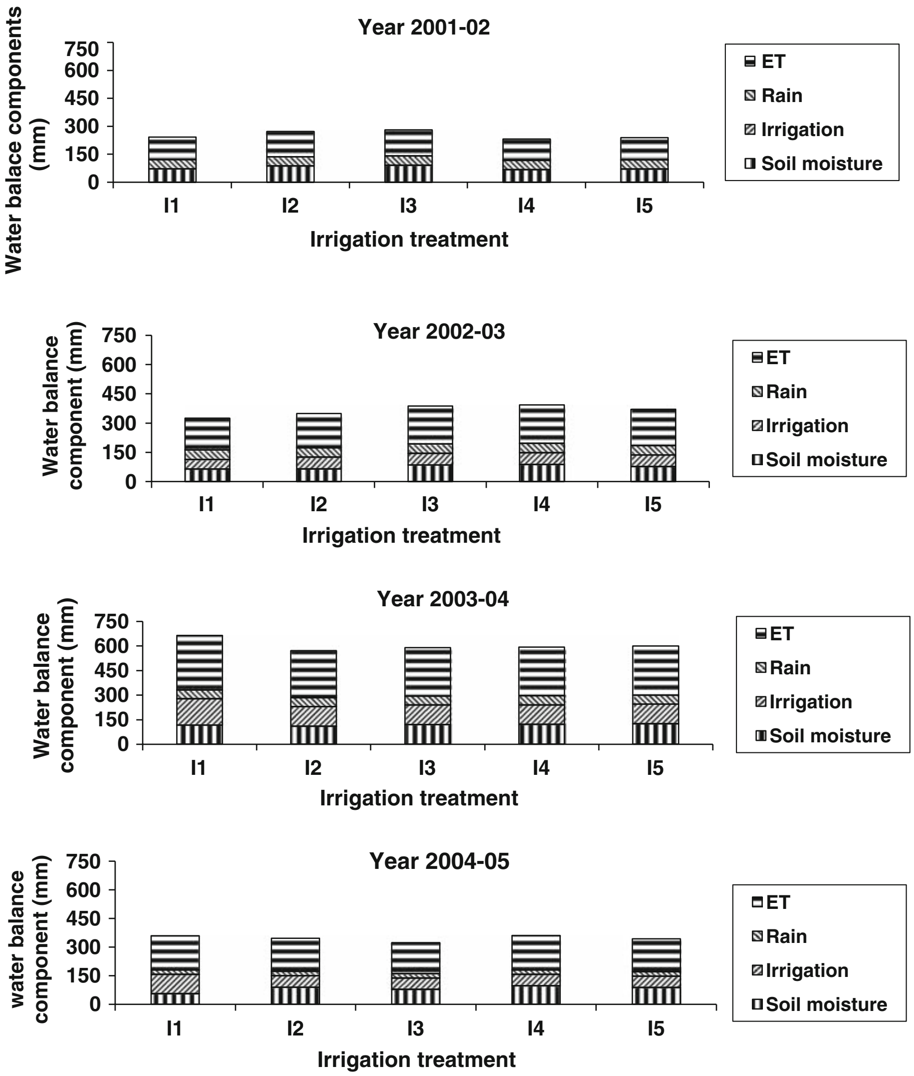

Fig. 6 Water balance components under different methods of irrigation in different years

crops from the surface layer due to availability of irrigation water and presence of active roots in the surface layer may be the possible reason for the decline in soil water extraction at lower depths (Hati et al. 2001). The soil moisture extraction from 0–30 cm soil depth under sprinkler irrigation or combination of sprinkler and flood irrigation was significantly higher than the flood irrigation treatment.

Table 6 Effect of irrigation scheduling and N application methods on seasonal evapo-transpiration of wheat under limited water supply

Treatment	Critical growth stage up to which irrigation was supplied [seasonal evapo-transpiration (mm)]			
	Sowing (0 DAS) (2001–2002)	CRI (25–30 DAS) (2002–2003)	Flowering (60–65 DAS) (2003–2004)	Tillering (40–45 DAS) (2004–2005)
Irrigation				
I_1	120.8a*	162.7d	332.2a	180.0a
I_2	135.8a	174.7c	285.0c	173.5a
I_3	140.3a	193.9a	294.9c	161.7b
I_4	115.9a	196.8a	296.1b	180.5a
I_5	119.3a	185.5b	300.2b	171.4a
Nitrogen				
N_1	126.7a	183.6a	305.3a	176.0a
N_2	126.1a	181.9a	298.0a	170.9a

* The numbers followed by the same letter in a column are not statistically different at $P < 0.05$ as per DMRT (Duncan's multiple range test)

Table 7 Effect of irrigation scheduling and N application methods on water use efficiency of wheat under limited water supply

Treatment	Critical growth stage up to which irrigation was supplied [water use efficiency (kg ha^{-1} mm^{-1})]			
	Presowing (2001–2002)	CRI (2002–2003)	Flowering (2003–2004)	Tillering (2004–2005)
Irrigation				
I_1	10.3a	8.5c	15.2ab	16.7a
I_2	10.2a	10.9b	16.3a	12.4c
I_3	10.5a	10.6b	16.1a	12.9bc
I_4	11.6a	12.6a	14.5b	13.1b
I_5	6.5b	10.0b	14.1b	11.3d
Nitrogen				
N_1	11.0a	10.6a	15.1a	13.0a
N_2	9.8a	10.5a	15.4a	13.5a

* The means followed by the same letter in a column are not statistically different at $P < 0.05$ as per DMRT (Duncan's multiple range test)

Yield of wheat

Across the years, the crop yield increased with the increase in levels of irrigation (Table 4). When wheat was grown with only one irrigation at sowing (2001–2002) or two irrigations up to the crown root initiation (CRI) stage (2002–2003), dry sowing of wheat followed by sprinkler irrigation and subsequent irrigation through flooding at CRI (I_4) gave the highest grain yield of wheat (Table 4). This may be attributed to the fact that under I_4 treatment, higher soil water storage was maintained in the profile up to CRI stage because of lower evaporation loss from the profile as the soil was not opened for sowing after irrigation. In the 3rd (2003–2004) and 4th (2004–2005) years, 20-cm irrigation up to the flowering stage or 14-cm irrigation up to the tillering stage through sprinkler in 4 and 3 installments, respectively, (I_1) gave the highest grain yield, which was significantly higher than the treatment where same amount of irrigation was applied through sprinkler (I_2) or flooding (I_5) in 3 and 2 installments, respectively. This finding confirms the superiority of light and frequent irrigation over heavy and infrequent irrigation (Gajri et al. 1993). There was no significant difference in the grain yield between sprinkler irrigation alone (I_2) and sprinkler at presowing followed by flood irrigation (I_3), when the same amount of water was applied at the same growth stages. This implies that combination of sprinkler and flooding treatment can be practiced in this soil, which will help in conserving energy. The straw yield of wheat followed a similar trend as grain yield of wheat. The harvest index increased with the increase in the water supply (Table 5).

The N application methods and the interaction of irrigation and N application methods were not significant on the grain and straw yield of wheat. This may be attributed to the fact that N applied after irrigation (N_2) might have been subjected to volatilization loss as ammonia because of high pH of this soil (Alcoz et al. 1993). So the advantage of split application of N (N_2) over basal application (N_1) could not be realized. No improvement in crop response due to split application of N under rainfed and water-stressed condition has also been reported by Benfield et al. (1981), Grant et al. (1985) and Arregui and Quemada (2008). In practice, the effects of split doses are not easily predictable because they can be biased by (1) number of applications, their timing

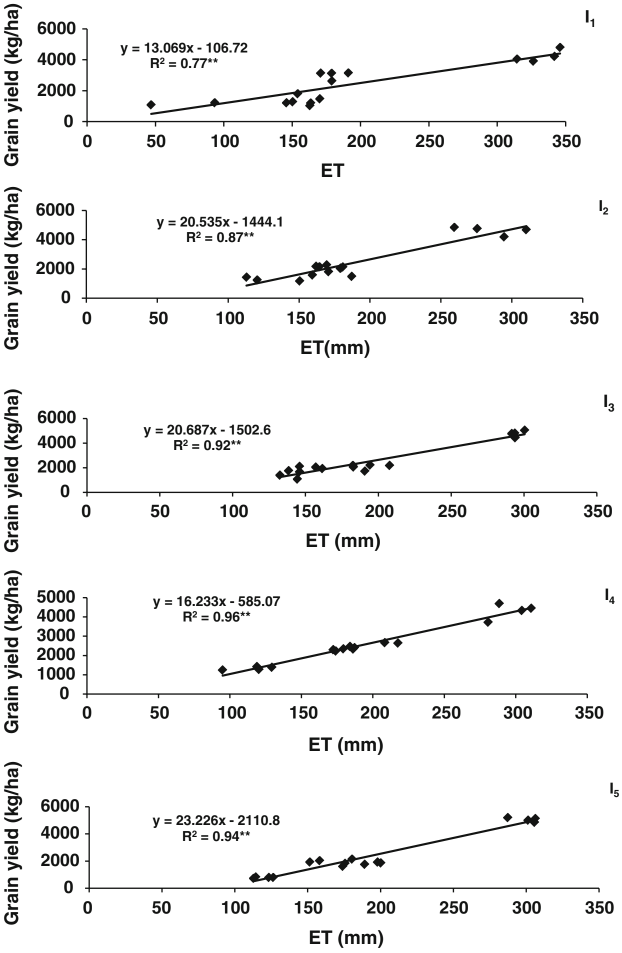

Fig. 7 Evapo-transpiration production functions of wheat under different irrigation methods; ** indicate significant at $P < 0.01$

and quantities (Mahler et al. 1994), (2) the weather conditions during the season that influence leaching, volatilization and crop growth (Alcoz et al. 1993) and (3) the mineral nitrogen amount present in the soil at the time of fertilizer application (Sowers et al. 1994).

Seasonal evapo-transpiration and water use efficiency

With the increase in the amount of irrigation application, the seasonal evapo-transpiration increased and maximum seasonal evapo-transpiration was recorded during the year 2003–2004 when 20-cm irrigation was applied (Fig. 6; Table 6). During the years 2003–2004 and 2004–2005, the maximum seasonal ET was recorded in I_1, whereas during the year 2002–2003, the maximum seasonal ET was recorded in I_4. However, during the year 2001–2002, there was no significant difference in the seasonal ET among the irrigation treatments. The effect of nitrogen management on seasonal ET was not significant in all the 4 years of study.

Except in the year 2002–2003, sprinkler irrigation (I_2) or combination of sprinkler and flood irrigation (I_3 or I_4) registered significantly higher water use efficiency over flood irrigation system (I_5) for the same amount and frequency of irrigation in the rest 3 years (Table 7). During the year 2001–2002 and 2002–2003, the maximum WUE was recorded in I_4, whereas during the year 2003–2004, the maximum WUE was recorded in I_2, and in the year 2004–2005, the maximum WUE was observed in I_1. This was attributed to uniform water application, better root proliferation, higher soil water extraction recorded in sprinkler-irrigated plots than flood-irrigated plots. The superiority of sprinkler irrigation over flood irrigation with respect to higher water use efficiency has been reported by Verma and Shrivastava (1992), Malik et al. (1987) and Ghani et al. (2001) in wheat, Home et al. (2002) in okra, Pawar et al. (2002) in potato and El Yazal et al. (1998) in cotton. There is also report that compared to surface flooding; sprinkler irrigation system improves physical property of soil, which might have contributed to higher water use efficiency in this irrigation system. Grazy et al. (1989) reported that there was improvement in the water stable aggregates under micro sprinkler irrigation than flood irrigation. Khan (1988) observed that in Vertisols, drying after surface irrigation resulted in 2–3 times wide and 0.5–1 m deep cracks compared to sprinkler irrigation, where only a few fine cracks were found.

The N application methods and the interaction of irrigation and N application method were not significant on the water use efficiency of wheat in all the 4 years of study.

Marginal analysis of evapo-transpiration production function

The grain yield of wheat vs. ET relationships, the evapo-transpiration production function (ETPF), across the years

Table 8 Crop water production functions of wheat under different methods of irrigation

Irrigation methods	Crop water production functions	R^2	WUEm	Ewp	Ky
I_1	13.069ET-106.72	0.77	13.069	1.15 ± 0.42	0.94
I_2	20.535ET-1444.1	0.87	20.535	1.74 ± 0.43	1.36
I_3	20.687ET-1502.6	0.92	20.687	1.73 ± 0.40	1.23
I_4	16.233ET-585.07	0.96	16.233	1.27 ± 0.13	1.14
I_5	23.226ET-2110.8	0.94	23.226	2.35 ± 0.84	1.39

WUEm marginal water use efficiency, *Ewp* elasticity of water production function, *Ky* yield response factor of Doorenbos and Kassam (1979) equation

Table 9 Nitrogen uptake by wheat grain and straw as influenced by irrigation scheduling and N application methods under limited water supply

Treatment	Critical growth stage up to which irrigation was supplied [total N uptake by wheat grain + straw (kg/ha)]			
	Presowing (2001–2002)	CRI (2002–2003)	Flowering (2003–2004)	Tillering (2004–2005)
Irrigation				
I_1	26.12b*	28.46d	102.61a	62.75a
I_2	27.81b	36.13bc	85.96b	41.94bc
I_3	30.69a	39.01b	85.62b	38.54c
I_4	27.70b	45.40a	76.64bc	43.49b
I_5	15.28c	30.90 cd	68.47c	31.51c
Nitrogen				
N_1	25.58a	36.61a	84.61a	43.39a
N_2	25.44a	35.35a	83.11a	43.90a

* Means in a column followed by the same letter are not statistically different at $P < 0.05$ as per DMRT (Duncan's multiple range test)

Table 10 Nitrogen requirement and Nitrogen harvest index of wheat as influenced by irrigation scheduling and N application the methods under limited water supply

Treatment	Critical growth stage up to which irrigation was supplied							
	Presowing (2001–2002)		CRI (2002–2003)		Flowering (2003–2004)		Tillering (2004–2005)	
	NR (kg N uptake/ 100 kg grain)	NHI (%)	NR (kg N uptake/ 100 kg grain)	NHI (%)	NR (kg N uptake/ 100 kg grain)	NHI (%)	NR (kg N uptake/ 100 kg grain	NHI (%)
Irrigation								
I_1	2.16a*	74.9a	2.06a	78.5b	2.03a	79.8cd	2.09a	77.6bc
I_2	2.02b	74.4a	1.92b	78.6b	1.86b	80.9c	1.95b	77.2bc
I_3	2.07b	68.7b	1.91b	74.3c	1.81c	78.9d	1.86c	76.4c
I_4	2.08b	71.0ab	1.83b	80.7b	1.78c	82.7b	1.85c	80.0b
I_5	1.93b	72.0ab	1.67c	83.8a	1.61d	86.5a	1.66d	84.3a
Nitrogen								
N_1	2.03a	72.9a	1.88a	78.6a	1.81a	81.5a	1.87a	79.0a
N_2	2.07a	71.5a	1.85a	79.8a	1.80a	82.0a	1.87a	79.2a

* Means followed by the same letter are not statistically different at $P < 0.05$ as per DMRT (Duncan's multiple range test)

were linear in the present study (Fig. 7). It was observed that 77–96% variation in crop yield could be explained by variation in ET (Table 8). The slope of the ETPF, the marginal water use efficiency (WUEm), was maximum for I_5 and minimum for I_1. With the increase in the ET by 1 mm, the grain yield of wheat increased by 13–23 kg. Zhang and Oweis (1999) and Steiner et al. (1985) also observed an increase in grain yield of wheat by 6.8–10.8 kg ha^{-1} per mm increase in ET. The intercept of the ETPF (a) is less than 0 in all the treatments indicating increase in WUE with the increase in ET (Liu et al. 2002). The elasticity of water production function (Ewp) was greater than 1 in all the treatments (Table 8). The maximum Ewp was recorded in I_5 and the minimum value was recorded in I_1. The yield response factor (Ky) of Doorenbos and Kassam (1979) was estimated from the ETPF and the maximum value of Ky (1.39) was recorded in I_5 and the minimum value (0.94) was recorded in I_1. Probably because of lower yield level in I_5 the Ky and Ewp were higher in this treatment.

Nitrogen uptake and nitrogen use efficiency by wheat

The N uptake by wheat grain and straw followed the trend similar to the grain yield of crop (Table 9). With the same amount and frequency of irrigation, the flood-irrigated plots (I_5) registered significantly lower N uptake than sprinkler-irrigated (I_2) or combination of sprinkler- and flood-irrigated (I_3 and I_4) plots in all the 4 years of study (Table 9). During the year 2003–2004 and 2004–2005, the highest N uptake was registered in I_1, whereas during the year 2002–2003, the highest N uptake was registered in I_4, and during the year 2001–2002, the highest N uptake was recorded in I_3. This increase in N uptake is mainly attributed to increase in biomass production. The effect of N application method on N uptake by wheat was not

Table 11 Partial factor productivity of nitrogen and nitrogen utilization efficiency of wheat as influenced by irrigation scheduling and N application methods under limited water supply

Treatment	Critical growth stage up to which irrigation was supplied							
	Presowing (2001–2002)		CRI (2002–2003)		Flowering (2003–2004)		Tillering (2004–2005)	
	PFPN (kg grain/kg N applied)	NUtE (kg grain/kg N uptake)	PFPN (kg grain/kg N applied)	NUtE (kg grain/kg N uptake)	PFPN (kg grain/kg N applied)	NUtE (kg grain/kg N uptake)	PFPN (kg grain/kg N applied)	NUtE (kg grain/kg N uptake)
Irrigation								
I_1	10.0b*	46.2c	11.4c	48.5d	42.1a	49.2d	25.1a	47.9d
I_2	11.4a	49.4ab	15.7b	52.2c	38.5ab	53.7c	18.0bc	51.3c
I_3	12.3a	48.4bc	17.0b	52.3c	39.6ab	55.5b	17.2c	53.7b
I_4	11.1ab	48.1bc	20.7a	54.7b	35.8b	56.1b	19.7b	54.2b
I_5	6.4c	51.6a	15.5b	60.1a	35.4b	62.0a	15.9c	60.4a
Nitrogen								
N_1	10.3a	49.2a	16.2a	53.1a	38.5a	55.1a	19.0a	53.5a
N_2	10.2a	48.2a	15.9a	54.0a	38.1a	55.5a	19.3a	53.6a

* Means followed by the same letter are not statistically different at $P < 0.05$ as per DMRT (Duncan's multiple range test)

significant as the biomass was not significantly influenced by the split application of N.

Across the years, the nitrogen harvest index (NHI), i.e., proportion of nitrogen uptake in grain, increased from 68.7 to 74.9% in 2001–2002 to 78.9 to 86.5% in 2003–2004 due to increase in water supply (Table 10). The maximum NHI was recorded in I_5, and the minimum value was recorded in I_3 in all the years except in 2001–2002. In the year 2001–2002, the maximum NHI was recorded in I_1. Lopez Bellido et al. (2006) reported that NHI was significantly affected by year, and the highest value was recorded with lowest biomass and grain yield.

The nitrogen requirement (NR) i.e., kg N uptake to produce 100 kg of wheat grain decreased in 2003–2004 (from 1.61 to 2.03) compared to 2001–2002 (from 1.93 to 2.16) due to increase in water supply (Table 10). Under the flood irrigation system (I_5), the nitrogen requirement was less than the sprinkler irrigation (I_1, I_2) or combination of sprinkler and flood irrigation system (I_3, I_4).

Across the years, similar to crop yield, the partial factor productivity of N (PFPN) i.e., kg grain produced per kg N applied, increased with the increase in the levels of water supply from 6.4 to 12.3 kg grain kg^{-1} N application in 2001–2002 to 35.4–42.1 kg grain kg^{-1} N application in 2003–2004 (Table 11). Except the year 2002–2003, the minimum PFPN was recorded in I_5 in the rest 3 years of study. In the year 2002–2003, the minimum PFPN was recorded in I_1. During the year 2002–2003, the maximum PFPN was recorded in I_4, and in the year 2001–2002, the maximum PFPN was observed in I_3, which was at par with I_2 and I_4, whereas during the year 2003–2004 and 2004–2005, the maximum PFPN was recorded in I_1.

The nitrogen utilization efficiency (NUtE), i.e., kg grain produced per kg N uptake, followed the reverse trend as that of PFPN (Table 11). Across the years, the NUtE increased from 46.2 to 51.6 kg grain kg^{-1} N uptake in 2001–2002 to 79.8 to 86.5 kg grain kg^{-1} N uptake in 2003–2004. The maximum value of NUtE was recorded in I_5, and the minimum value of NUtE was recorded in I_1 in all the 4 years of study. Lopez Bellido et al. (2006) also reported that the behavior of NUtE was erratic, and the highest value was recorded with zero N treatment.

There was no significant difference in the nitrogen application methods with respect to the nitrogen use efficiency parameters in all the 4 years of study. This may be attributed to the fact that biomass and grain yield of wheat was not significantly influenced by the N application methods.

Thus, from this study, it may concluded that, under limited water supply, when irrigation water is available up to the crown root initiation stage, farmers may follow dry sowing of wheat followed by sprinkler irrigation and subsequent irrigation through flooding, and when irrigation water is available up to the tillering or flowering stage, sprinkler irrigation in three or four installments, respectively, at critical growth stages may be practiced to obtain higher yield and water and nitrogen use efficiency of wheat in Vertisols.

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