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Tillage and Rice-Wheat Cropping Sequence Influences on Some Soil Physical Properties and Wheat Yield under Water Deficit Conditions

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ABSTRACT

Adopting a better tillage system not only improves the soil health and crop productivity but also improves the environment. A field experiment was conducted to investigate the effects of tillage and irrigation management on wheat (*Triticum aestivum* L.) production in a post-rice (*Oryza sativa* L.) management system on silty clay loam soil (acidic Alfisol) for 2003-2006. Four irrigation levels (RF: rainfed; I_1: irrigation at crown root initiation (CRI); I_2: irrigation at CRI + flowering; I_3: irrigation at CRI + tillering + flowering), and two tillage systems (ZT: zero tillage and CT: conventional tillage) were tested. Zero tillage compared to CT, resulted in higher bulk density (1.34 vs 1.23 $Mg \cdot m^{-3}$), lower total porosity (48.7% vs 52.9%), higher penetration resistance (1.51 vs 1.37 MPa), lower saturated hydraulic conductivity (1.60 vs 92.0 $mm \cdot h^{-1}$), lower infiltration rate (9.40 vs 36.6 $mm \cdot h^{-1}$) and higher volumetric available water capacity (7.9% vs 7.5%) in the surface 0.15 m soil layer. Irrigation levels significantly affected crop water use, wheat yield, and water use efficiency (WUE). Average total water use was 461, 491, 534 and 580 mm under RF, I_1, I_2 and I_3 treatments, respectively. Grain and straw yield of wheat were statistically the same under ZT and CT during 2003-2004; the values, averaged over four irrigation levels were 2.10 and 2.38 $Mg \cdot ha^{-1}$ for grain, and 3.46 and 3.67 $Mg \cdot ha^{-1}$ for straw, respectively. Grain yield declined by 22%, 11% and 8% of I_3 (2.32 $Mg \cdot ha^{-1}$) with RF, I_1 and I_2 treatments, respectively, under ZT; and by 13%, 8% and 5% of I_3 (2.61 $Mg \cdot ha^{-1}$) with RF, I_1 and I_2 treatments under CT. Average values of WUE were 4.33 $kg \cdot ha^{-1} \cdot mm^{-1}$ and 2.35 $m^3 \cdot kg^{-1}$ grain for the ZT and CT treatments. Wheat yield increased with increased irrigation levels for all the cropping seasons. Results from this study concluded that ZT system was better compared to the CT system even with lower yields due to lower input costs for this treatment.

Keywords: Conventional Tillage; Soil Physical Properties; Infiltration; Water Retention; Water Use Efficiency; Zero Tillage

1. Introduction

Rice and wheat in sequence are cultivated in two contrasting soil environments. Rice requires soft, puddled and water-saturated soil conditions, while wheat requires well aggregated and well aerated soil with fine tilth. Puddling (wet tillage) is the most common technique of land preparation for rice in South Asian countries. Puddling creates soil conditions ideal for rice cultivation, but unsuitable for upland crops which follow rice [1,2]. After rice harvest, puddled soils, upon drying shrink, become compact and hard, and develop surface cracks of varying sizes and shapes. The draught power requirement for tilling such soils is very high, sometimes beyond the reach of local ploughs and small tractors. Nevertheless, when tilled, these soils often break into larger clods, having high breaking energy [3]. In spite of spending significant time and energy, it is often difficult to obtain seedbeds with the desired tilth for sowing wheat. Wheat planted in seedbeds with coarse tilth, due mainly to poor seed-soil contact, results in poor seedling emergence and unsatisfactory crop stands. This lowers wheat productivity.

Frequent stirring opens the soil, breaks soil clods and aggregates, and enhances the oxidation of soil organic matter [4,5]. The loose soils especially on sloping landscapes and in high rainfall areas, are excessively prone to soil erosion. Thus, this system enhances land degradation and results in a decline in soil quality.

To achieve satisfactory soil tilth, soils must be tilled at optimum moisture content. The optimum water content

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range in puddled soils is generally narrow [1], and many times difficult for farmers to observe. Further, puddled soils may take from several weeks to months to dry and reach a moisture content optimum for tillage. This increases the lag time between rice harvest and wheat planting. The delayed sowing of wheat is another cause of low productivity in post-rice management. An estimate suggests each day delay in planting after 15th of November lowers wheat yield by about 0.04 $Mg \cdot ha^{-1}$ [6,7].

Conventional cultivation of wheat involves several repetitions (3 to 7) of ploughing and planking with animal-drawn local ploughs and wooden planks. The idea of repeated tillage is to create a seedbed with fine tilth and create a dust mulch to conserve soil moisture in the seedbed. In high rainfall areas (annual rainfall varying between 1500 - 2500 mm), these soils suffer from severe soil erosion. Hence, a conservation tillage system is required which is less intensive, is better for the environment (reduces carbon emissions), and enhances soil structural stability and helps to conserve soil by reducing erosion risks [8].

Field experiments with zero tillage in wheat at several locations in the Indo-Gangetic plains have shown encouraging results [9-11]. Farmers have found direct drilling of wheat into post-rice systems without tillage feasible and beneficial at several locations. Wheat yields with zero tillage are either equal or even better than those obtained with conventional tillage because of timely planting of wheat, efficient use of fertilizers and weed control. In addition, zero tillage is fuel and energy efficient but also reduces greenhouse gas emissions [12]. Zero tillage systems conserve the land resource and are cost effective and efficient. Moreover, this tillage system also avoids challenges with clod formation.

Benefits of zero-till planting have been reported under irrigated conditions. Whether similar benefits can be obtained under deficit water conditions still remains a question. The issue is more relevant to hilly areas, as in the Himachal Pradesh (HP) state of India, where wheat is principally a rainfed crop. Irrigated areas under wheat in HP, India are less than 18%. Deficit irrigation systems also need to be evaluated relative to performance with zero-till planting. The objectives of the current study were to 1) compare soil physical properties under zero and conventional tillage systems for a rice-wheat cropping system, and 2) compare wheat yields, and wheat water use efficiency (WUE) for zero and conventional tillage systems.

2. Materials and Methods

2.1. Experimental Site and Management

The experiment was conducted at the Experimental Farm of the Department of Soil Science, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur, Himachal Pradesh (HP). The experimental site was situated at 32˚6'N latitude and 76˚3'E longitude at an elevation of about 1290 m above mean sea level. The area lies in the Palam Valley of Kangra district in the foothills of Dhauladhar Range and represents the high rainfall, mid-elevation, wet-temperate zone of Himachal Pradesh in the North-west Himalayas.

The climate of the study area is wet temperate, characterized by severe winters and mild summers. The average annual rainfall of the study area in the last 10 years was 2058 mm and pan evaporation was 1215 mm. The annual maximum temperature is 22.4˚C and the minimum temperature is 13.3˚C. Annual mean temperature varies from 8.2˚C in January to around 28.0˚C during the months of May-June. The soil temperature drops as low as 2˚C during the winters and frost incidences are common.

The soils of the region are classified as Gray Brown Podzols, as per the Genetic System of Classification. Taxonomically, these soils fall under the order of Alfisols [13]. These soils owe their origin to the fluvio-glacial parent materials developed from rocks like slate, phyllites, quartzites, schists and gneisses. The soils are acidic (pH 5.2 to 6.3). The experimental soils belonged to subgroup Typic Hapludalfs.

2.2. Treatment Details

A field experiment was conducted in 2003-2006. Soil physical properties were measured for 2003-2004 year, and wheat yield and water use efficiency were also compared for three cropping seasons from 2003 to 2006 for different treatments. Two tillage systems (ZT: zero tillage and CT: conventional tillage) and four irrigation levels (RF: rainfed; I_1: irrigation at CRI; I_2: irrigation at CRI + flowering; I_3: irrigation at CRI + tillering + flowering) were tested. The two tillage systems included 1) zero tillage: wheat sown in lines 0.20 m apart by opening narrow slits with a hand plough in untilled plots (ZT), and 2) conventional tillage: wheat was sown in lines 0.20 m apart with the help of a hand plough in well pulverized plots (CT). The four irrigation management systems included 1) rainfed (RF), 2) irrigation at CRI (CRI), 3) irrigation at CRI and flowering stage (CRI + F), and 4) irrigation at CRI, active tillering and flowering stages (CRI + T + F). It is noted that each irrigation of about 5 cm was applied as surface flooding per treatment. One pre-sowing irrigation was applied to all plots.

The total number of treatment combinations was eight with three replications for 24 total number of plots (9 m^2 areas). The treatment effect was investigated for wheat crop (Surbhi, HPW-89) and the experimental design was a randomized complete block. Land preparation was done with the help of a power tiller (Model CT-85, V.S.T. Tillers Tractors Ltd., Bangalore, India). Different field operations and irrigation scheduling during the experiment are summarized in **Tables 1** and **2**.

Each plot received a uniform application of 120 N $kg \cdot ha^{-1}$, 60 $kg \cdot ha^{-1}$ P_2O_5 and 40 $kg \cdot ha^{-1}$ K_2O as urea, single super phosphate and muriate of potash during the growing season. For the rainfed treatment (no irrigation applications), all fertilizers were band-placed at the time of sowing in November. For the irrigation treatment at crown root initiation (CRI; I_1), 50% of the N and all of the P and K were band-placed at the time of sowing with 50% of N broadcast applied at CRI stage during November and December. For the irrigation treatments at CRI + flowering (I_2) and irrigation at CRI + active tillering + flowering (I_3), 50% of the N and all of the P and K were band-placed at sowing with 25% of N broadcast applied, each at CRI and flowering stage.

2.3. Soil Physical Properties

Particle size analysis of surface and sub-surface soil samples (0 - 0.15 and 0.15 - 0.30 m) was done using the pipette method [14]. Particle density of the soil was determined by the pycnometer method [15]. The soil textural class was silty clay loam and the particle density of the soil was 2.60 and 2.61 $Mg \cdot cm^{-3}$, respectively for 0 - 0.15 and 0.15 - 0.30 m soil depths. The soil bulk density (ρ_b) was determined before land preparation and 30-days after sowing of wheat by the core sampler method [16], using metallic cores having 0.138 m length and 0.103 m internal diameter. Undisturbed soil cores were collected from the 0 - 0.60 m depth at 0.15 m depth intervals in all plots. Four soil cores were removed at each depth and the moist mass was recorded. Gravimetric moisture content was determined in a sub-sample of each soil core and was used to determine the dry mass of soil in each core.

The total porosity (f) of the 0 - 0.15 m soil layer was determined at 30-days after seeding from data on particle density and ρ_b, using the following relationship:

$$f = \left(1 - \rho_b / \rho_s\right) \times 100 \tag{1}$$

where, f is the total porosity (%), ρ_b the bulk density ($Mg \cdot m^{-3}$) and ρ_s the particle density ($Mg \cdot m^{-3}$).

Table 1. Summary of field operations performed during the study for the 2003-2004 cropping season. The same operations were performed for the 2004-2005 and 2005-2006 cropping years within a couple days of the dates for the 2003-2004 season.

Date	Field operation	Remarks
Nov. 6	Pre-plant irrigation	Flood-irrigation method.
Nov. 9	Land preparation in conventionally-tilled plots	Land prepared using a power tiller.
Nov. 11	Planting of wheat	Wheat sown in rows at 0.20 m spacing using hand plough at 100 $kg \cdot ha^{-1}$ seed rate.
Dec. 27	Hand weeding and hoeing	Weeding in all plots. Hoeing only in conventionally-tilled plots.
Jan. 28	Hand weeding and hoeing	Weeding in all the plots. Hoeing only in conventionally-tilled plots.
May 6	Crop harvesting	Wheat harvested in 5.76 m^2 area in centre of each plot.

Table 2. Irrigation timing and amount of water applied to the zero tillage (ZT) and conventional tillage (CT) treatments for the irrigation regime treatments for the 2003-2004 cropping year. The same amounts were applied within a couple of days of the dates for the 2003-2004 cropping years for the 2004-2005 and 2005-2006 cropping years.

Irrigation Regime Treatment	Tillage Treatment	Amount of Irrigation Water Applied (mm)				
		Irrigation Application Dates				Total water applied
		Nov. 6	Dec. 12	Jan. 11	March 3	
RF	ZT	50	-	-	-	50
	CT	50	-	-	-	50
I_1	ZT	50	50	-	-	100
	CT	50	50	-	-	100
I_2	ZT	50	50	-	50	150
	CT	50	50	-	50	150
I_3	ZT	50	50	50	50	200
	CT	50	50	50	50	200

RF = Rainfed; I_1 = Irrigation at crown root initiation (CRI); I_2 = Irrigation at CRI and flowering stage; I_3 = Irrigation at CRI and active tillering and flowering stage.

Undisturbed soil cores were collected from the 3 replicates in metal cores of 0.11 m length and 0.081 m diameter in the 0 - 0.15 m soil depth in both zero-till and conventionally-tilled plots at crop harvest. The saturated hydraulic conductivity (K_{sat}) was determined by the constant head method [17].

2.4. Soil Water Content

Soil water content was determined gravimetrically in the 0 to 0.60 m profile at 0.15 m depth intervals at sowing, one-day before and after each irrigation and at crop harvest. The mass wetness was converted into volume wetness for each soil layer using the ρ_b of each respective soil layer.

2.5. Soil Penetration Resistance

Soil penetrometer resistance (SPR) refers to the resistance offered by the soil to a metal probe (representing a plant root) pushed into soil. The SPR at field moisture content was determined in the 0 - 0.03 and 0.10 - 0.13 m soil depths at tillering stage. A Proctor penetrometer having a 0.18 m long probe with a flat tip of 6 mm diameter was used for SPR determination. About seven observations were made per plot at each depth for computing the average SPR. After recording the SPR value, soil samples from the layer of the same depth thickness were collected with the help of a tube auger for determining gravimetric moisture content.

2.6. Soil Water Retention

Undisturbed soil core samples, 0.03 m long and 0.054 m diameter were collected from each replication in the middle of the 0 - 0.075 m soil layer with metal cores at the flowering stage of wheat. Moisture content at –33, and –1500 kPa matric potential was determined with a pressure plate apparatus (Soil Moisture Equipment Co., Santa Barbara, California, USA). Soil samples were saturated for 24 hours on the porous plate and then equilibrated to the applied pressures.

Plant-available water capacity (PAWC) was determined for each treatment at flowering stage of wheat as follows:

$$\text{PAWC} = \text{FC} - \text{PWP} \tag{2}$$

where FC is the moisture retained at –33 kPa matric potential, and PWP (permanent wilting point) is the moisture retained at –1500 kPa matric potential.

2.7. Infiltration Measurements

The infiltration behavior of the soil under zero and conventional tillage treatments was studied at the time of wheat harvest using double ring infiltrometers. The infiltrometers were pushed into the ground to a depth of 0.15 m. Care was taken to avoid formation of cracks at the soil surface while the infiltrometers were driven into the soil. Water was filled almost to the same level in the inner and outer rings with 0.25 and 0.30 m of inner and outer diameter, respectively. The volume of water which infiltrated into the soil as a function of time was measured. The depth of water infiltrated was computed by dividing the volume by the cross-sectional area of the inner infiltrometer. Regular determinations were made at periodical intervals until a steady water flux was reached. The water intake rate (i) and the cumulative intake (I) were plotted on a simple scale as a function of time. The Gree-Ampt model (1911) was used to fit the infiltration data.

The Green-Ampt [18] infiltration equation was modified by Philip [19] for time (t) vs. cumulative infiltration (I), as follows:

$$t = \frac{I}{K_s} - \frac{\left[S^2 \ln\left(1 + \frac{2IK_s}{S^2}\right)\right]}{2K_s^2} \tag{3}$$

where t (T) is time (h), I (L) is the cumulative infiltration (mm), S ($L \cdot T^{-0.5}$) is the sorptivity ($mm \cdot h^{-0.5}$), and K_s ($L \cdot T^{-1}$) is the saturated hydraulic conductivity ($mm \cdot h^{-1}$). For estimating the S and K_s parameters, the method proposed by Clothier *et al*. [20] was used.

The method to estimate field saturated hydraulic conductivity (K_{fs}) suggested by Reynolds *et al*. [17] was used for estimating this parameter. It assumes one-dimensional water flow in the infiltration ring, and uses the following equation:

$$K_{fs} = \frac{q_s}{\left(\frac{H}{C_1 d + C_2 a}\right) + \left\{\frac{1}{\left[\alpha^* \left(C_1 d + C_2 a\right)\right]}\right\} + 1} \tag{4}$$

where K_{fs} is the field-saturated hydraulic conductivity ($mm \cdot h^{-1}$), q_s is the quasi-steady infiltration rate ($mm \cdot hr^{-1}$), a is the radius of the infiltration ring (mm), H is the hydraulic head of ponded water in the ring (mm), d is the depth of ring insertion into the soil (mm), C_1 and C_2 are dimensionless quasi-empirical constants (C_1 = 0.993 and C_2 = 0.578 for this infiltrometer), and α^* is the soil macroscopic capillary length, assumed to be equal to 0.0036 mm^{-1} for the conventional tillage, and 0.012 mm^{-1} for the zero tillage treatment [17].

2.8. Wheat Yield and Water Use Efficiency

The wheat crop was harvested from ground level from the net plot area of 5.76 m^2, centered in the plot, with the help of sickles, and was left in the respective plots for sun-drying for 2 - 3 days. When most of the straw in a handful bundle broke up on folding, total produce was weighed and recorded as biological yield. The produce was then threshed with thresher and grains were separated out. The grains thus collected were weighed and the yield was recorded as $Mg \cdot ha^{-1}$.

The water use efficiency (WUE) was computed as: 1) WUE ($kg \cdot grains \cdot ha^{-1} \cdot mm^{-1}$) = Grain yield ($kg \cdot ha^{-1}$)/Total water use (mm), and 2) WUE ($m^3 \cdot kg^{-1}$) = Total water use (m^3)/Wheat grains (kg).

2.9. Statistical Analysis

The statistical design for the study was a factorial experiment with two levels of tillage and four levels of irrigation arranged in a randomized complete block design with three replicates. Some parameters were only evaluated for tillage plots; these were sampled from the rainfed (RF) irrigation treatment. Statistical differences were declared significant at the $\alpha = 0.05$ level. The statistical analysis was conducted with SAS software [21].

3. Results and Discussion

3.1. Soil Penetration Resistance

Soil penetration resistance (SPR) values, determined immediately before the application of irrigation at the tillering stage of wheat in the 0.10 - 0.13 m soil layer, are shown in **Table 3**. The SPR was significantly affected by tillage, but the effect of irrigation treatments for the CT tillage system on SPR was non-significant. SPR values varied between 1.40 and 1.61 MPa with a mean value of 1.51 MPa under ZT, and between 1.31 and 1.35 MPa with a mean value of 1.34 MPa under CT. The SPR was significantly higher under ZT than CT for all irrigation levels. The gravimetric soil moisture content was 17.6% - 20.0% under ZT, and 19.1% - 21.8% under CT (**Table 3**).

Soil penetration resistance (SPR) values averaged over four irrigation levels, determined at 0 - 0.03 m and 0.10 - 0.13 m soil depths at crop harvest are shown in **Table 4**. The SPR at field moisture content (9.3% - 12.2%) was higher in the ZT system than the CT system with a magnitude of about 4 times in the 0 - 0.03 m layer, and about 2.5 times in 0.10 - 0.13 m layer. Higher SPR in the ZT plots were found due to the higher soil ρ_b value (1.34 $Mg \cdot m^{-3}$) in ZT plots compared to CT plots (1.23 $Mg \cdot m^{-3}$; **Table 5**).

3.2. Soil Bulk Density, Saturated Hydraulic Conductivity and Porosity

The ρ_b was about 8.9% higher in ZT compared to CT plots (**Table 5**). The soil K_{sat} (0 - 0.15 m depth), determined at wheat harvest, was 57 times higher under CT than ZT (**Table 5**). Infiltration rate and K_{sat} are both functions of pore size distribution. Both of these processes increase with an increase in soil macroporosity. Conventional tillage caused loosening of the surface soil layer thereby increasing the macroporosity and hence increasing the infiltration rate and K_{sat}.

Singh *et al.* [22] also observed an increase in K_{sat} in a post-rice soil after tillage. Higher values of infiltration as well as K_{sat} under CT than ZT were also reported by Barzegar [23]. The situation, however, may be different under continuous zero till systems than in rice-wheat system. A soil, continuously under zero till management, especially when crop residues are left on the soil surface, may show higher infiltration rates and K_{sat} values due to root channels formed in soil and enhanced earthworm

Table 3. Soil penetration resistance (SPR), and soil water content in the subsurface soil layer (0.10 - 0.13 m) at tillering stage of wheat under different tillage and irrigation treatments measured during the 2003-2004 cropping season.

Tillage Treatment	Irrigation Regime Treatment	Gravimetric soil water content (g/g %)	SPR (MPa)
ZT	RF	17.9^{de}	1.61^{a}
	I_1	17.6^{e}	1.55^{b}
	I_2	20.0^{bc}	1.44^{c}
	I_3	19.5^{c}	1.40^{d}
CT	RF	19.8^{bc}	1.35^{e}
	I_1	21.8^{a}	1.31^{f}
	I_2	19.1^{dc}	1.33^{ef}
	I_3	21.0^{ab}	1.35^{e}
	Analysis of variance $P > F$		
Treatment		<0.01	<0.01

ZT = Zero tillage; CT = Conventional tillage; RF = Rainfed; I_1 = Irrigation at CRI stage; I_2 = Irrigation at CRI and flowering stage; I_3 = Irrigation at CRI, tillering and flowering stage; Note: The SPR values have been averaged over different irrigation treatments because of small differences in soil moisture content.

Table 4. Soil penetration resistance (SPR) and soil water content for two soil depths at crop harvest in the zero tillage (ZT) and conventionally-tilled (CT) treatments measured at crop harvest during the 2003-2004 cropping season.

Tillage	0 - 0.03 m soil depth		0.10 - 0.13 m soil depth	
	Water content	SPR	Water content	SPR
	(g/g %)	(MPa)	(g/g %)	(MPa)
ZT	12.2[a†]	5.16[a]	9.3[a]	8.36[a]
CT	11.7[b]	1.28[b]	11.4[b]	3.39[b]
Treatment	<0.01	<0.01	<0.01	<0.01

[†]Means with different letters are significantly different at the 0.05 probability level.

Table 5. Saturated hydraulic conductivity (K_{sat}), bulk density, and total porosity of the surface soil layer (0 - 0.15 m) under zero tillage (ZT) and conventional tillage (CT) treatments at 30 days after seeding of wheat for the 2003-2004 cropping season.

Tillage	K_{sat} (mm·h^{-1})	Bulk density (Mg·m^{-3})	Total porosity (%)
ZT	1.62[a†]	1.34[a]	49.3[a]
CT	92.0[b]	1.23[b]	53.7[b]
	Analysis of variance $P > F$		
Treatment	<0.01	<0.01	<0.01

[†]Means with different letters are significantly different at the 0.05 probability level.

activity as was observed by Barnes and Ellis [24]. Several other workers reported higher infiltration rate under ZT system due to the formation of continuous soil biopores [25-27]. Loch and Coughlan [28] reported higher deep drainage under ZT than CT due to the presence of continuous macropores under ZT.

3.3. Soil Water Retention

Water retention of the surface 0.075 m soil layer on a mass basis at –33 kPa and –1500 kPa soil water pressure was always higher in CT than in ZT plots. The differences, however, narrowed with the decrease in water potential. Water content on a volume basis was higher in the ZT system than the CT system at –33 and –1500 kPa pressure due to differences in ρ_b (**Table 6**). The plant available water capacity (PAWC) on a volume basis was lower for the CT (7.5%) than ZT (7.9%) treatment (**Table 6**).

Soil water retention (0 - 0.75 m soil layer) at –33 and –1500 kPa water pressures varied with tillage system. These differences could be explained with differences in pore size distribution since the water retention of soils depends primarily on 1) the number and size distribution of soil pores and 2) the specific surface area of soils. Pore size distribution affects water retention mainly at higher water potentials, such as those at saturation and field capacity, where the water retention is a function of soil structure. At lower water potentials, close to the permanent wilting point, the water retention is a function of soil texture, and also depends on the specific surface area of soil particles [29]. Tillage modified the soil structure thereby affecting water retention at –33 kPa water potential; however, tillage did not affect soil texture, hence differences in water retention between CT and ZT narrowed at –1500 kPa water potential.

The water retention on a volume basis at –33 and –1500 kPa pressure was higher under ZT than CT (**Table 6**). This occurred in part because of the higher ρ_b under ZT than CT. Although differences in PAWC between ZT and CT were not very large, the soil water retention under ZT was slightly better than under CT.

3.4. Infiltration Rate

The steady-state infiltration rate in conventionally-tilled plots (32.6 mm·h^{-1}) was more than 4 times higher than that of zero tilled plots (7.2 mm·h^{-1}). The cumulative infiltration was also higher in CT (665 mm) than in ZT plots (278 mm). The steady-state infiltration in both cases was achieved in about an 11-hour period (**Figure 1**).

The Green-Ampt (GA) model was fitted to measured infiltration data. The GA model appeared to fit the measured infiltration data (**Figure 1**). The K_s parameter was significantly different, whereas, the S parameter was not significantly different between the tillage systems (**Table 7**). The K_s parameter was 47 times higher for the conventional tillage compared to zero tillage treatment (**Table 7**).

The K_{fs} and q_s parameters were significantly different between the CT and ZT systems (**Table 8**). The K_{fs} was about 5.4 times higher for CT compared to ZT (**Table 8**); whereas the q_s was about 4.5 times higher for this system

Table 6. Effect of tillage treatment on soil water retention at selected water potentials (0 - 0.075 m soil layer) for the 2003-2004 cropping season.

Water potential (kPa)	Volume wetness, (m^3/m^3 %)	
	ZT	CT
–33	36.5[a]	33.5[b]
–1500	28.6[a]	26.0[b]
PAWC	7.9	7.5

[†]Means with different letters are significantly different at the 0.05 probability level. The comparisons were made between ZT and CT at respective pressures; Note: average bulk density values of soil cores were 1.34 and 1.23 $Mg \cdot m^{-3}$ in ZT and CT plots, respectively; ZT = Zero tillage; CT = Conventional tillage; PAWC: plant available water capacity.

Table 7. Means of saturated hydraulic conductivity (K_s) and sorptivity (S) fitted parameters estimated with the Green-Ampt model for the zero and conventional tillage treatments under a rice-wheat cropping system along with analysis of variance for the 2003-2004 cropping season.

	K_s	S
Tillage	Mean ($mm \cdot h^{-1}$)	Mean ($mm \cdot h^{-0.5}$)
ZT	0.63[a†]	62.55[a]
CT	29.88[b]	61.28[a]
	Analysis of variance $P > F$	
Treatment	<0.01	0.95

[†]Means with different letters are significantly different at the 0.05 probability level.

Table 8. Means of quasi-steady state infiltration rate (q_s) and field-saturated hydraulic conductivity (K_{fs}) for the zero and conventional tillage systems along with analysis of variance for the 2003-2004 cropping season.

	q_s	K_{fs}
Tillage	Mean ($mm \cdot h^{-1}$)	Mean ($mm \cdot h^{-1}$)
ZT	7.19[a†]	4.49[a]
CT	32.59[b]	24.1[b]
	Analysis of variance $P > F$	
Treatment	<0.01	<0.01

[†]Means with different letters are significantly different at the 0.05 probability level.

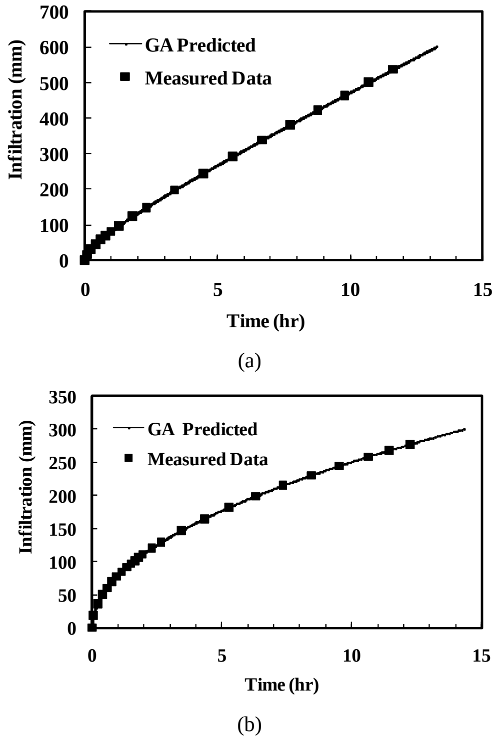


Figure 1. The Green-Ampt (GA) model fitted to measured ponded infiltration data for typical replicates under (a) conventional and (b) zero tillage for a rice-wheat cropping system.

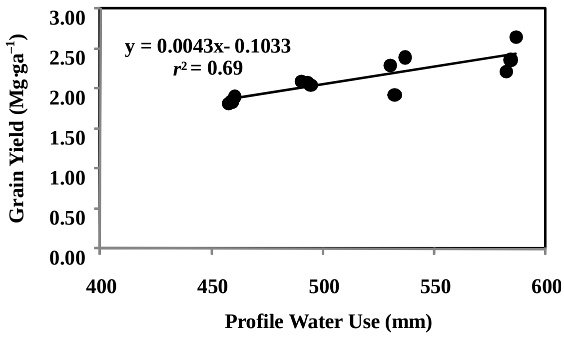
compared with the ZT treatment.

3.5. Crop Yield

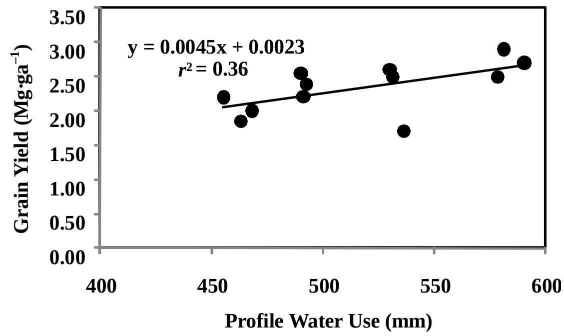
The wheat yield was observed for three cropping seasons during 2003-2004, 2004-2005 and 2005-2006. The yield was not consistent for all the three cropping seasons. Grain yield was affected significantly by irrigation levels but not by tillage treatments during 2003-2004 and 2005-2006 (**Table 9**).

During 2003-2004, grain yield decreased progressively with the reduction in irrigation levels under both ZT and CT systems, but yield differences were significant between RF and I_2 in ZT, and RF and I_3 in CT; I_1, I_2 and I_3 were statistically at par for grain yield under both ZT and CT. Grain yields with RF, I_1 and I_2 were about 80%, 89% and 92% of I_3 under ZT, and about 77%, 92% and 95% of I_3 under CT, respectively (**Table 9**). Thus grain yield declined by about 8%, 11% and 20% under ZT, and 5%, 8% and 23% under CT, respectively, with reduction in irrigation levels from I_3 to I_2, I_1 and RF. According to these data, ZT was relatively more sensitive to moisture stress than CT for RF and I_1 levels. At each irrigation level, CT numerically produced more grain than ZT. Averaged over four irrigation levels, grain yield with CT was about 13% higher than ZT. The grain yield showed a significant linear relationship with total water use with r^2 ranging from 0.36 to 0.69 for CT and ZT, respectively (**Figure 2**).

Tillage system had a significant effect on wheat yield; however, results were different between the 2003-2004 and 2004-2005 seasons. During 2004-2005, average yield across four irrigation levels was higher with ZT (2.56 $Mg \cdot ha^{-1}$) by about 22 percent relative to CT (2.10 $Mg \cdot ha^{-1}$). This difference was attributed to good precipitation distribution during the 2004-2005 cropping year;



(a)



(b)

Figure 2. Relationship between wheat yield and total water use for zero tillage (a) and conventional tillage (b) for the 2003-2004 cropping season.

no irrigation (except, pre-sown irrigation) was needed during the entire cropping season. During the 2005-2006 cropping year, wheat grain yield increased significantly over the RF treatment by 18, 46 and 52 per cent with the I_1, I_2 and I_3 irrigation treatments, respectively (**Figure 3**). According to these data (2005-2006), wheat yield under both tillage systems (zero and conventional) responded similarly to deficit irrigation.

Higher SPR in ZT plots probably resulted in higher root resistance and less root growth and less wheat yield during the 2003-2004 cropping year. In contrast, the lower ρ_b, higher K_{sat} and infiltration rate in CT plots probably resulted in less runoff and better plant growth and wheat yield compared to ZT plots.

Yield data for tillage treatments showed that in 2003-2004, CT performed better; for 2004-2005, ZT produced higher yield; and for 2005-2006, no differences occurred in the wheat yield between tillage treatments. Compared to irrigation management, grain yield increased with increased number of irrigations; except for 2004-2005 since during this year rainfall distribution was enough to meet the irrigation requirement for the wheat crop. Results from this study conclude that irrespective of irrigation levels; there were not large differences in yield between the ZT and CT systems; however, ZT was more economical compared to CT system because of low input cost. When compared to rainfed treatments, ZT performed better compared to CT, hence farmers can make more profit by relying on the ZT treatment rather than on the CT system.

3.6. Water Use Efficiency

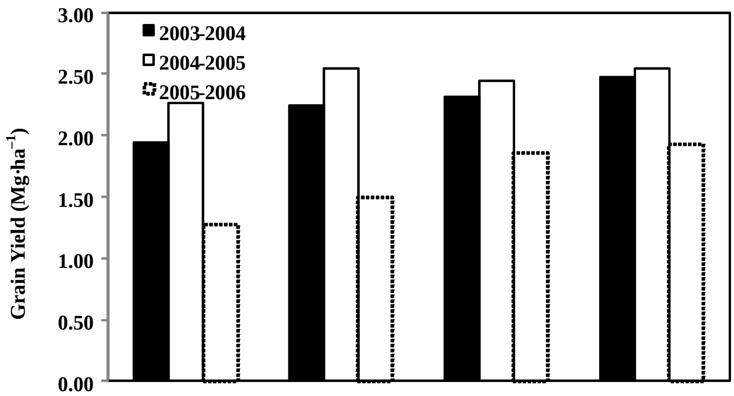
Tillage treatments as well as irrigation levels showed a significant effect on water use efficiency (WUE) during the 2003-2004 cropping year (**Table 9**). Numerically, the highest WUE of 4.93 kg·ha^{-1}·mm^{-1} was found under CT with I_1 treatment and the lowest of 3.99 kg·ha^{-1}·mm^{-1} under ZT with I_3. Conversely, the amount of water used (m^3) to produce 1 kg of wheat grain varied between 2.03 m^3·kg^{-1} in I_1 (CT) and 2.51 m^3·kg^{-1} in I_3 (ZT) treatments. Similar to grain yield data, the WUE for 2003-2004 and 2004-2005 cropping seasons were different. During 2004-2005, the highest WUE (3.47 kg·ha^{-1}·mm^{-1}) was obtained with the I_1 and ZT treatment, and the lowest (2.48 kg·ha^{-1}·mm^{-1}) with the RF and CT treatment (**Table 10**). During 2005-2006, WUE was statistically the same with zero and conventional tillage (data not shown). The WUE increased progressively with the level of irrigation from rainfed through the three irrigation treatments (**Figure 3**).

Averaged over two tillage and four irrigation levels, WUE values were 4.33 kg·grain·ha^{-1}·mm^{-1} and 2.32 m^3·kg^{-1} grain. The interaction of tillage × irrigation was also significant ($P < 0.01$) for WUE for the 2003-2004 cropping season (**Table 9**). It was concluded that more water was needed for less grain production with ZT compared to CT plots.

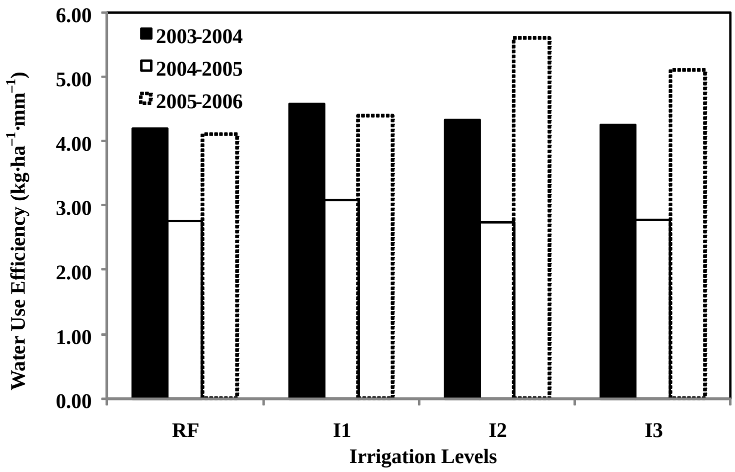
4. Conclusions

The irrigation treatments did not affect soil physical properties but tillage systems did affect these properties. The ρ_b and SPR values of CT plots were 8.2% and 13%, respectively, lower compared to ZT plots which increased the porosity (8.9%), K_{sat} (57 times) and the steady infiltration rate (4.5 times) under CT plots.

The rice crop management, rice crop was grown previous to the wheat crop, created adverse soil conditions which partially caused the lower values of infiltra- tion rate and K_{sat} in wheat plots which followed rice. When comparing tillage systems, the soil was loosened with a plough for CT which decreased the ρ_b, increased soil porosity and also increased K_{sat} as well as the steady infiltration rate compared to zero-tilled wheat at the time of crop harvest. The improved soil properties under CT systems improved the wheat yield; however the yield differences were not significant between tillage treatments during the 2003-2004 cropping year. The results were



(a)



(b)

Figure 3. Wheat yield (a) and water use efficiency (b) for RF (rainfed), I_1 (irrigation at CRI), I_2 (irrigation at CRI and flowering), and I_3 (irrigation at tillering, CRI and flowering stages) irrigation levels during the 2003-2004, 2004-2005 and 2005-2006 cropping seasons.

Table 9. Effect of different irrigation regime treatments on total water use, grain yield, and water use efficiency (WUE) for wheat under zero tillage (ZT) and conventional tillage (CT) treatments for the 2003-2004 cropping season.

Irrigation regime Treatment	Tillage Treatment	Total water use (mm)	Grain yield (Mg·ha^{-1})	WUE (kg·grain·ha^{-1}·mm^{-1})
RF	ZT	458.9^{d}	1.85^{c}	4.03^{f}
	CT	463.2^{d}	2.02^{bc}	4.36^{d}
I_1	ZT	491.9^{c}	2.07^{bc}	4.21^{e}
	CT	489.1^{c}	2.41^{ab}	4.93^{a}
I_2	ZT	534.8^{b}	2.14^{ab}	4.00^{gf}
	CT	533.5^{b}	2.47^{abc}	4.62^{b}
I_3	ZT	581.1^{a}	2.32^{ab}	3.99^{g}
	CT	578.7^{a}	2.61^{a}	4.51^{c}
		Analysis of variance $P > F$		
Tillage		0.95	0.06	<0.01
Irrigation		<0.01	0.01	<0.01
Tillage × Irrigation		0.69	0.81	<0.01

RF = Rainfed; I_1 = Irrigation at CRI stage; I_2 = Irrigation at CRI and flowering stage; I_3 = Irrigation at CRI, tillering and flowering stage; WUE = Water use efficiency.

Table 10. Effect of different irrigation regime treatments on total water use, grain yield, and water use efficiency (WUE) for wheat under zero tillage (ZT) and conventional tillage (CT) treatments during the 2004-2005 cropping season.

Irrigation regime Treatment	Tillage Treatment	Total water use* (mm)	Grain yield ($Mg \cdot ha^{-1}$)	WUE ($kg \cdot grain \cdot ha^{-1} \cdot mm^{-1}$)
RF	ZT	820	2.48^b	3.02^e
	CT	820	2.03^f	2.48^c
I_1	ZT	820	2.85^a	3.47^d
	CT	820	2.22^d	2.71^a
I_2	ZT	820	2.41^c	2.93^f
	CT	820	2.08^e	2.54^b
I_3	ZT	820	2.48^b	3.02^e
	CT	820	2.06^{ef}	2.51^c
		Analysis of variance $P > F$		
Tillage		-	<0.01	<0.01
Irrigation		-	<0.01	<0.01
Tillage × Irrigation		-	<0.01	<0.01

*No irrigation other than pre-sown was given to wheat crop during 2004-2005 season as enough rainfall received during this season.

different for the 2004-2005 and 2005-2006 cropping seasons. Irrespective of the tillage system, however, grain yield and WUE increased with increased level of irrigation (except for the 2004-2005 cropping season which received frequent rains) and values were higher with the three irrigation treatments for the cropping seasons which had deficit rain. Although grain yield was inconsistent between the tillage systems over years, economic costs were lower for the ZT tillage system which implies it may be the best system for occasional increases in yield and consistently lower input costs. Furthermore, this ZT system conserves soil moisture and reduces soil erosion as residues are left on the plots.

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