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Impact of tillage and crop establishment methods on crop yields, profitability and soil physical properties in rice–wheat system of Indo-Gangetic Plains of India

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Running title: Impact of tillage on crop yield and soil health.

Abstract

Conservation agriculture (CA) based on *best-bet* crop management practices may increase crop and water productivity, as well as conserve and sustain soil health and natural resources. In a 2-year study, we assessed the effects of tillage and crop establishment (TCE) methods on productivity, profitability and soil physical properties in a rice–wheat (RW) system. The six TCE treatments were used to study the impact, which are puddled transplanted rice followed by conventionally tilled wheat (CTPR–CTW), direct seeded rice on the flat followed by zero till wheat (CTDSR–ZTW), zero till direct seeded rice with residue followed by zero till wheat with residue (ZTDSR+R–ZTW+R), transplanted rice after rotavator puddling followed by zero till wheat (RTTPR–ZTW), transplanted rice after rotavator puddling followed by rotary till wheat (RTTPR–RTW) and farmer practice rice–wheat (FP–RW). Result of the study revealed that mean rice yield was not significantly affected by different TCE methods. Wheat planted with ZTDSR+R–ZTW+R gave 30% larger grain yield than FP. Overall, among all the TCE treatments the RW system yields and net returns were maximum under ZTDSR+R–ZTW+R. The fastest mean infiltration rate (0.10 cm/h) was registered in ZTDSR+R–ZTW+R plots, whereas the slowest was in FP plots (0.05 cm/h). Bulk density at 15–20-cm soil depth was least in ZTDSR+R–ZTW+R (1.70 Mg/m^3) and greatest in FP (1.73 Mg/m^3). Results from this study revealed that conventionally tilled (CT) and transplanting of rice could be successfully replaced by adoption of the profitable double ZT–RW system.

Keywords: Direct seeded rice; Zero tillage; Infiltration rate; Tubo Happy Seeder; Bulk density.

Introduction

Rice (*Oryza sativa*-L.)–wheat (*Triticum aestivum*-L.) (RW) system of Indo-Gangetic Plains (IGP) covering 13.5 million hectares is vital for current and future food security in the region (Paroda *et al.,* 1994; Ladha *et al.,* 2003). In any cropping system, crop management practices are the key factors for its sustainability and soil health (Parihar *et al.,* 2016). The land preparation (both dry and wet tillage) for transplanted rice and conventionally tilled (CT) wheat is not only cost intensive and time consuming, but also the practices were less water efficient and soil physical properties deteriorate through breakdown of soil aggregates and reduction in capillary pores (Kumar *et al.,* 2013; Gathala *et al.,* 2015; 2016; 2017). In general, tillage and crop establishment (TCE) methods accounts for 25–30% of the total production cost of RW system (Saharawat *et al.,* 2011; Gathala *et al.,* 2014).

In recent years the growth in productivity of RW system in South Asia has stagnated due to continuous adoption of conventional crop production technologies, which leads to decline in profit margin compared to conservation agriculture (CA) practices (Jat *et al.,* 2009). Similarly, adoption of CA based no-till planting has been found to enhance crop & water productivity and reduce the cost of cultivation in RW system (Gathala *et al.,* 2011a). Other studies also showed that CA based management practices are effective for increasing crop and water productivity, and economic sustainability and soil health in different cropping systems (Jat *et al.,* 2013; Das *et al.,* 2014; Gathala *et al.,* 2017). However, implementation of CA in whole RW system is not possible until there is a suitable alternative available to transplant rice into fully puddled soils. Thus, to address these challenges in RW production, the system needs to have alternate and viable crop production technologies that produce greater yield at less cost, providing a sustainable system (Jat *et al.,* 2011; Gathala *et al.,* 2011b).

In practice, ZT and residue retention have emerged as the two cardinal principles of CA in the RW system. In the IGP of South Asia, despite wider adoption of ZT in wheat, rice is still mainly transplanted into puddled soil (churning of soil by tillage under ponding water), and the benefits attained during the wheat phase are lost during the rice phase. Therefore, to capture the full benefits of CA, both rice and wheat need to be grown under ZT conditions and because of this there is increasing interest in shift from puddled transplanting to dry direct-seeded rice (DSR) (Kumar & Ladha, 2011).

In this study we hypothesized that RW system could be effectively established and achieve greater yields and net returns using CA based-ZTDSR and ZTW with residue retention compared with farmer practice (conventional till puddled transplanted rice followed by conventional till wheat). The objectives were: (i) to evaluate the impacts of CA and CT on crop grain yield and above-ground biomass productivity (net primary productivity) under a rice–wheat system, (ii) to assess the effects of CA and CT practices on energy requirement, net returns and soil physical properties during a 2-year study. In this paper, we provide and discuss the effect of six tillage practices, crop establishment and residue management combinations on crop, system productivity and specific energy, economic profitability and soil structural conditions.

Materials and Methods

Experimental site

A field experiment was established in the rainy season of 2008 on the research farm (29°01′ N, 77°45′ E, and 237m above mean sea level) of the Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India. The experimental site had been under traditional rice–wheat cropping system for more than ten years prior to 2008. The Climate of the region is sub-tropical with an average annual rainfall of 800 mm (70–80% of which is received during July–September), minimum temperature of 0 to 4°C in January, maximum temperature of 41 to 45°C in June, and relative humidity of 67 to 83% throughout the year. Soil samples were collected at the start of the experiment (2008) from 0 to 45-cm depth (at intervals of 15-cm) using an auger of 5-cm diameter. They were air-dried and crushed to pass through a 2-mm sieve before storing in plastic jars for analysis of organic C (Walkley & Black, 1934), total N (Kjeldahl digestion), Olsen P (0.5 *M* $NaHCO_3$ extractable) and 1 *M* neutral NH_4OAC-extractable K (by emission spectrophotometry) using the methods described by Olsen *et al.* (1954) and Page *et al.* (1982). Particle-size distribution was determined by using the hydrometer method (Bouyoucos, 1962). Based on the analysis, the experimental soil (0–15-cm) was sandy loam in texture (19 g clay, 28 g silt, and 53 g sand/kg soil) with pH 8.2; electrical conductivity 0.43 dS/m; organic C 8.3 g/kg; total N 0.88 g/kg; Olsen P 26 mg/kg; and 1 *M* NH_4OAC-extractable K 125 mg/kg.

Experimental details and management

The experiment was conducted in plots 30 m × 4 m (120 m^2). All treatments were completely randomized and replicated three times. The treatment details are given in Table 1.

Residue management

Rice and wheat crops were harvested manually, leaving about 15-cm long anchored stubble in all the plots except for T_3. The dry biomass of stubble (mean 1.8 Mg/ha) was recorded from each plot after the harvest of every crop. The stubble was incorporated into the soil in puddled/CT plots, whereas, rice in DSR and wheat in ZT plots were directly seeded into standing stubbles using a ZT seed-and-fertilizer drill, the Turbo Happy Seeder'. This was a planter designed and developed for seeding any crop, simply managing crop residue in front of the seeding furrow opener by beating, cutting and removing through flies operated by tractor. All remaining residue was kept undisturbed. Seed and fertilizer was simultaneously placed at the required soil depth through the residue. In T_3, around 8.0 Mg/ha crop residues (rice + wheat) were managed as surface mulch using the Turbo Happy Seeder.

Seeding and seed rate

Rice variety *Pusa 1121* was used in both the years for all the treatments. Direct drill–seeded rice (DSR) was sown in the first week of June and the nursery was raised on same day for the transplanted treatments. The rice was transplanted in the last week of June to the first week of July depending on treatments. The seeding rate for DSR was 25 kg/ha. Wheat variety *PBW 343* was sown in both years in the first week of November with a seed rate of 100 kg/ha in treatments T_1 – T_5 and 120 kg/ha in T_6.

Fertilizer application

In rice, all plots received 100 kg N, 26 kg P, 50 kg K, and 25 kg $ZnSO_4$/ha. Whole of P and K, and one–third of N was applied as band placement at the time of seeding under DSR using a ZT seed-cum-fertilizer-planter, whereas fertilizers were broadcasted manually at the time of transplanting in CTPR. In DSR, $ZnSO_4$ was broadcasted at 10 DAS and in CTPR at 2 DAT. The remaining N was applied in two equal splits at 35 to 40 DAS and 50–55 DAS in DSR plots, and 20 DAT and 40–45 DAT in CTPR plots. In wheat, all treatments received 150 kg N, 26 kg P and 50 kg K/ha, where P and K fertilizer was applied at seeding and N was applied in three splits equally 1/3rd at seeding, 1st irrigation and 2nd irrigation, respectively.

Weed management

Weeds in ZT plots were controlled before seeding of rice and wheat by spraying glyphosate @ 900 g a.i./ha. In DSR, pendimethalin @ 1000 g a.i./ha was applied at 2 DAS, followed by post emergence spray of ethoxysulfuron @ 18 g a.i./ha and fenoxaprop @ 56 g a.i./ha at 21 DAS for broad-leaf weeds and 30 DAS for grassy weeds, respectively. In transplanted rice, butachlor @ 1000 g a.i./ha was applied at 2 DAT. In transplanted rice and DSR, the plots were kept weed free with a single hand weeding. In wheat, grassy and broad leaf weeds were controlled by spraying sulfosulfuron + metsulfuron methyl @ 35 g a.i. + 4 g a.i. /ha at 25 to 30 DAS.

Measurement of soil physical parameters

Soil physical properties, such as bulk density and steady state infiltration were measured at the harvest of rice for 2008 and 2009. Bulk density was determined by collecting soil cores from 0 to 5-, 5 to 10-, 10 to 15-, and 15 to 20-cm-depth, using a metal core of 3-cm long and 5-cm diameter. A double ring infiltrometer was used to determine the infiltration rate. The infiltration rate was measured by recording the amount of water needed to maintain a constant level in the inner ring as a function of time (Gathala *et al.,* 2011b). Two rings of the infiltrometer in each plot were pushed into the ground upto 10-cm depth. A constant water level (30-cm) was maintained in both the inner and outer rings of the infiltrometer. The measurements were continued until a steady state infiltration rate was achieved.

Measurement of yield and yield attributes

At maturity, rice and wheat yield parameters *i.e.* total number of effective panicles or tillers, panicle or ear length, number of grains/earhead and 1000-grain weight were measured. Total number of panicles was recorded using a 1.0 m^2 quadrat at two places in each plot. Simultaneously, 10 plants were randomly selected from each quadrate for measurements of yield parameters. Both the crops were harvested manually by cutting at 15-cm above from ground level in all treatments except ZTDSR+R–ZTW+R treatment (T_3), where 100 and 30% residues of rice and wheat crop were retained, respectively. The rice grains were threshed manually and wheat grains were threshed using a plot thresher, dried in a grain dryer and weighed. Grain yields of rice and wheat were reported at 14% and 12% moisture content, respectively.

Economic analysis

All the cost of inputs (tractor use, seed, fertilizer, fuel, biocides, irrigation and labor) and the returns from outputs for respective years were used in the study (Gathala *et al.,* 2011a). These data were obtained from current market prices paid for inputs. The cost of human labor used for tillage, seeding, irrigation, fertilizer and pesticide application, weeding, and harvesting of rice and wheat crops was based on person-day/day (Minimum Wages Act, 1948). Time (h) required to complete a particular field operation was recorded and expressed as person-day/ha, considering 8 h to be equivalent to 1 person-day. Similarly, time (h) required by a tractor-drawn machine to complete a field operation such as tillage, seeding, fertilizer application and harvesting was recorded, and expressed as h/ha. Time (h) required for irrigating a particular plot and consumption of diesel (l/h) for pumping was also recorded. Cost of irrigation was calculated by multiplying time (h) required to irrigate a particular plot, consumption of diesel by the pump (1/h) and cost of diesel (varied 41–48 Rs./l). The cost of production was calculated by taking into account the costs of all the inputs and the hiring charges of human labor and machines for different purposes, as stated above, based on current market rates (Minimum Wages Act, 1948). Gross returns (GR) were calculated by multiplying grain yield of rice/wheat by minimum support price offered by the Government of India (Economic Survey of India, 2009), and straw value of rice/wheat was calculated using current market rates. Net returns (NR) were calculated as the difference between gross returns and total cost of cultivation (NR = GR–TCP). The benefit/cost ratio computed by dividing the gross returns (GR) by the total cost of production (TCP).

Energy analysis

The analysis of energy in the study was performed by comparing the energy input and output in all the treatment combinations considering differential requirement of inputs and management. Energy value of every treatment was calculated by converting their physical units to energy units through multiplication with the conversion coefficients (Yadav *et al.,* 2018). The energy equivalents of input and output indices; the specific energy (SE) was calculated by Eq 1-2 (Parihar *et al.,* 2018).

$$\text{Energy input} = \sum_{i=1}^{n}(C1 + C2 + \cdots . Ci) \qquad (1)$$

$$SE = \sum_{i=1}^{n}(EI / SP) \qquad (2)$$

where, EI-energy input/Energy requirement (MJ/ha); C1,C2, …Ci, are energy requirement of each input component (MJ/ha).

Data analysis

Analysis of variance (ANOVA) for completely randomized block design was performed using the general linear model procedures of the statistical analysis system (SAS Institute, Cary, NC) for completely randomized block design. Treatment means were compared by Fishers least significant difference (LSD) test (Gomez & Gomez, 1984). Unless stated otherwise, differences were considered significant only when $P < 0.05$.

Results and Discussion

Rice yield attributes and yield

In rice 2-year the mean number of panicles/m^2 was significantly affected by tillage, crop establishment practices (Table 2), however all other yield attributes (panicle length, number of grains/panicle, 1000–grain weight and harvest index) of rice were the same in all the TCE treatments. Despite significantly increased panicle density in DSR treatments, similar yields of rice were observed in DSR (CTDSR–ZTW and ZTDSR+R–ZTW+R) and RTTPR, which may be due to more spikelet sterility compensating greater panicle density. Similar results of increased panicle density and spikelet sterility in DSR than in TPR were also reported by Choudhury *et al.* (2007) and Bhushan *et al.* (2008). Unfavourable moisture regimes during pollination and subsequently drying of pollen under DSR may be responsible for increased spikelet sterility. Whereas, Ladha *et al.* (2003) concluded that alternate tillage and crop establishment strategies may or may not have positive crop response in RW systems.

A 2-year combined ANOVA showed no significant main and interaction effects of TCE treatments and year on rice grain yield (Table 4). The 2-year mean rice grain yield was statistically similar in all the TCE treatments. Although, DSR produced similar grain yield to that of TPR and other TCE treatments, but DSR has other advantages such as 7 to 10 days earlier maturity than TPR, which allows timely planting of succeeding crops i.e. wheat (Saharawat *et al.,* 2010). The DSR also helps in reducing the labor, time, water, energy requirement and thus cost of production (Kumar & Ladha, 2011; Gathala *et al.,* 2011a; 2014). Whereas, field studies conducted in India by Jat *et al.* (2009) & Gill *et al.* (2011) showed similar grain yields of TPR and DSR while in another study based on large datasets, Kumar & Ladha (2011) reported 10% less yield in ZT–DSR compared to TPR.

Wheat yield attributes and yield

ANOVA of 2-year mean data showed significant treatment effects of the TCE on yield attribute components resulted in an increase in grain yield of wheat. The yield attributes (effective tillers, spike length, number of grains/earhead and 1000-grain weight) of wheat were significantly greater with ZTDSR+R–ZTW+R treatment in comparison with CT treatments (FP–RW, RTTPR–RTW and CTPR–CTW). However, yield attributes of wheat were recorded at par under ZTDSR+R–ZTW+R and ZTW with partial residue retention (CTDSR–ZTW and RTTPR–ZTW) treatments, except the number of effective tillers, was also at par with the RTTPR–RTW treatment (Table 3). Similar results of about 15% greater spike density have also been reported in ZTW compared with CTW by other researchers (Saharawat *et al.,* 2010; Gathala *et al.,* 2011a). The analysis of the 2-years mean data indicated that harvest index of wheat ranged from 0.33–0.35 in all the TCE treatments.

The TCE methods had significant effects on 2-year mean wheat grain yield and was greater in ZTDSR+R–ZTW+R plots (4.84 Mg/ha) compared to ZTW with partial residue retention (CTDSR–ZTW & RTTPR–ZTW) (4.49 & 4.52 Mg/ha) and CT treatments (FP–RW, RTTPR–RTW & CTPR–CTW) (3.71–4.52 Mg/ha) (Table 4), this increase in yield could be attributed to the increased spike length, number of grains per spike and 1000-grain weight. The findings of this study are well supported by Gathala *et al.* (2009), who reported 3–10% greater wheat grain yield with ZTW+R than CTW. Jat *et al.* (2009) and Gathala *et al.* (2014) also reported higher wheat yields after DSR than that after puddled TPR. The yield increase in ZTW may also be due to better soil structure by eliminating the negative effects of puddling on succeeding wheat crop (Gathala *et al.,* 2011a; 2014; 2017, Kumar & Ladha, 2011).

System grain yields

The average system productivity (rice+wheat) was significantly influenced by different TCE treatments, and it ranged from 7.41 to 8.69 Mg/ha across different treatments (Table 4). The ZTDSR+R–ZTW+R (8.69 Mg/ha) gave 10% and 17% greater system productivity than CTPR–CTW (7.87 Mg/ha) and FP–RW (7.41 Mg/ha), respectively. Similar to the present study, the results from a number of studies in South Asia, clearly showed that the gain in RW system productivity was mainly contributed by wheat when it was planted under a zero-till systems with partial and/or full residue retention (Jat *et al.,* 2009; Saharawat *et al.,* 2010; Jat *et al.,* 2013; Gathala *et al.,* 2011a; Gathala *et al.,* 2014). Similarly, in rice-maize systems, zero tillage planting with partial residue retention was reported to increase system productivity (Jat *et al.,* 2013; Gathala *et al.,* 2015; Gathala *et al.,* 2016). In our study, eliminating wet tillage (puddling) in rice had significant yield benefit (0.73–1.13 Mg/ha/year) on subsequent wheat by eliminating puddling (Table 4) probably due to better germination and deeper rooting of wheat due to improved soil physical properties. Similar to our results Gathala *et al.* (2011b), also found that eliminating puddling in rice under rice–wheat cropping systems increased wheat yield. Puddling leads to suboptimal permeability in subsurface layer and formation of a hard pan. The poor soil physical structure leads to reduced root growth and is responsible for reduced wheat yield after puddled rice. Reduced nutrient use efficiency associated with poor root development in wheat after transplanted rice may be responsible for smaller wheat yield in TPR treatments (Ishaq *et al.,* 2001)

Soil physical properties

Changes in soil physical properties were not readily noticeable over a short period of time. The steady state infiltration rates after rice harvest did not show any significant difference among the various treatments in the first year (data not presented) but a significant effect was observed in the second year of the study (Fig.1). Steady state infiltration was consistent and significantly faster in DSR treatments with an average of 0.10 cm/h in T_2 (CTDSR–CTW) followed by T_3 (ZTDSR+R–ZTW+R) compared to all other treatments (Fig.1). Infiltration rate was significantly slower in CT treatments after two cropping cycles as compared to CA based treatments probably because of progressive destruction in soil structure by dispersion of soil particles during puddling operations, reduction of soil macroporosity under intensive tillage and increase in subsoil compaction (Jat *et al.,* 2009).

Similar to this study, Savabi *et al.* (2007) reported enhanced infiltration rate with time under CA based ZT practices.

In general, across the TCE treatments bulk density (BD) increased with increase in soil depth. Soil bulk density at upper two layers (0–5 & 5–10-cm) was not significantly affected by TCE methods but in sub-soil depths (10–15 & 15–20-cm) influenced after two years of experimentation (Fig. 2). The puddling omitted treatments (CTDSR–ZTW and ZTDSR+R–ZTW+R) reduced bulk density in sub-soil depths , over the puddling treatments after two crop cycles. This may be due to compaction caused by trafficking of machines used during tillage operations in both rice and wheat crops (Gathala *et al.,* 2011b). Formation of an impervious layer to restrict percolation losses is an aim of puddling and this creates a hard plough-pan layer which increases bulk density and penetration resistance (Kumar & Ladha, 2011). As bulk density is inversely related to total porosity, smaller bulk density implies greater pore space and improved aeration, developing a suitable environment for soil biological activity (Min *et al.,* 2003; Parihar *et al.,* 2016).

Similar to bulk density, the soil penetration resistance (SPR) was also significantly influenced by TCE methods at sub-soil depths only (Fig.3). The SPR was reduced under both puddling omitted treatments (ZTDSR+R–ZTW+R and CTDSR–ZTW) compared with treatments with puddling. Penetration resistance in a given soil is directly related to bulk density and inversely related to soil water content (Sharma & De Datta, 1986). The soil water content (volume basis) at the time of SPR measurements varied by less than 3% among the treatments (Data not presented). The greater SPR below tillage depth (15–20-cm) under puddling/CT (CTPR–CTW, RTTPR–ZTW, RTTPR–ZTW, FP–RW) was associated with larger soil bulk density and compacted plough-pan layer in sub-surface layers of these plots. The improvement in soil physical properties with enhanced SOC under CA (Parihar *et al.,*

2016) is consistent with results reported elsewhere on reduced penetration resistance (Yang & Wander, 1999), and improved soil aggregation (Six *et al.,* 2002), and saturated hydraulic conductivity (Osunbitan *et al.,* 2005). Published studies corroborate the results that SPR remains greater under puddling than under ZT/conservation tillage (Jat *et al.,* 2009; Gathala *et al.,* 2011b).

Energy

The two–year mean energy requirement (MJ/ha) and specific energy (MJ/kg grain) was significantly influenced by TCE methods (Table 5). The least energy requirement in rice cultivation was recorded with ZTDSR+R–ZTW+R (25110 MJ/ha) followed by CTDSR–ZTW, RTTPR and greatest was 30552 MJ/ha in FP–RW and CTPR–CTW treatments. In the case of wheat, all ZTW plots consumed less energy followed by RTW, CTW and was largest in FP–RW (24149 MJ/ha). The system energy requirement followed least to largest order of ZTDSR+R–ZTW+R<CTDSR–ZTW<RTTPR–ZTW<RTTPR–RTW<CTPR–CTW<FP–RW. The ZTDSR+R–ZTW+R used 17% less total system energy over FP–RW. The specific energy was smallest in ZTDSR+R–ZTW+R and was 2.55, 1.38 and 1.84 MJ/kg grain for rice, wheat and system, respectively, which was significantly less than CTPR–CTW and FP–RW plots. In CA based ZT system reduced energy and specific energy used contributed to less fuel consumption by omitting tillage operation, reduced labor use and a smaller number of farm operations and greater yields (Kumar *et al.,* 2013; Gathala *et al.,* 2016).

Economics

The mean cost of cultivation (averaged over 2 years) for rice and wheat production was significantly affected by TCE methods (Table 6). The cost of rice production was greater (Rs. 37,111/ha) in CTPR–CTW and FP–RW treatments followed by use of rotavator for puddling (RTTPR–ZTW and RTTPR–RTW), CTDSR–ZTW and was least (Rs. 33,470/ha) in ZTDSR+R–ZTW+R treatment. The cost of wheat production was greater in FP–RW and least in ZTW (CTDSR–ZTW, ZTDSR+R–ZTW+R & RTTPR–ZTW) treatments. The RW system cost of production followed the order of FP–RW>CTPR–CTW>RTTPR–RTW>RTTPR–ZTW>CTDSR–ZTW>ZTDSR+R–ZTW+R. The net income in rice was not influenced by TCE methods though greater net income was associated with RTTPR–RTW and the least with FP–RW treatment. However, ZTDSR+R–ZTW+R gave significantly greater net returns compared to FP–RW and CTPR–CTW in wheat which was attributed to reduced production costs (tillage operations). The greatest system net return was recorded in ZTDSR+R–ZTW+R and least in FP–RW. Adoption of the CA practices (ZTDSR+R–ZTW+R) increased the net returns by Rs. 24,998 to 32,601/ha/yr over CT treatments (CTPR–CTW & FP–RW). These increments in net returns were mainly due to there being no requirement for preparatory tillage under CA. The greater benefit/cost ratio in wheat and rice system was in ZTDSR+R–ZTW+R and least in FP–RW. The positive effects of CA practices in RW cropping system on yields were reflected in economic benefits. Consistent to our results more net returns and reduction in cost of cultivation with CA practices was reported by many workers in cereal based cropping systems (Saharawat *et al.,*2010; Gathala *et al.,* 2011a; Jat *et al.,* 2011).

Conclusions

The analysis of the two years study indicated that irrespective of TCE practices, wheat and system productivity increased by 17.8–30.4% and 10.4–17.3% under CA-based plots compared to CT (CTPR–CTW & FP–RW), respectively. Indicating gradual increase in productivity and hence helping in breaking the yield plateau. ZT based systems were more energy use efficient than conventional tillage. On a system basis, ZTDSR+R–ZTW+R provided greater farm profit than all the other treatments. Similarly, ZT treatment provided better soil physical conditions (reduced bulk density and faster steady state infiltration rate) compared with conventional tillage practices for the RW system. CA based ZT and double ZT system are energy efficient as indicated by reduced specific energy. This study showed that under multiple challenges the resource conserving technologies

(ZTDSR followed by ZTW + residue retention) need to be popularized among farmers of IGP for more profitability, overcoming labour shortages and restoration of soil structural conditions, provided a Turbo Happy Seeder machine is easily available for seeding wheat into heavy loads of rice residue.

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Figure 1 Effect of different tillage and crop establishment methods on steady state infiltration rate after 4-crops in rice–wheat cropping system

CTPR–CTW: puddled transplanted rice followed by conventional till wheat; CTDSR–ZTW: direct seeded rice on flat after dry tillage followed by zero till wheat; ZTDSR+R–ZTW+R: zero till direct seeded rice with residue followed by zero till wheat with residue; RTTPR–ZTW: transplanted rice after rotavator puddling followed by zero till wheat; RTTPR–RTW: transplanted rice after rotavator puddling followed by rotary till wheat; FP–RW: farmers practice rice–wheat. The bar followed by a different letter are significantly different according to Fishers least significant difference (LSD) test at *P*=0.05.

Figure 2 Effect of different tillage and crop establishment methods on soil bulk density after 4- crops in rice–wheat cropping system

CTPR–CTW: puddled transplanted rice followed by conventional till wheat; CTDSR–ZTW: direct seeded rice on flat after dry tillage followed by zero till wheat; ZTDSR+R–ZTW+R: zero till direct seeded rice with residue followed by zero till wheat with residue; RTTPR–ZTW: transplanted rice after rotavator puddling followed by zero till wheat; RTTPR–RTW: transplanted rice after rotavator puddling followed by rotary till wheat; FP–RW: farmers practice rice–wheat. NS: non-significant according to Fishers least significant difference (LSD) test at P=0.05; The lines followed by a different letter within a depth are significantly different according to Fishers least significant difference (LSD) test at *P*=0.05.

Figure 3 Effect of different tillage and crop establishment methods on soil penetration resistance after 4-crops in rice–wheat cropping system

CTPR–CTW: puddled transplanted rice followed by conventional till wheat; CTDSR–ZTW: direct seeded rice on flat after dry tillage followed by zero till wheat; ZTDSR+R–ZTW+R: zero till direct seeded rice with residue followed by zero till wheat with residue; RTTPR–ZTW: transplanted rice after rotavator puddling followed by zero till wheat; RTTPR–RTW: transplanted rice after rotavator puddling followed by rotary till wheat; FP–RW: farmers practice rice–wheat. NS: non-significant according to Fishers least significant difference (LSD) test at *P*=0.05; The lines followed by a different letter within a depth are significantly different according to Fishers least significant difference (LSD) test at *P*=0.05.

Table 1 Description of the tillage and crop establishment practices treatments in rice–wheat system

Treatment	**Rice**	**Wheat**
T$_1$:CTPR–CTW	2–3 Dry tillage (3 disc harrowings) operations by tractor operated tiller before rain occurred followed by supplementary irrigation (if no rain) for 2-wet tillage (for puddling) using spring tyne cultivator and 1planking (CTTPR); =~21-d-old 1–2 seedlings transplanted at 20 × 15-cm plant^{-1} hill spacing; grown as irrigated. The plots were kept submerged (5-cm depth) initially for 2 weeks to establish the seedlings and for effective weed control, and subsequent irrigations (5-cm depth of standing water) were applied on the appearance of hair-line cracks on soil surface.	Conventional tillage (2 disc harrowings+2 passes of spring tyne cultivator+2 plankings) followed by wheat seeding with seed-cum-fertilizer drill (CTW). Wheat was seeded in rows 20-cm apart using inclined plate seed metering seed-cum-fertilizer drill. Five irrigations (5-cm each) were applied at crown root initiation (21 days after seeding, DAS), maximum tillering (40–50 DAS), flowering (50–70 DAS), dough (85–100 DAS), and late dough (115–125 DAS) stages of the wheat.
T$_2$:CTDSR–ZTW	Direct seeded rice after dry tillage (2 harrowings+1cultivator+1planking) (CTDSR); seeding at 20-cm row spacing using inclined plate seed metering seed-cum-fertilizer drill. The plots were irrigated (3-cm depth of standing water) one day after seeding to ensure proper germination, and then the plots were irrigated (4-cm depth of standing water) at a regular interval of 3 to 4 days for the next 4 weeks. Thereafter subsequent irrigations were given same as of T$_1$.	Zero till wheat (ZTW) was seeded at 20-cm row spacing using inclined plate seed metering seed-cum-fertilizer drill. The irrigation schedule was same as of in T$_1$.
T$_3$:ZTDSR+R–ZTW+R	Zero till direct seeded rice in partial (30%) standing wheat stubbles (ZTDSR+R) using turbo happy seeder at 20-cm row spacing. Prior to seeding, glyphosate herbicide was applied to control weeds. Irrigation scheduling for DSR was same as in T$_2$.	Zero tillage wheat (ZTW+R) was seeded into rice residue (100%) using turbo happy seeder at 20-cm row spacing. The irrigation schedule was the same as in T$_1$.
T$_4$:RTTPR–ZTW	Transplanted rice after two criss-cross puddling/wet tillage operations by rotavator (RTTPR) followed by planking; =~21-d-old 1–2 seedlings transplanted at 20 × 15-cm plant/ hill spacing; grown as irrigated. The plots were irrigated as applied in T$_1$.	For zero till wheat (ZTW) the TCE practices were same as in T$_2$.
T$_5$:RTTPR–RTW	For transplanted rice after puddling/wet tillage by rotavator (RTTPR) the TCE operations were same as in T$_4$.	After rice harvest, wheat was planted in a cross two operations using rotary till (RTW). In roto till, both seed and fertilizer are surface broadcasted and mixed in the

		surface soil layer with tillage operation. The irrigation schedule was same as in T_1.
T_6:FP–RW	In farmers practice, rice TCE practices were similar to that in T1, 30-days old seedlings were randomly transplanted (2–3 seedlings hill^{-1}) with ~20 plants m^{-2}. The plots were continuously flooded during the crop season.	In farmers practice, wheat, plots were prepared using disc harrow and tyne cultivator (2 disc harrowings+2 cultivators+1 planking) followed by broadcasting of seed and mixed with criss-cross pass of cultivator and one planking. The irrigation schedule was same as in T_1.

Table 2 Effect of tillage and crop establishment methods on rice yield attributes (2-year mean) in rice–wheat system

Treatment	Panicle density(m^{-2})	Panicle length (cm)	Number of grains ($panicle^{-1}$)	1000 grain weight (g)	Harvest index
CTPR–CTW	334^{b}	28.28	85.63	23.91	0.41
CTDSR–ZTW	414^{a}	27.67	79.97	23.33	0.41
ZTDSR+R–ZTW+R	417^{a}	27.28	82.10	23.32	0.39
RTTPR–ZTW	338^{b}	29.03	89.53	24.38	0.39
RTTPR–RTW	330^{bc}	28.21	87.27	24.11	0.39
FP–RW	316^{c}	28.16	80.60	23.55	0.41
ANOVA	Probability (*P*=0.05)				
Yr	0.669	0.034	0.272	0.301	0.514
Rep	0.848	0.002	0.005	0.652	0.412
Trt	<0.001	0.061	0.078	0.746	0.572
Yr ● Trt	0.963	0.800	0.900	0.983	0.938

CTPR–CTW: puddled transplanted rice followed by conventional till wheat; CTDSR–ZTW: direct seeded rice on flat after dry tillage followed by zero till wheat; ZTDSR+R–ZTW+R: zero till direct seeded rice with residue followed by zero till wheat with residue; RTTPR–ZTW: transplanted rice after rotavator puddling followed by zero till wheat; RTTPR–RTW: transplanted rice after rotavator puddling followed by rotary till wheat; FP–RW: farmers practice rice–wheat. Data not allocating by the same letters within a column are significantly different according to Fishers least significant difference (LSD) test at *P*=0.05.

Table 3 Effect of tillage and crop establishment methods on wheat yield attributes (2- year mean) in rice–wheat system

Treatment	Eff. Tillers (m^{-2})	Ear length (cm)	Grains (ear^{-1})	1000 grain weight (g)	Harvest index
CTPR–CTW	247^{bc}	9.90^{c}	43.01^{c}	42.40^{c}	0.35^{a}
CTDSR–ZTW	262^{ab}	11.05^{b}	56.92^{a}	44.80^{ab}	0.35^{a}
ZTDSR+R–ZTW+R	281^{a}	12.03^{a}	56.19^{a}	45.70^{a}	0.33^{a}
RTTPR–ZTW	265^{ab}	10.97^{b}	58.28^{a}	44.77^{ab}	0.34^{a}
RTTPR–RTW	269^{ab}	9.60^{cd}	49.22^{b}	44.22^{b}	0.35^{a}
FP–RW	237^{c}	9.37^{d}	43.53^{c}	41.33^{d}	0.34^{a}
ANOVA	Probability (*P*=0.05)				
Yr	0.933	0.091	0.035	0.727	0.731
Rep	0.386	0.163	0.472	0.042	0.415
Trt	0.005	<0.001	<0.001	<0.001	0.622
Yr ● Trt	0.882	0.075	0.009	0.237	0.706

CTPR–CTW: puddled transplanted rice followed by conventional till wheat; CTDSR–ZTW: direct seeded rice on flat after dry tillage followed by zero till wheat; ZTDSR+R–ZTW+R: zero till direct seeded rice with residue followed by zero till wheat with residue; RTTPR–ZTW: transplanted rice after rotavator puddling followed by zero till wheat; RTTPR–RTW: transplanted rice after rotavator puddling followed by rotary till wheat; FP–RW: farmers practice rice–wheat. Data not allocating by the same letters within a column are significantly different according to Fishers least significant difference (LSD) test at *P*=0.05.

Table 4 Crop productivity (2-year mean) of rice and wheat under different tillage and crop establishment methods in rice–wheat cropping system

Treatment	Grain yield (Mg ha^{-1})		
	Rice	Wheat	System
CTPR–CTW	3.80	4.11^{c}	7.87^{bc}
CTDSR–ZTW	3.95	4.49^{b}	8.44^{ab}
ZTDSR+R–ZTW+R	3.85	4.84^{a}	8.69^{a}
RTTPR–ZTW	4.13	4.52^{b}	8.64^{a}
RTTPR–RTW	3.87	4.52^{b}	8.39^{ab}
FP–RW	3.70	3.71^{d}	7.41^{c}
ANOVA	Probability (*P*=0.05)		
Yr	0.517	0.014	0.411
Rep	0.412	0.269	0.814
Trt	0.573	<0.001	0.001
Yr ● Trt	0.939	0.858	0.825

CTPR–CTW: puddled transplanted rice followed by conventional till wheat; CTDSR–ZTW: direct seeded rice on flat after dry tillage followed by zero till wheat; ZTDSR+R–ZTW+R: zero till direct seeded rice with residue followed by zero till wheat with residue; RTTPR–ZTW: transplanted rice after rotavator puddling followed by zero till wheat; RTTPR–RTW: transplanted rice after rotavator puddling followed by rotary till wheat; FP–RW: farmers practice rice–wheat. Data not allocating by the same letters within a column are significantly different according to Fishers least significant difference (LSD) test at *P*=0.05.

Table 5 Energy consumption (2-year mean) under different tillage and crop establishment methods in rice–wheat cropping system

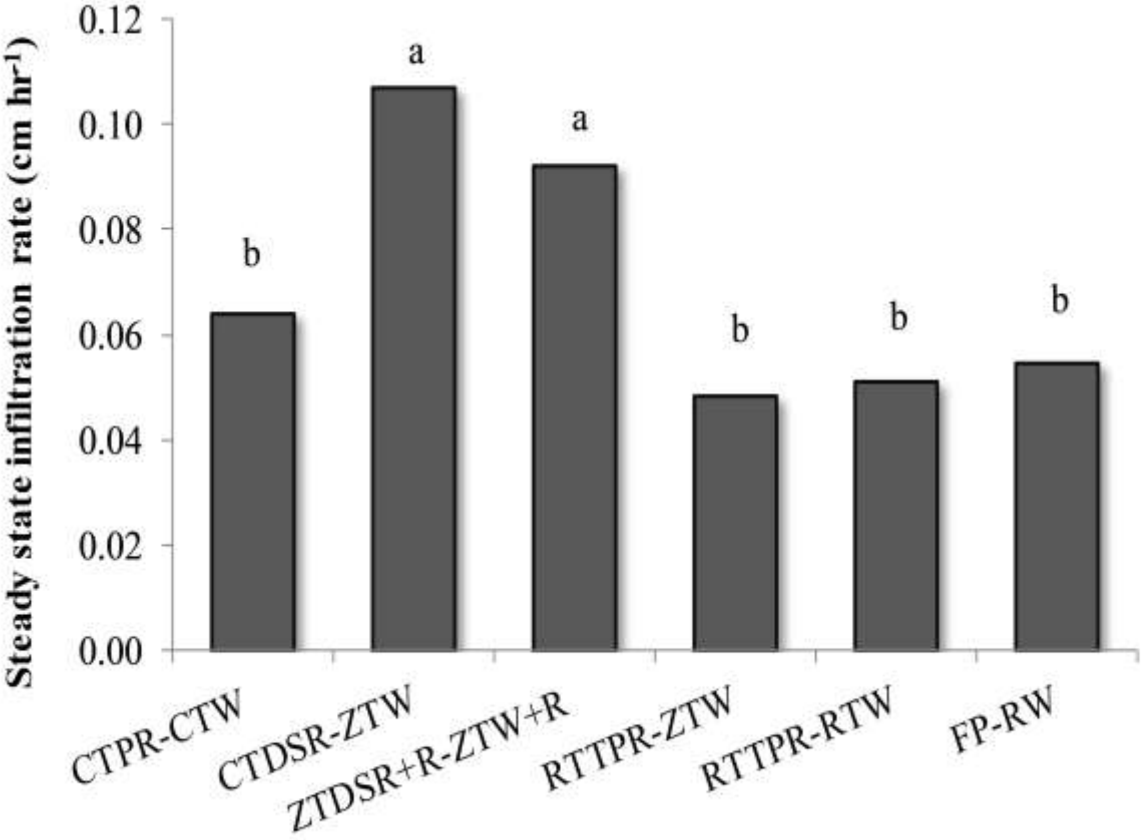
Treatment	Energy requirement (MJ ha^{-1})			Specific energy (MJ kg^{-1} grain)		
	Rice	Wheat	System	Rice	Wheat	System
CTPR–CTW	30552^{a}	23562^{b}	54114^{b}	3.34^{a}	2.06^{a}	2.62^{a}
CTDSR–ZTW	26648^{c}	20356^{d}	47004^{e}	2.76^{bc}	1.59^{bc}	2.08^{b}
ZTDSR+R–ZTW+R	25110^{d}	20451^{d}	45561^{f}	2.55^{c}	1.38^{c}	1.84^{c}
RTTPR–ZTW	29990^{b}	20356^{d}	50346^{d}	2.82^{bc}	1.55^{bc}	2.11^{b}
RTTPR–RTW	29990^{b}	21332^{c}	51323^{c}	3.02^{ab}	1.63^{b}	2.23^{b}
FP–RW	30552^{a}	24149^{a}	54701^{a}	3.43^{a}	2.23^{a}	2.75^{a}
ANOVA	Probability (*P*=0.05)					
Yr	0.001	0.552	0.052	0.968	0.279	0.389
Rep	0.408	0.587	0.356	0.936	0.992	0.875
Trt	<0.001	<0.001	<0.001	0.002	<0.001	<0.001
Yr ●Trt	0.776	0.987	0.965	0.813	0.861	0.761

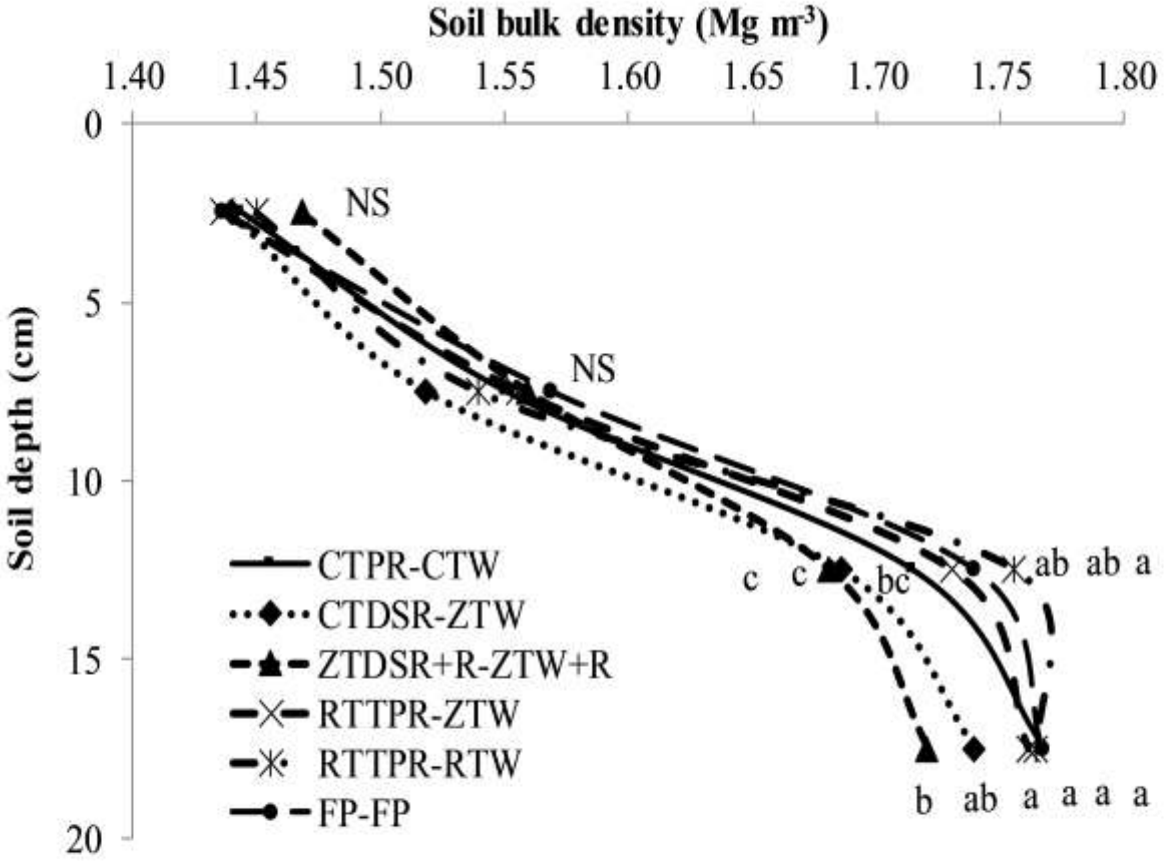
CTPR–CTW: puddled transplanted rice followed by conventional till wheat; CTDSR–ZTW: direct seeded rice on flat after dry tillage followed by zero till wheat; ZTDSR+R–ZTW+R: zero till direct seeded rice with residue followed by zero till wheat with residue; RTTPR–ZTW: transplanted rice after rotavator puddling followed by zero till wheat; RTTPR–RTW: transplanted rice after rotavator puddling followed by rotary till wheat; FP–RW: farmers practice rice–wheat. Data not allocating by the same letters within a column are significantly different according to Fishers least significant difference (LSD) test at *P*=0.05.

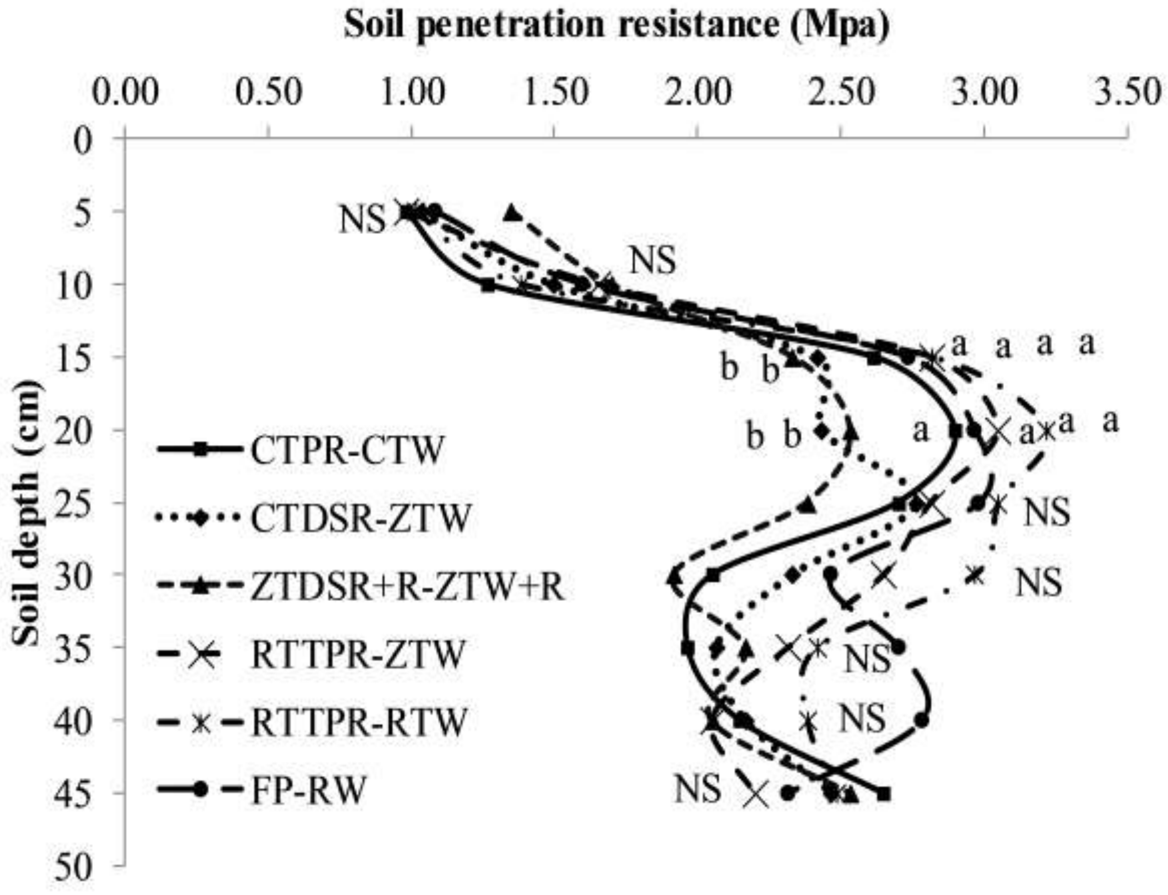
Table 6 Economic returns under different tillage and crop establishment method in rice–wheat cropping system

Treatment	Cost of production (Rs. ha^{-1})			Net return (Rs. ha^{-1})			Benefit: cost ratio		
	Rice	Wheat	System	Rice	Wheat	System	Rice	Wheat	System
CTPR–CTW	37111^{a}	31131^{b}	68242^{b}	46489	36844^{c}	83333^{b}	2.27	2.18^{c}	2.23^{c}
CTDSR–ZTW	35133^{c}	27326^{d}	62459^{e}	51657	48790^{b}	100448^{a}	2.48	2.78^{b}	2.61^{ab}
ZTDSR+R–ZTW+R	33470^{d}	27466^{d}	60936^{f}	51230	57101^{a}	108331^{a}	2.56	3.08^{a}	2.79^{a}
RTTPR–ZTW	36287^{b}	27326^{d}	63614^{d}	54463	49465^{b}	103928^{a}	2.51	2.81^{b}	2.64^{ab}
RTTPR–RTW	36287^{b}	28506^{c}	64793^{c}	48779	48189^{b}	96969^{a}	2.36	2.69^{b}	2.50^{b}
FP–RW	37111^{a}	32267^{a}	69378^{a}	44289	31441^{c}	75730^{b}	2.20	1.97^{c}	2.09^{c}
ANOVA	Probability (P=0.05)								
Yr	<0.001	<0.001	<0.001	0.029	0.013	0.481	0.001	0.069	0.002
Rep	0.499	0.872	0.651	0.399	0.829	0.615	0.384	0.744	0.568
Trt	<0.001	<0.001	<0.001	0.428	<0.001	<0.001	0.122	<0.001	<0.001
Yr ● Trt	0.909	0.264	0.860	0.942	0.787	0.788	0.893	0.749	0.753

CTPR–CTW: puddled transplanted rice followed by conventional till wheat; CTDSR–ZTW: direct seeded rice on flat after dry tillage followed by zero till wheat; ZTDSR+R–ZTW+R: zero till direct seeded rice with residue followed by zero till wheat with residue; RTTPR–ZTW: transplanted rice after rotavator puddling followed by zero till wheat; RTTPR–RTW: transplanted rice after rotavator puddling followed by rotary till wheat; FP–RW: farmers practice rice–wheat. Data not allocating by the same letters within a column are significantly different according to Fishers least significant difference (LSD) test at *P*=0.05.


Steady state infiltration rate (cm hr^{-1})
0.12
0.10
0.08
0.06
0.04
0.02
0.00
b
a
a
b
b
b
CTPR-CTW
CTDSR-ZTW
ZTDSR+R-ZTW+R
RTTPR-ZTW
RTTPR-RTW
FP-RW


Soil bulk density (Mg m-3)
1.40
1.45
1.50
1.55
1.60
1.65
1.70
1.75
1.80
Soil depth (cm)
0
5
10
15
20
NS
NS
c c bc ab ab a
b ab a a a a
CTPR-CTW
CTDSR-ZTW
ZTDSR+R-ZTW+R
RTTPR-ZTW
RTTPR-RTW
FP-FP


Soil penetration resistance (Mpa)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
Soil depth (cm)
0
5
10
15
20
25
30
35
40
45
50
NS
NS
a a a a
b b
b b
a a a a
NS
NS
NS
NS
NS
CTPR-CTW
CTDSR-ZTW
ZTDSR+R-ZTW+R
RTTPR-ZTW
RTTPR-RTW
FP-RW