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Wheat yield response to line source sprinkler irrigation and soil management practices on medium-textured shallow soils of arid environment

S. S. Rao · P. L. Regar · S. P. S. Tanwar · Y. V. Singh

Abstract A field experiment was conducted for 3 years to evaluate the effect of deficit irrigation under different soil management practices on biomass production, grain yield, yield components and water productivity of spring wheat (*Triticum estivum* L.). Soil management practices consisted of tillage (conventional and deep tillage) and Farmyard manure (0 and 10 t ha^{-1} FYM). Line source sprinkler laterals were used to generate one full- (ETm) and four deficit irrigation treatments that were 88, 75, 62 and 46 % of ETm, and designated as ETd$_1$, ETd$_2$, ETd$_3$, and ETd$_4$. Deep tillage significantly enhanced grain yield (14–18 %) and water productivity (1.27–1.34 kg m^{-3}) over conventional tillage. Similarly, application of FYM at 10 t ha^{-1} significantly improved grain yield (10–13 %) and water productivity (1.25–1.31 kg m^{-3}) in comparison with no FYM. Grain yield response to irrigation varied significantly (5,281–2,704 kg ha^{-1}) due to differences in soil water contents. Water productivity varied from 1.05 to 1.34 kg m^{-3}, among the treatments in 3 years. The interactive effect of irrigation × tillage practices and irrigation × FYM on grain yield was significant. Yield performance proved that deficit irrigation (ETd$_2$) subjected to 75 % soil water deficit had the smallest yield decline with significant water saving would be the most appropriate irrigation level for wheat production in arid regions.

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Introduction

Wheat (*Triticum estivum* L.) is an important food crop for irrigated perimeters of the arid and semi-arid region of India. Every year, increasing areas of irrigated land are being sown to wheat in the arid zone of Rajasthan; however, its production is showing a stable growth rate (Gajja et al. 2008). The wheat productivity in medium-textured shallow soils of this region is low (2.5 t ha^{-1}) owing to low water retention, poor inherent fertility, low organic carbon status of soil and rapid development of mechanical impedance with drying caused by high soil crust strength (Laddha and Totawat 1997). The high soil temperature during early and later parts of a growing season in general is a major production limitation in the North West Plain Zone (NWPZ) of India (Joshi et al. 2007). The low organic carbon content of arid zone soil was mainly attributed to harsh climate and low use or non-use of organics by the farmers of this region. These constraints can be alleviated through practices such as irrigation, deep tillage and organic manuring (Barzegar et al. 2002; Arora et al. 2011).

In the fringes of the Indian arid zone, irrigation is practiced even though water is scarce and available water is insufficient to meet the full evapotranspiration (ET) needs of the crop, and therefore, the crop is often subjected to deficit irrigation that results in low yields. In those situations, deficit irrigation (DI), defined as the application of irrigation water below the full crop ET, is an important tool to increase the efficiency of water use (English et al. 2002). Deficit irrigation almost always increases water use efficiency as the applied water is less than the depletion by ET, and most or all of the applied water remains in the root zone (Fereres and Soriano 2007). Wheat has the potential for efficient use of small irrigation amounts applied throughout the growing season (English and Nakaruma

1989). Hence, its production calls for strategic measures like adopting water saving irrigation technologies. One such technology is sprinkler irrigation which provides the benefits of water savings and an increase in water use efficiency over flood irrigation methods (Singh and Mann 1979; Bandyopadhyay et al. 2010) for wheat.

The concept of using a single line source sprinkler to impose a continuous variable water application across a field research plot was introduced in the early 1970s (Hanks et al. 1976, 1980; Willardson et al. 1987). Subsequently, many line source–sprinkler research studies of crop response to variable amount of irrigation water have been conducted (Gallardo et al. 1996; Guttieri et al. 2000; Sezen and Yazer 2006; Okwany et al. 2012). The line source sprinkler–irrigation strategy provided sufficient room to carry out research to find out what minimum amount of water should be applied to have maximum yield per amount of water applied (Hanks et al. 1976). In recent years, focus has now shifted from maximizing total production to maximizing water productivity in water-scarce regions. Pandey et al. (2001b) concluded that with a limited water supply, water managers can either provide water to a few growers to meet full crop demand or adopt deficit irrigation to supply water to a larger number of farmers, providing more equitable distribution of scarce resources. Because of the differences in regional variability in environmental and agronomic practices, information specific to this region is needed for developing and refining limited irrigation schemes.

Irrigation expands the opportunity to overcome poor soil physical properties through soil management practices such as tillage and farmyard manure. Shallow and compacted soils of arid regions have low organic matter and are prone to crusting which may decrease infiltration, seedling emergence and plant growth (Unger and McCalla 1980). For soils that are hard setting or have a root-restricting layer, some form of mechanical loosening through deep tillage is necessary to conserve soil and water and facilitate crop growth (Lal 1989). Adequate tillage has been found to be highly useful in improving soil physical conditions and crop yield without adverse effects on the edaphic environment (Gupta and Agarwal 1991). Deep tillage in medium-textured soils has been found to provide continuous low soil strength silt for root proliferation and partially alleviate the water stress effects (Bennie and Botha 1986; Gill et al. 1996) and caused substantial yield gain in wheat (Gajri et al. 1991, 1997). Incorporation of organic matter in the form of farmyard manures has been shown to improve soil structure and water retention capacity (Bhagat and Verma 1991). Organic matter affects crop growth and yield directly by supplying nutrients and indirectly by modifying soil physical properties that can improve the root environment and stimulate plant growth (Darwish et al. 1995).

It is hypothesized that integrated use of these soil management practices with deficit irrigation influences the biomass production and it's partitioning, which ultimately influence the water productivity of wheat.

Zwart and Bastiaanssen (2004) viewed the crop water productivity (CWP) values for major crops and reported the range of CWP for wheat varied between 0.6 and 1.7 kg m^{-3}, and this offers tremendous opportunities for maintaining or increasing production with 20–40 % less water resources. They stated the reasons for the variability of CWP as (1) climate (2) irrigation water management, and (3) soil (nutrient) management. Practices such as plowing, mulching for fast leaf expansion—in order to shade the ground as rapidly as possible—reduce evaporation and increase productive transpiration (Sadras and Angus 2006) and can enhance water productivity at field level. In a recent review, Molden et al. (2010) observed that in water—limited conditions, influence of non-water factors (soil fertility, tillage and crop residues) on crop water productivity assumes greater importance through their effects on reducing evaporation (E) component of evapotranspiration (ET). Thus, there appears to be a considerable scope for raising the amount of yield relative to ET by the combined effect of tillage practices and organic manure application with deficit irrigation on shallow soils of arid fringes.

In this backdrop, this study examines the sole and combined effect of deficit irrigation and soil management practices on biomass production, grain yield, yield components and water productivity of spring wheat (*Triticum aestivum* L.) in a medium-textured shallow soil in the arid environment of northwest India.

Materials and methods

Soil and climate

Field experiments were conducted at Central Arid Zone Research Institute, Regional Research Station, Pali-Marwar located at 25°45′N latitude, 75°50′E longitudes at an elevation of 225 m above mean sea level under semi-arid to arid sub-tropical climatic conditions. The experimental soil was fine sandy clay loam in texture, mixed hyper-thermic belonging to the family Lithic Calciorthids having shallow depth of 30–45 cm and underlying dense layer of *murrum* (highly calcareous weathered granite fragment coated with lime) up to 10–15 m depth. The soil pH was 7.9, 0.35 % organic carbon, 90 mg kg^{-1} available N, 4.8 mg kg^{-1} Olson's extractable P and 102 mg kg^{-1} exchangeable K content in 0–15 cm depth. The field capacity, wilting point, and infiltration rate of the top 0–44 cm soil were 18.7 %, 8.4 %, and 12 mm h^{-1} with an average bulk density of

1.39 g cm^{-3}. A complete description of the soil is presented in Table 1.

Experiment layout and irrigation system

The experiment was conducted for 3 years during the winter seasons of 2007–08, 2008–09 and 2009–10 to investigate the effects of deficit irrigation and soil management practices on biomass production, grain yield, yield components and water productivity of spring wheat (*Triticum estivum* L.). The experiment was laid out in split–split plot technique with tillage in main plots, farmyard manure in subplots and deficit irrigation regime in sub–sub plots. Tillage consisted of : conventional tillage (CT)—tilling once with disk harrow (10–12.5 cm depth) followed by two runs of tyne cultivator and planking; and Deep tillage (DT)—disk plowing to a depth of 25–40 cm followed by CT. Farmyard manure (FYM) application rates were: 0 (as control); and 10 t (dry weight) ha^{-1}. Well-decomposed FYM was incorporated in soil 2 weeks before sowing. The FYM used contained 0.42 % N, 0.21 % P, and 0.44 % K with a pH of 7.1.

The line source sprinkler irrigation technique was used to create a gradually varying irrigation regime (Hanks et al. 1976). The sprinkler irrigation was supplied through 75-mm HDPE pipes line with a total of seven sprinklers (double nozzle, 3.1 mm × 5.1 mm size having discharge rate of 33.5 lpm at 2.5 kg cm^{-2} pressure with G I riser pipes of 20 mm × 90 cm; M/S Dinesh Irrigations Ltd, Jaipur, India), spaced at 9.0 m intervals provided a continuous variable supply of water with wetted diameter of 20 m. The experimental site was a 60 m × 54 m field with a replication size of 20 m × 54 m. Sprinkler line was laid out in between the replication which offered two main plots of size 10 m × 54 m in either side to which tillage treatments were randomly assigned. Each main plot was divided into two sub plots (10 m × 19 m) to which farmyard manure treatments were randomly assigned. There was 8 m spacing between the two subplots and 4 m borders on the lengthwise end of the plots. The line source sprinkler system applies water uniformly along the length of an experimental area with a reduction in application rate, with

distance from the line of sprinklers. Five treatments, namely one full (ETm) and four deficit (88, 75, 62 and 46 % of ETm and designated as ETd$_1$, ETd$_2$, ETd$_3$, and ETd$_4$) irrigations regimes at every 2 m distance were delineated (2 m wide × 19 m long). Three such sprinkler lines (separate) were kept for three replications. In all, there were twenty treatment combinations (2 × 2 × 5 = 20) in one replication and with three replications total number of plots were sixty (20 × 3 = 60). A complete schematic layout plan of the field site showing the sprinkler lines and replications were presented in Fig. 1.

A flow-meter and pressure-regulated valve were installed at the head of the irrigation system to measure the applied water and to control the system pressure. Sprinkler irrigations were performed in the morning provided wind speed was <2 ms^{-1}. The irrigation water was applied to meet plant water requirements of the control treatment (ET$_m$) which was based on 100 % Class A Pan evaporation (E_{pan}) minus precipitation (P), ET$_m$ = E_{pan} − P (Allen et al. 1998). Subsequent irrigations were applied after ≥40 mm of cumulative pan evaporation (CPE). This resulted in irrigations every 7–10 days. Daily pan evaporation data were obtained from India Meteorology Department Class-1 meteorological observatory located in the campus itself about 1.0 km away from the experimental field. The sprinkler irrigation depth was measured by calibrated catch-cans, mounted on extendable metal rods, placed at the center of each irrigation regime above the crop canopy following Hanks et al. (1976) and Winward and Hill (2007) protocol. The catch-cans were placed on both sides of the lateral lines in all three replications.
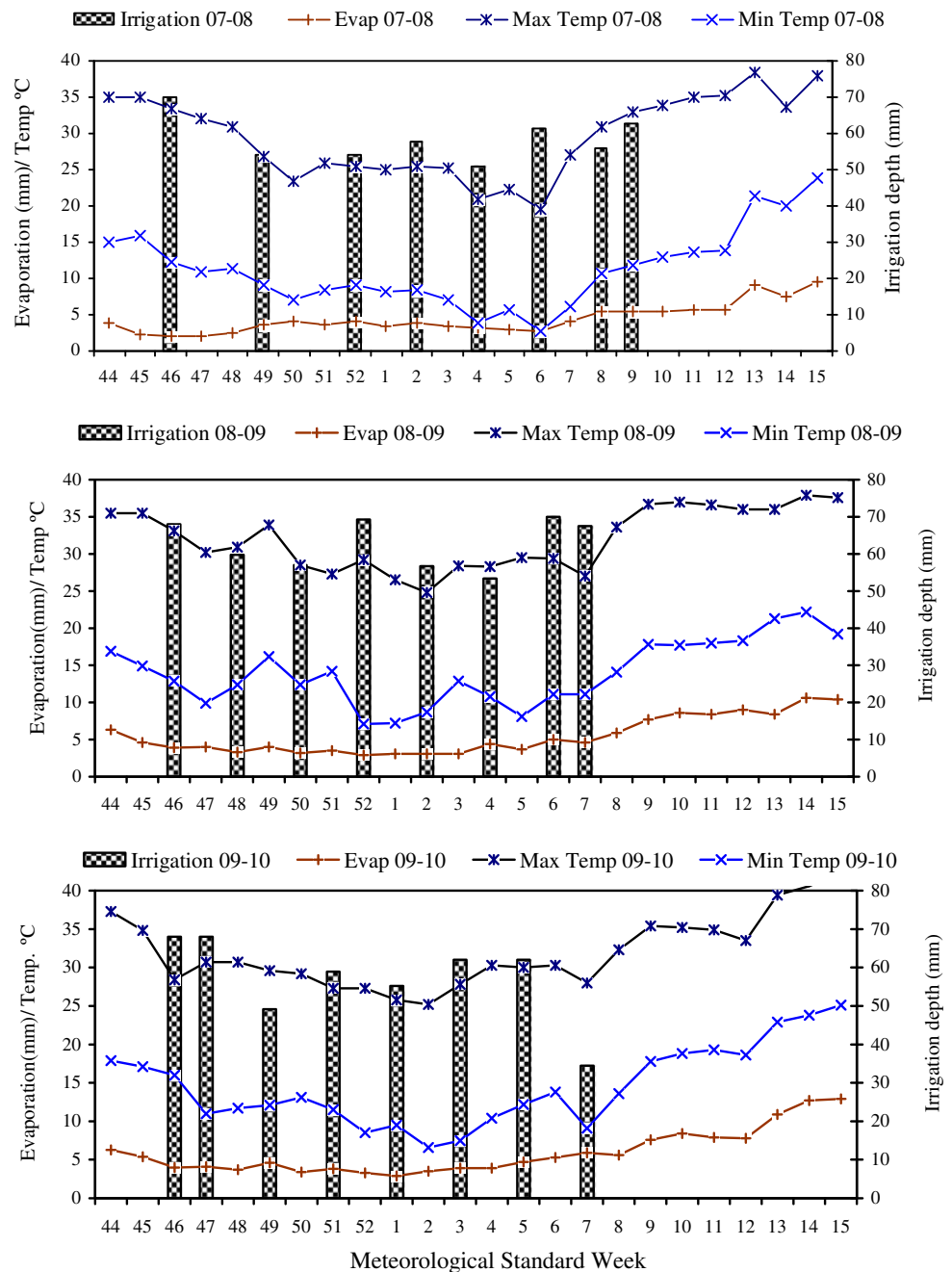
Experimental detail

The spring wheat cultivar "Raj 4037" was sown on November 20, 12, and 16 during the year 2007, 2008, and 2009, respectively. First irrigation of 68 mm was applied uniformly by placing a sprinkler line at a distance every 10 m for identical germination and emergence; thereafter, irrigation water was applied as per treatments in all the years. Nitrogen was applied in two splits at 30 and 50 days after sowing as side dressing through urea uniformly to all

Table 1 Physico-chemical properties of the experimental soil

Depth (cm)	Soil texture (%)				pH (1:2.5)	Organic carbon (%)	Bulk density (g cm^{-3})	Field capacity (%)	Wilting point (%)	EC (dS m^{-1})
	Fine sand	Coarse sand	Silt	Clay						
0–10	29.7	16.6	35.8	17.9	8.1	0.37	1.42	17.2	7.1	0.16
10–22	28.0	15.9	36.4	19.7	7.9	0.37	1.39	17.2	7.3	0.16
22–34	23.9	14.1	35.8	26.2	7.9	0.42	1.36	20.6	10.1	0.15
34–44	22.1	16.0	33.9	28.0	7.9	0.42	1.39	18.7	9.1	0.15
45–100	Gravelly clay loam with weathered granite fragments coated with powdery lime									

Fig. 1 Schematic field layout plan showing the line source sprinklers

plots. All other agronomic practices were carried out as per local recommendations. The crop was harvested on March 25, 16, and 13 during the year 2008, 2009, and 2010, respectively. Weather parameters including minimum and maximum temperature (°C), pan evaporation (mm), and the irrigation (amount and frequency) recorded during the crop growth period for 3 years were provided as Fig. 2.

Measurements

Soil water content

During the experiment, both thermo-gravimetric and soil moisture meter method was used to determine soil water content (SWC) at the beginning of the experiment and at harvest in all 3 years. During growing seasons, the variation in the soil water content was measured before and after every irrigation at every 7–10 days interval. The moisture content at the 0–15 cm depth was measured gravimetrically by sampling undisturbed cores of soil 15 cm long by 5.4 cm diameter from each plot, while at greater depth, it was measured by soil moisture meter (PR1-C profile probe; Delta-T Devices Ltd., Cambridge, UK) through pre-installed access tubes in each irrigation regime. The probe was field calibrated against gravimetric method as well as standard procedure described in user's manual. The profile probe determined soil moisture content (%) at 15, 30, 45, 60 and 75 cm depth to represent soil profile depths of 10–25, 25–40, 40–55, 55–70, 70–90 cm, respectively. It was converted into soil water content on volume basis (cm^3 cm^{-3}) by considering the bulk density of the respective soil layers and depths.

Crop evapotranspiration

The crop evapotranspiration (ETc) was calculated using a soil water balance equation, where changes in soil water content were measured every 7–10 days using the PR1-C probe:

$$\text{ETc} = P + I + \text{Cp} - \Delta S - \text{Dp} - \text{Rf} \tag{1}$$

where P is precipitation, I is irrigation, Cp is contribution through capillary rise from ground water, ΔS is the change in soil water storage over the irrigation cycle, Dp is deep percolation, Rf is runoff. Since there was no water table and depth of ground water was very low (>20 m), Cp was assumed negligible. Rf from the experimental plots was negligible as there was sufficient surface roughness (due to dry sowing) for water infiltration. Also there were low ridges and furrows system of sowing lines. Dp was determined to be zero because there was negligible changes in the soil water content below 90 cm soil depth, and the soil water content beyond 90 cm soil depth was well below the field capacity. Sezen and Yazer (2006) and Okwany et al. (2012) under similar soil and climatic condition and irrigation amount also pointed out that deep percolation and runoff losses were negligible when sprinkler irrigation amount was controlled.

Yield components: Primary yield components such as number of spikes m^{-2}, number of kernels $spike^{-1}$, number of grains m^{-2}, and 1,000 grain weight were recorded from the five 1-m-row-length samples per treatment from each replication at harvest.

Final yield: At maturity, total above-ground biomass production and grain yield were determined on an area of

Fig. 2 Weather characteristics and irrigation during 2007–08, 2008–09 and 2009–10

$38\ m^2$ (2 m wide × 19 m long strip) from each sub–sub plots in all replications by manual harvesting and allowed to dry in the field. Total air-dried weight of biomass production was measured in the field using a digital spring balance. The harvested produce was mechanically threshed; grain yield was recorded and adjusted to 13 % moisture content. The yield data were converted into t ha^{-1} and/or kg ha^{-1}.

Harvest index: The harvest index (HI) was calculated as the ratio of grain yield to total above-ground biomass at maturity was determine for each treatment.

Crop water productivity: It was calculated as the ratio of grain yield (kg ha^{-1}) to total crop water use (m^3) in mm

and expressed in physical terms (kg m^{-3}) following Kijine et al. (2002)

Yield water relationship: To determine water use yield relationship, dimensionless parameters in relative yield reduction and relative water consumption were used:

$$1 - \frac{Ya}{Ym} = k_y \left[1 - \frac{ETa}{ETm} \right] \tag{2}$$

where Ya is actual yield (kg ha^{-1}), Ym is maximum yield (kg ha^{-1}), Ya/Ym is relative yield, $1 - (Ya/Ym)$ is decrease in relative yield, ETa is actual crop water consumption (mm), ETm is maximum crop water consumption

(mm), ETa/ETm is relative crop water consumption, $1 -$ (ETa/ETm) is decrease in relative crop water consumption, and k_y is yield response factor defined as decrease in yield with respect to per unit decrease in ET (Doorenbos and Kassam 1979).

Statistical analyses

All data were statistically analyzed using standard analysis of variance (ANOVA) as applicable to split–split plot design with SPSS 11.5 version. The significance of the treatment effects was determined using the F-test, and the critical differences (CD) between the treatments mean was calculated by using standard error (Gomez and Gomez 1984). Statistical comparison between soil management practices and its interaction with irrigation (Tillage × irrigation; FYM × irrigation, and FYM × Tillage) can be made, but statistical analyses of irrigation effect are not strictly valid as irrigation treatments are allocated systematically (Hanks et al. 1980). Hence, irrigation treatment means were compared with a Least Squares Means procedure (Morgan and Carr 1988). Statistical comparisons were consider significant at $P < 0.05$ level.

Results and discussion

Soil water content

The line source sprinkler–irrigation system provided a uniformly decreasing application depth across the plots as was desired. The amount of irrigation water applied for three experimental years ranged from 467 to 502 mm in the ETm (Control) plots, 400–432 mm in ETd$_1$ plots, 346–367 mm in ETd$_2$ plots, 282–308 mm in ETd$_3$ plots, and 214–229 mm at the furthermost distance (ETd$_4$) plots (Table 2). The precipitation during the growing season from November to March was absolutely zero in all the 3 years, and evapotranspiration was mainly from applied irrigation water. Hence, the values of crop water use (ETc) and irrigation water applied were proportional with respect to different irrigation regimes (Fig. 3). Crop water use decreased with the decrease in the amount of irrigation water applied. The crop water use varied from 397 mm

under ETm to 180 mm in the ETd$_4$ treatment plots in the three experimental years.

Deep tillage increased the volumetric soil water content at all soil depths measured during the crop growth period from November to March for each irrigation regime over conventional tillage, across the years. The spatial and temporal changes in soil water content (SWC) under conventional and deep tillage at 30 cm soil depth were depicted in Fig. 4 (because of similarity in all the years, only one representative figure was given for the year 2008–09). Gajri et al. (1997) and Laddha and Totawat (1997) have also observed that deep tillage leads to an improvement in volumetric soil water content over conventional tillage. The temporal variation in SWC for higher-order irrigation treatments were considerably larger in the 0–40 cm soil layer than in lower-order irrigation treatments, and it was lesser at deeper depths. Panda et al. (2003) reported that wheat plants extracted most of the soil moisture from 0 to 45 cm soil layer. The depth wise changes in vertical SWC at deeper depths (40–60 cm) were small and uniform, but SWC was decreased as the distance from the laterals increased.

Yield components

Deep tillage significantly increased primary yield components of wheat such as spike m^{-2}, kernels spike^{-1}, number of grains m^{-2} and 1,000 grain weight in the range of 8–12, 8–13, 19–22 and 7–9 % over conventional tillage in three years, respectively (Table 3). The higher value of these yield components under deep tillage may be ascribed to high dry matter production and its conversion into reproductive parts due to the enhanced soil water profile (Gajri et al. 1997). Application of FYM at 10 t ha^{-1} significantly increased spikes m^{-2} by 8–10 %, kernel spike^{-1} by 9–14 %, number of grains m^{-2} by 14–23 % and 1,000 grain weight by 7–9 % in comparison with the control plots, where no FYM was applied, in 3 years. The beneficial effect of FYM owing to its amorphous (capacity to absorb moisture) nature is that it absorbs more water and has mulching effects (Joshi 1987). The combined effect of deep tillage and FYM application in further increasing these yield components was not significant.

Yield components were significantly affected by deficit irrigation regimes in all years (Table 3). Spikes m^{-2},

Table 2 Experimental treatments and their corresponding irrigation depths and frequency in 3 years

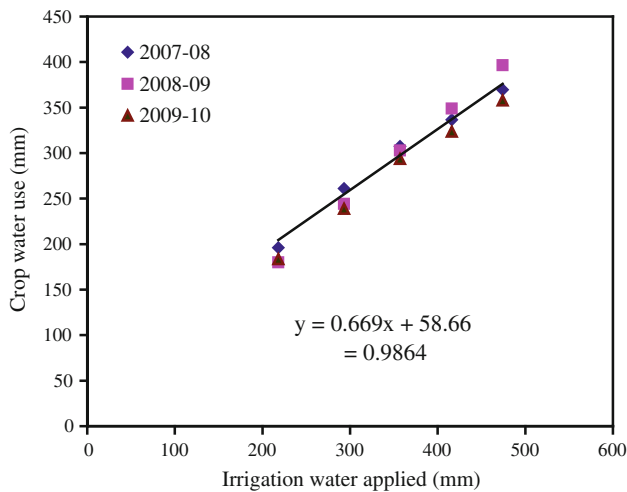| Experimental season	Cumulative pan evaporation (mm)	Irrigation depth (mm)					Total irrigations
		ETm	ETd$_1$	ETd$_2$	ETd$_3$	ETd$_4$	
2007–08	466.8	467.4	415.9	367.3	308.4	229.1	8
2008–09	500.3	501.6	431.6	357.8	288.6	210.3	8
2009–10	449.7	452.7	399.8	345.6	282.0	214.6	8

Fig. 3 Relationship between irrigation water applied and crop water use (3 years pooled data; each point represents an average value of 12 samples)

grains spike^{-1}, number of grains m^{-2} and 1,000 grains weight responses to deficit irrigation was variable. Treatment ETm recorded the maximum value with respect to above characteristics, and the differences with ETd$_1$ irrigation level were not significant across the years. On a pooled basis, spikes m^{-2}, grains spike^{-1}, and number of grains m^{-2} in the ETd$_2$, ETd$_3$, and ETd$_4$ levels were reduced significantly from the ETm irrigation level. However, the 1,000 grains weight was reduced significantly at only the ETd$_3$, and ETd$_4$ deficit irrigation levels. The lowest irrigation treatment (ETd$_4$) caused an average reduction in spikes m^{-2}, kernels^{-1} spike, number of grains m^{-2} and 1,000 grain weight by 22.0, 19.1, 34.8 and 18.6 % of the maximum value, respectively. A similar reduction in primary yield components of wheat under irrigation deficit has also been reported by Pandey et al. (2001a) and Ali et al. (2007).

Fig. 4 Variation in soil water content at 30 cm soil depth for irrigation treatment under (1) deep tillage and (2) conventional tillage during 2008–09 growing season

(i) Conventional tillage
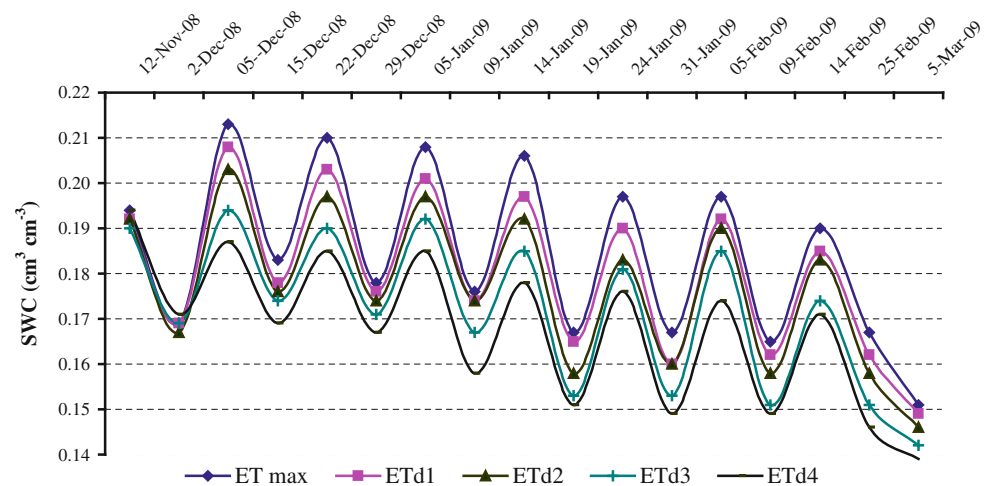
(ii) Deep tillage
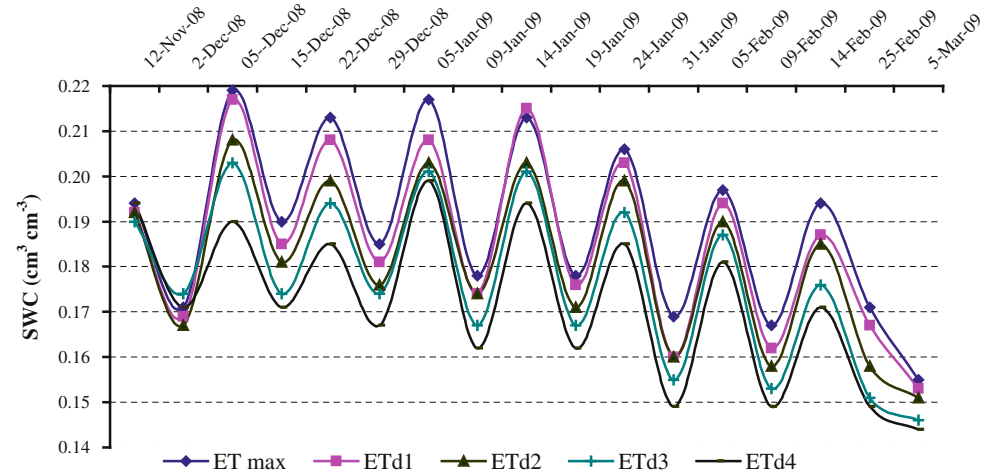
Table 3 Mean value for spike m^{-2}, grains spike^{-1}, number of grains m^{-2} and 1,000 grain weight of wheat

Treatment	Spike m^{-2}				Grains spike^{-1}				Number of grains m^{-2} (×10^3)				1,000 grain weight (g)			
	2007–08	2008–09	2009–10	Pooled	2007–08	2008–09	2009–10	Pooled	2007–08	2008–09	2009–10	Pooled	2007–08	2008–09	2009–10	Pooled
Tillage																
Con. tillage	312b	330b	314b	319b	35b	35b	34b	35b	10b	11b	11b	10b	39b	40b	37b	39b
Deep tillage	350a	357a	343a	350a	38a	39a	38a	38a	12b	13a	13a	13a	43a	43a	40a	42a
Farmyard manure																
Control	316b	329b	317b	320b	34b	36b	34b	35b	10b	11b	11b	11b	39b	40b	37b	39b
FYM @ 10 t ha^{-1}	346a	360a	341a	348a	39a	39a	38a	38a	12a	12a	12a	12a	43a	43a	39a	42a
Deficit irrigation																
ETm	359a	361a	362a	361a	39a	42a	38a	40a	13a	13a	14a	13a	44a	45a	41a	43a
ETd$_1$	358a	359ab	358a	358ab	39a	41a	38a	39a	12ab	13a	13a	13a	44a	44a	40a	43a
ETd$_2$	345a	354b	348b	349b	37ab	40a	36b	37b	12b	13a	12b	12b	43a	43a	39a	42a
ETd$_3$	317b	340bc	311c	322c	34bc	34b	35bc	34c	10c	11b	11c	10c	39b	40b	36b	38b
ETd$_4$	273c	304d	264d	281d	33c	31c	33c	32d	8d	9d	9d	9d	35c	35c	34b	35c

Means followed by the same letter in a column are not statistically different at $P < 0.05$ level of significance

Biomass production

The results indicated that tillage practices as well as the FYM application rates caused a significant difference in biomass production (Table 4). Deep tillage significantly increased biomass production by 12–14 % in comparison with conventional tillage in 3 experimental years. Gajri et al. (1991) reported that beneficial effects of deep tillage are primarily ascribed to a reduction in soil strength. Similarly, FYM at 10 t ha^{-1} increased biomass production by 8–10 % over control. Across the years, the biomass production decreased with the increase in irrigation water deficit. The total biomass production varied between 12.64 and 6.57 t ha^{-1} due to irrigation treatments in 3 years. Treatment ETm gave the highest 11.85 t ha^{-1} biomass production on mean basis compared to 6.80 t ha^{-1} recorded under severe deficit irrigation (ETd$_4$) treatment as that was only 57.4 % of ETm. This may be attributed to the fact that under ETm treatment, higher soil water storage was maintained in the profile throughout the growing season because of higher water supply (Pandey et al. 2001b).

Grain yield

Deep tillage (DT) significantly increased grain yield over conventional tillage (CT) across the years. The magnitude of increase in grain yield with DT was 12.6, 16.6 and 18.1 % over CT which recorded 4,045, 4,027 and 3,750 kg ha^{-1} grain yield during 2007–08, 2008–09, and 2009–10, respectively (Table 4). Better yields under deep tillage treatment in fine sandy clay loam Lithic Calciorthids in the present investigation are attributed to the higher soil water contents in profile (Fig. 4) creating a better environment for crop growth. Deeper tillage decreases the proportion of larger sized aggregates (2–5 mm) and increases the proportion of smaller aggregates (1–0.1 mm) increasing the total pore space and decreasing the bulk density of the soil (Bhushan et al. 1973; Nitant and Singh 1995). Laddha and Totawat (1997) have also observed that the beneficial effects of deep tillage are primarily attributed to the improvement in total soil moisture contents owing to improvement in capillary porosity and hydraulic conductivity of the soil. The reduction in grain yield with CT may have been due to low till depth which led to less soil moisture content during the crop growth period. Gajri et al. (1997) reported DT-increased wheat grain yield by 27–28 % over CT in three experimental years. Application of FYM at 10 t ha^{-1} caused significant increase in grain yield to 4,497, 4,577, and 4,346 kg ha^{-1} over no FYM which recorded 4,102, 4,144 and 3,832 kg ha^{-1} during 2007–08, 2008–09 and 2009–10, respectively. The higher grain yield obtained under FYM may be ascribed to increased yield attributes of wheat due to stimulated

Table 4 Effect of soil management and deficit irrigation on total biomass, grain yield, harvest index and crop water productivity of wheat

Treatment	Total biomass (t ha⁻¹)				Grain yield (kg ha⁻¹)				Harvest index				Water productivity (kg m⁻³)			
	2007–08	2008–09	2009–10	Pooled	2007–08	2008–09	2009–10	Pooled	2007–08	2008–09	2009–10	Pooled	2007–08	2008–09	2009–10	Pooled
Tillage																
Con. tillage	9.8b	9.3b	8.9b	9.3b	4045b	4027b	3750b	3941b	0.41a	0.43a	0.42a	0.42a	1.14b	1.16b	1.11b	1.13b
Deep tillage	11.0a	10.6a	10.1a	10.5a	4554a	4694a	4428a	4559a	0.42a	0.44a	0.44b	0.43a	1.27a	1.34a	1.30a	1.30a
Farmyard manure																
Control	9.9b	9.5b	9.1b	9.5b	4102b	4144b	3832b	4026b	0.41a	0.44a	0.42b	0.42a	1.15b	1.19b	1.13b	1.16b
FYM at 10 t ha⁻¹	10.8a	10.4a	9.8a	10.4a	4497a	4577a	4346a	4474a	0.41a	0.44a	0.44a	0.43a	1.25a	1.31a	1.28a	1.28a
Deficit irrigation																
ETm	12.6a	11.8a	11.1a	11.9a	5281a	5279a	5007a	5190a	0.42ac	0.45a	0.45a	0.44a	1.13c	1.05c	1.09b	1.09c
ETd₁	12.3a	11.4a	10.7a	11.4b	5228a	5114a	4747a	5030b	0.43a	0.45a	0.44a	0.44a	1.26a	1.19b	1.19a	1.21b
ETd₂	11.3b	10.8b	9.9b	10.7c	4603b	4790b	4346b	4580c	0.41b	0.44ac	0.44a	0.43b	1.25a	1.34a	1.26a	1.28a
ETd₃	9.0c	8.9c	8.5c	8.8d	3679c	3845c	3511c	3679d	0.41b	0.43 cd	0.41b	0.42c	1.19ab	1.33a	1.25a	1.26a
ETd₄	6.6d	6.6d	7.3d	6.8e	2704d	2776d	2835d	2772e	0.41bc	0.42d	0.39c	0.41d	1.18bc	1.32a	1.24a	1.25a

Means followed by the same letter in a column are not statistically different at $P < 0.05$ level of significance

vegetative growth on account of adequate and prolonged supply of essential nutrients through FYM (Barzegar et al. 2002; Regar et al. 2005).

The result revealed that deficit irrigation treatments, that is, less than 75 % of ETm caused significant reduction in grain yield of wheat across the years (Table 4). The treatment receiving full irrigation water (ETm) produced significantly higher grain yield 5,281, 5,279 and 5,007 kg ha⁻¹ during 2007–08, 2008–09 and 2009–10, respectively. The decrease in the applied water from ETm to ETd₁ irrigation did not affect the grain yield significantly, across the years. Further, decrease in water supply beyond the ETd₁ irrigation treatment caused significant reduction in grain yield. Grain yield obtained under the ETd₂ treatment was 87.2, 90.7 and 86.8 % of ETm in 3 years, respectively. Treatment ETd₄ represents a severe soil water deficit condition in this study. The grain yields of the ETd₄ treatment were at 51.1, 52.2 and 56.7 % of ETm in 3 years, which shows that severe soil water deficit markedly decreased grain yield of wheat compared with other treatments. The results indicated that in experimental years, grain yield and seasonal water use were dependent on the controlled range of irrigation water supply. The grain yield response to irrigation varied considerably due to differences in irrigation levels under deficit irrigation; this has also been observed by Pandey et al. (2001a) and Sezen and Yazer (2006).

The interaction effect of tillage practices and deficit irrigation on grain yield of wheat was significant (Table 5). The yield differences between DT and CT were significantly higher at all irrigation levels (ETm to ETd₃), except at the severe soil water deficit (ETd₄) level. Maximum grain yield of 5,600 kg ha⁻¹ was obtained from DT under the ETm irrigation, and it declined by 48 % due to CT under the ETd₄ irrigation (2,685 kg ha⁻¹). A significant point is that yield obtained under DT at ETd₂ irrigation (4,967 kg ha⁻¹) was on par with yield recorded under CT at ETm irrigation (4,779 kg ha⁻¹) on a mean basis. Thus,

Table 5 Interaction effect of irrigation × tillage and irrigation × FYM on grain yield of wheat (3 years pooled data)

Irrigation deficit	Grain yield (kg ha⁻¹)			
	Tillage type		FYM	
	Conventional	Deep	Control	10 t ha⁻¹
ETm	4,779bc	5,600a	4,881b	5,498a
ETd₁	4,586c	5,473a	4,713b	5,346a
ETd₂	4,193d	4,967b	4,319c	4,841b
ETd₃	3,462f	3,895e	3,532e	3,826d
ETd₄	2,685g	2,860g	2,686f	2,858f

Means followed by the same letter within tillage type and FYM rates are not statistically different at $P < 0.05$ level of significance

it can be argued that the effect of deep tillage on grain yield was equivalent to the yield differences between ETm and the ETd_2 irrigation level (4,779 – 4,193 = 586 kg ha^{-1}), and this signifies the role of deep tillage in medium-textured shallow soils of this part of the world under limited irrigation conditions. Gajri et al. (1991) and Gajri et al. (1997) reported that deep tillage should be combined with frequent small irrigations for higher wheat yields and input use efficiencies.

Similarly, the interaction effect of FYM application and deficit irrigation on grain yield of wheat was also significant (Table 5). Highest grain yield of 5,498 kg ha^{-1} was obtained from application of FYM at 10 t ha^{-1} with the ETm irrigation followed by 5,346 kg ha^{-1} obtained under FYM with the ETd_1 irrigation and 4,881 kg ha^{-1} obtained under no FYM with the ETm irrigation. Fan et al. (2005) reported that the addition of organic material to soil maximizes the use of stored soil water and arrested grain yield decline in wheat. Further, the result of the present investigation (Table 5) reveals that manure application was able to compensate to a significant degree for increased yield due to tillage practices (Mosaddeghi et al. 2009). The comparable yield response to deep tillage or FYM on shallow sandy clay loam soil suggests that either of the options depending on their cost and availability can be employed for improving grain yield of wheat.

Harvest index

The harvest index values varied between 0.41 and 0.44 with no significant difference in 2007–08 and 2008–09 due to any of the soil management practice, but it increased significantly with DT as well as FYM application over the control in 2009–10 (Table 4). Musick and Porter (1990) stated that HI varies between 0.38 and 0.60 for high-yielding wheat varieties under irrigation. Irrigation treatments had a significant effect on harvest index in all 3 years. In general, HI values in ETm, ETd_1 and ETd_2 irrigation plots were relatively higher than in other treatments, meaning that appropriate irrigation and controlled soil water content can increase harvest index as a result of the good water supply during the reproductive stage (Zhang et al. 1998; Sezen and Yazer 2006; Bandyopadhyay et al. 2010).

Water productivity

Deep tillage (DT) significantly increased water productivity of wheat to 1.27, 1.34 and 1.30 kg m^{-3} from 1.14, 1.16 and 1.11 kg m^{-3} obtained under conventional tillage (CT) during 2007–08, 2008–09 and 2009–10, respectively (Table 4). Arora et al. (2011) reported that WP gains are ascribed to tillage-induced reduction in soil mechanical

resistance and moderation of water conservation. Application of FYM to wheat resulted in higher water productivity as compared to control. WP increased from 1.15, 1.19 and 1.13 kg m^{-3} under no FYM to 1.25, 1.31 and 1.28 kg m^{-3} due application of 10 t FYM ha^{-1} in the year 1, 2 and 3, respectively. Barzegar et al. (2002) reported farmyard manure application significantly increased infiltration rate, water content and wheat grain yield in semi-arid region. Ali and Talukder (2008) in a synthesis pointed out that WP gains could be achieved by addition of organic matter.

Irrigation treatments significantly changed the water productivity of wheat across the years. The WP value varied from 1.05 to 1.34 kg m^{-3}, among the treatments in 3 years. The maximum WP was found with irrigation treatments of ETd_1 during 2007–08 and ETd_2 during 2008–09 and 2009–10. However, the least WP was found with treatments receiving the highest irrigation water (ETm) in all years. On a pooled basis, the maximum WP was in the ETd_2 treatment, which was significantly greater than the ETm and ETd_1 treatments, but not significantly different from the deficit levels of ETd_3 and ETd_4. Applying more water than required by ETc will not increase WP as the water may be lost through unproductive soil evaporation (Geerts and Raes 2009). Zhang et al. (2006) pointed out that the higher IWUE with lower depth may be attributable to the efficient use of available soil water in the root zone. Under full irrigation conditions, part of the irrigation water may not be used, but left in the soil profile at harvest, and may also decrease IWUE. Results indicated that the increasing distance from the line source created water deficit to the extent of 88, 75, 62 and 46 % of ETm which had caused decline in grain yield of wheat to the extent of 97, 88, 71 and 53 % of maximum yield. In the present investigation, highest mean WP of 1.28 kg m^{-3} in wheat was observed in ETd_2 irrigation treatment representing 25 % water deficit range which opened the scope to use limited water through sprinkler irrigation in wheat.

Table 6 Interaction effect of irrigation × tillage on water productivity of wheat (3 years pooled data)

Irrigation deficit	Water productivity (kg m^{-3})	
	Conventional tillage	Deep tillage
ETm	1.01c	1.18c
ETd_1	1.10b	1.32b
ETd_2	1.17a	1.39a
ETd_3	1.18a	1.33ab
ETd_4	1.21a	1.29b

Means followed by the same letter within column and rows are not statistically different at $P < 0.05$ level of significance

A closer analysis of data further shows significant interaction effect between tillage practices and deficit irrigation on water productivity of wheat (Table 6). The WP under DT increased with decrease in water supply from ETm to ETd_2 irrigation, and thereafter, it declined. On the other hand, WP under CT tended to increase with the reduction in irrigation water supply from ETm to ETd_4. The highest WP of 1.39 kg m^{-3} was recorded under DT at ETd_2 irrigation as compared to least WP of 1.01 kg m^{-3} obtained under CT at ETm irrigation level. Tillage-enhanced synergistic effect of irrigation on crop water use (Arora et al. 1993, 2011).

Crop water production function

The relationship between grain yield and the total applied water is useful for optimizing irrigation strategy. The response of grain yield to irrigation water was described using a regression analysis. A highly significant polynomial relationship exist between grain yield and the total applied water for each experimental year and combined data ($R^2 = 0.96$) (Fig. 5). The curvilinear relationships of yield with the total applied water suggest that a policy for maximizing yield under limited water resources conditions should be avoided, and maximizing water productivity is recommended for sustainable use of water resources in this region. Ali et al. (2007) suggested that high WUE for an irrigation scheduling should be associated with high (or acceptable) yield, particularly in water scare areas. Based on this idea, we used the two curves of crop yield and WP with irrigation depth to determine the optimum irrigation depth (Fig. 6). The intersection point of the two curves
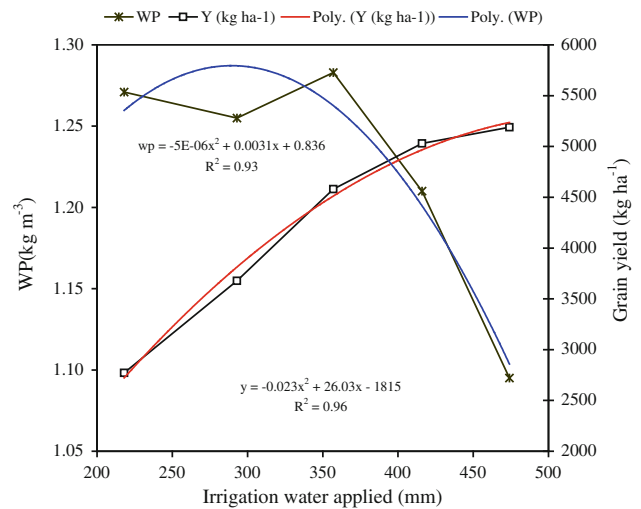

Fig. 6 Irrigation water use, yield and water productivity relationship in wheat (3-year mean data; each point represents an average value of 36 samples)
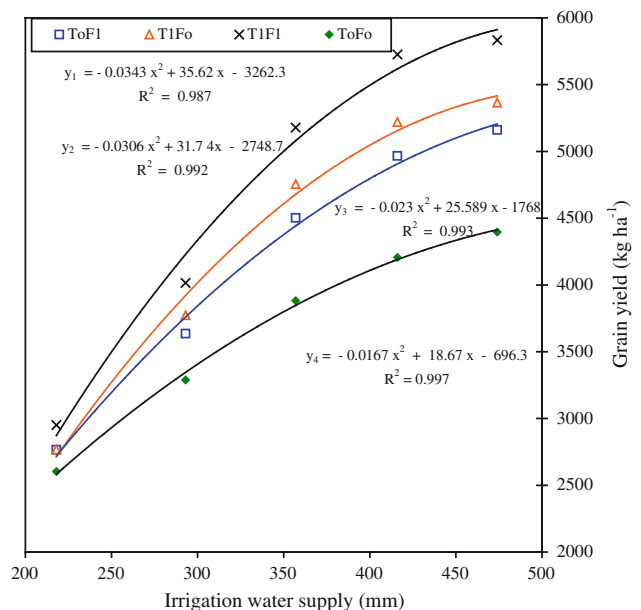

Fig. 7 Wheat grain yield response to irrigation water supply under different soil management practices (T_0—conventional tillage; T_1—deep tillage; F_0—No FYM; F_1—FYM at 10 t ha^{-1}; each point represents an average value of 9 samples)

showed that optimum irrigation depth was 388 mm with 4,830 kg ha^{-1} grain yield. With this optimal irrigation depth, 93 % of the maximum grain yield and 97 % of maximum WP can be achieved.

Singh and Mann (1979) reported that the relationship between grain yield and applied water was linear for wheat grown in rainless winter months in arid northwest India when a low range of irrigation was applied and curvilinear when a higher range was applied. Geerts and Raes (2009) in a recent review also reported similar results. In the present
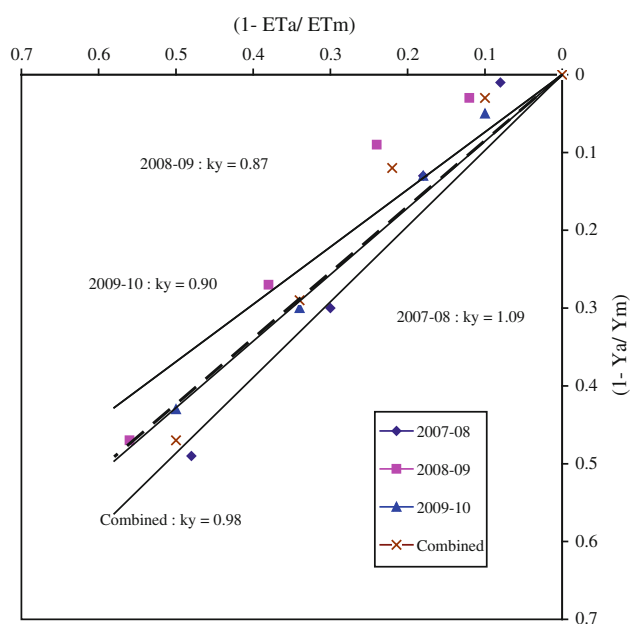

Fig. 5 Relationship between wheat grain yield (y) and irrigation water applied in the experimental years (each point represents an average value of 12 samples)

Fig. 8 Relationship between relative yield reduction and relative evapotranspiration deficit for wheat (each point represents an average value of 12 samples; due to over lapping of data points, only three lines seems to be shown on the *graph*)

investigation, the crop production functions with the total applied water under different soil management practices showed significant curvilinear relationships (Fig. 7). These empirical relationships may be used to estimate the levels of irrigation water for maximizing yield under limited water resources, as well as to determine the most beneficial use of water for prediction of optimum yield with soil management practices. In this study, three years mean seasonal crop water use (ETc) for the best water regime (ETd$_2$ treatment) was 301 mm, which was in close agreement to 303 mm reported by Hati et al. (2001) in the dry tracts of central India. The relationship between relative yield reduction and relative evapotranspiration deficit for wheat grain yield is linear (Fig. 8). The yield response factor (k_y) for wheat varied between 0.87 and 1.09 for the 3 years. When combined values were used, a k_y factor of 0.98 was obtained. The crop yield response factor (k_y) of 1.15 calculated for spring wheat are only valid for relative evapotranspiration reductions from 1 to 0.5 (Doorenbos and Kassam 1979). In the present study, the relative evapotranspiration reduction was from 1 to 0.49–0.42 in different years, the k_y value estimated in the present study seems logical in arid environments of northwest India.

Conclusion

This study has shown that management intervention of deep tillage and/or farmyard manure positively influenced the ensuing wheat biomass production and final grain yield.

The yield and WP gains are ascribed to greater water conservation with tillage-induced reduction in soil strength and FYM application. The comparable yield response to deep tillage or FYM on shallow sandy clay loam soil suggest that either of the options depending on their cost and availability can be employed for improving grain yield and water productivity of wheat. The potential benefits of deficit irrigation appear significant for wheat production in arid regions of northwestern India. When irrigable fields are abundant and water is scarce, the optimum water deficit strategy would be to irrigate with a 22–25 % water deficit relative to ETm. This study showed that optimizing irrigation and soil management practices in coarse-textured shallow soils of arid environment can maximize wheat production.

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