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Double no-till and permanent raised beds in maize–wheat rotation of north-western Indo-Gangetic plains of India: Effects on crop yields, water productivity, profitability and soil physical properties

M.L. Jat[a,b], M.K. Gathala[c], Y.S. Saharawat[d,*], J.P. Tetarwal[e,f], Raj Gupta[a,e], Yadvinder-Singh[a]

[a] International Maize and Wheat Improvement Centre (CIMMYT), India Office, Pusa, New Delhi 110012, India
[b] Project Directorate for Cropping Systems Research, Modipuram 250110, Meerut, India
[c] International Maize and Wheat Improvement Centre (CIMMYT), Dhaka, Bangladesh
[d] Indian Agricultural Research Institute (IARI), New Delhi, India
[e] Rice–Wheat Consortium for the Indo-Gangetic Plains, NASC Complex, New Delhi, India
[f] Maharana Pratap University of Agriculture and Technology, Agriculture Research Station, Kota, Rajasthan, India

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ABSTRACT

Excessive pumping of groundwater over the years to meet the high water requirement of flooded rice crop and intensive tillage have threatened the sustainability of irrigated rice–wheat system (RWS) in the Indo-Gangetic plains (IGP) of South Asia. Replacement of rice with less water requiring crops such as maize in the RWS and identification of effective strategies for alternate tillage systems will promote sustainable cropping systems in the IGP. To this effect a 3-year field experiment was established with annual maize–wheat rotation in the north-western IGP of India to evaluate the effect of 3 tillage systems (conventional flat, CTF; no-till flat, NTF; permanent raised beds, NTB) on crop production, water use efficiency, economic profitability and soil physical quality. Grain yield of maize was highest (8.2–73.4%) under NTB followed by NTF and CTF across the years. Wheat yield was significantly higher under NTF during the 1st year while tillage practices had non-significant effect in the succeeding two years. On average, maize planted on NTB recorded about 11% lower water use and 16% higher water use efficiency compared to CT. The NTB and NTF required 24.7% and 10.8% less irrigation water than CTF system, respectively with 11.5% higher system productivity and demonstrated higher water productivity. The NTB and NTF systems provided similar net returns (averaged over 3 years) in maize–wheat system (MWS), which were US$ 281 ha^{-1} higher compared to CTF system. The CTF system had higher bulk density and penetration resistance in 10–15 and 15–20 cm soil layers due to compaction caused by the repeated tillage. The steady-state infiltration rate and soil aggregation (>0.25 mm) were higher under NTB and NTF and lower in the CTF system. Similarly, mean weight diameter (MWD) of aggregates was higher under NTF and NTB compared to CTF. The study reveals that NTB and NTF systems could be more viable options for MWS in order to save input costs and enhance profitability; however, the long-term effects of these alternative technologies need to be studied under varying agro-ecologies.

1. Introduction

Maize grown in sequence with wheat is the 5th dominant cropping system of India occupying ~2.0 million ha in Indo-Gangetic Plains (IGP), the heartland of rice–wheat (RW) production system of South Asia (Yadav and Subba Rao, 2001; Jat et al., 2009). The relatively high productivity of the RW system South Asia is occurring at the costs of over-exploitations of natural resources such as water and soil with increasing air pollution. Continuous pumping of groundwater over the years to meet the high water requirement of flooded rice has resulted in a drastic decline in groundwater tables (Humphreys et al., 2010; Sharma et al., 2012) leading to potential reduction in water availability in the future and an increase in socio-economic instability. These detrimental factors have given impetus to pursue alternative crops and cropping systems, which are more environmentally friendly and efficient in utilizing natural resources (Aulakh and Grant, 2008). Maize has a significantly lower irrigation requirement than rice and can enhance the productivity of the system, and sustain soil health and environment quality (Meelu et al., 1979). In the recent past, owing to diminishing

* Corresponding author. Tel.: +91 9311007818.
E-mail address: yssaharawat@gmail.com (Y.S. Saharawat).

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water availability as well as increasing cost of pumping for rice cultivation coupled with high yielding cultivars of maize, the acreage under maize–wheat system (MWS) has shown increasing trends in north-western India. By 2020, the demand for maize in developing countries will surpass the demand for both wheat and rice and to meet this rising demand, higher maize production is necessary (Srinivasan et al., 2004). Traditionally, maize and wheat are grown by broadcast seeding on flat layout after 6–7 tillage operations and using flood irrigation. The traditional practice of growing these crops is costly and results in inefficient utilization of irrigation water and nutrients leading to low productivity and input efficiency. Conservation agriculture based crop management technologies, such as no-till and permanent raised beds with residue retention and judicious crop rotation, are gaining more attention in recent years with the rising concern over degradation of natural resources, mainly soil and water, and to offset the production cost (Ladha et al., 2009; Jat et al., 2009; Saharawat et al., 2012). Tillage practices contribute greatly to the energy and labour cost in any crop production system resulting to lower economic returns (Labios et al., 1997; Jat et al., 2005; Saharawat et al., 2010; Vivak-Kumar et al., 2013). Furthermore, intensive tillage systems results to a decrease in soil organic matter due to acceleration of the oxidation and breakdown of organic matter and ultimately degradation of soil properties (Biamah et al., 2000; Gathala et al., 2011b). No-till (NTF) system is now being widely used by farmers in many parts of the world. The origin and use of permanent raised beds (NTB) have traditionally been associated with water management issues, either by providing opportunities to reduce the adverse impact of excess water on crop production or to irrigate crops in semi-arid and arid regions (Connor et al., 2003; Sayre and Hobbs, 2004; Bhushan et al., 2008; Gathala et al., 2011a). The NTB with only superficial reshaping in the furrows between the raised beds as needed before planting of each succeeding crop can reduce cultivation costs and increase sustainability of MWS systems (Govaerts et al., 2005). Moreover, it controls machine traffic, limiting compaction to furrow bottoms, allows the use of lower seeding rates than with CTF planting systems and reduces crop lodging (Sayre and Moreno-Ramos, 1997).

The farmers in the IGP of India are yet to grow maize and wheat using a NTF system either on flat or NTB, though it is a common practice in many western countries. Bed planting of maize can help in proper plant establishment, increases input efficiency, increases yields, and opens up avenues for NTF system. Adoption of NTF practice helps in timely seeding of either of the crops, hence leads to increase in productivity. From a preliminary study, Dhadli et al. (2009) reported lower yields of soybean and maize with CTF and NTF compared with NTB on a clay loam due to intermittent flooding observed during monsoon rains, which adversely affected the crop yields in the flat systems. From a 4-year study on sandy clay loam soil in Pakistan, Hassan et al. (2005) reported mean increases of 30%, and 65% in grain yield and water productivity of maize, respectively, under NTB compared to traditional practice. However, Ram-Singh et al. (2012) recently reported similar productivity but higher economic returns from MWS under NTB and NTF compared with CTF on coarse-textured loamy sand soil. Various on-farm participatory trials revealed little or no difference in productivity under NTF compared to best managed CTF maize (Gupta et al., 2002). They further reported that despites the similar yields economic advantage of US$ 50 ha^{-1} saved by farmers in tillage and irrigation costs under NTF maize. More such studies are needed to evaluate NTB and NTF systems over conventional tillage under different soil and climatic conditions. With this in view an experiment was established to evaluate the NTF and NTB vis-a-vis CTF in terms of crop and water productivity, farm income and soil physical health for long-term sustainability of maize–wheat rotation on sandy loam soil in northwestern India.

2. Materials and methods

2.1. Experimental site

The experiment was conducted at the research farm (29°4′N, 77°46′E, and 237-m above mean sea level) of the Project Directorate for Cropping Systems Research, Uttar Pradesh, India, during 2004–2007. Before start of the experiment, the field was under continuous conventional tillage and puddled transplanted rice-conventional till wheat system since past over 6 years. The soil (0–15-cm) of the experimental field was a typic Ustochrept with a sandy loam in texture with pH 8.1, 0.40% organic carbon (Walkley and Black, 1934), 135 kg ha^{-1} alkaline $KMnO_4$ oxdizable N (Subbiah and Asija, 1956), 13 kg ha^{-1}Olsen-P and 165 kg ha^{-1} ammonium acetate extractable-K.

The climate of the area is semi-arid subtropical, characterized by very hot summers and cool winters. The hottest months are May and June, when the maximum temperature reaches 45–46 °C, whereas, during December and January, the coldest months of the year, the temperature often drops below 5 °C. The average annual rainfall is 863-mm, 75–80% of which is received through the north-west monsoons during July to September. Weekly distribution of rainfall, minimum and maximum temperatures, and sunshine hours for the three cropping system years (May–April) are shown in Fig. 1.

2.2. Experimental design and treatments

The three treatments consisting of double no-tillage, permanent raised beds and conventional tillage in a maize–wheat rotation were evaluated in a randomized block design with three replications (see below for treatment details). The each experimental unit consisted of 16.0-m × 8.5-m (136 m^2) plot.

T1. Conventional till drilling of maize and wheat after conventional tillage (CTF). Maize (HQPM-1) was drilled on flat land at 67-cm row and 20-cm plant to plant spacing after conventional dry tillage (three passes of tillage, one with a harrow and two with cultivator followed by planking with a wooden planker). After the harvest of maize, the field was prepared with conventional-tillage (same as for maize) that followed pre-sowing irrigation for sowing of wheat (PBW-343) at 20-cm row spacing.

T2. No-till maize direct drilling of maize and wheat after no-tillage (NTF). Both maize and wheat were directly seeded without any preparatory tillage using the no-till planter seeded without any preparatory tillage using the no-till planter keeping row to row and plant to plant spacing similar to that in T1.

T3. Direct drilling of maize and wheat on permanent raised beds (NTB). At the beginning of the experiment, raised beds were prepared after conventional tillage (as in T1) using a raised-bed planter and were left for 30 days to settle. The beds were 37 cm wide at the top and 15 cm in height and separated by furrows having a 30-cm-wide top (Jat et al., 2009). The distance between the centre to centre of the two adjoining furrows was kept at 67 cm. The maize was directly drilled using a raised-bed planter with 20-cm plant to plant spacing, keeping one row in the centre of the top of the bed. Total plant population (74,627 plants ha^{-1}) was kept similar in the three treatments. After maize, wheat was directly drilled using the same raised bed planter that reshapes the beds along with seeding and fertilizer placement in single operation.

2.3. Crop management

For maize, an inverted T-type furrow opener along with a zero-till planter having an inclined plate seed metering system with fertilizer attachment was used for seeding in all the three treatments. A seed rate of 20 kg ha^{-1} was used and the seed depth

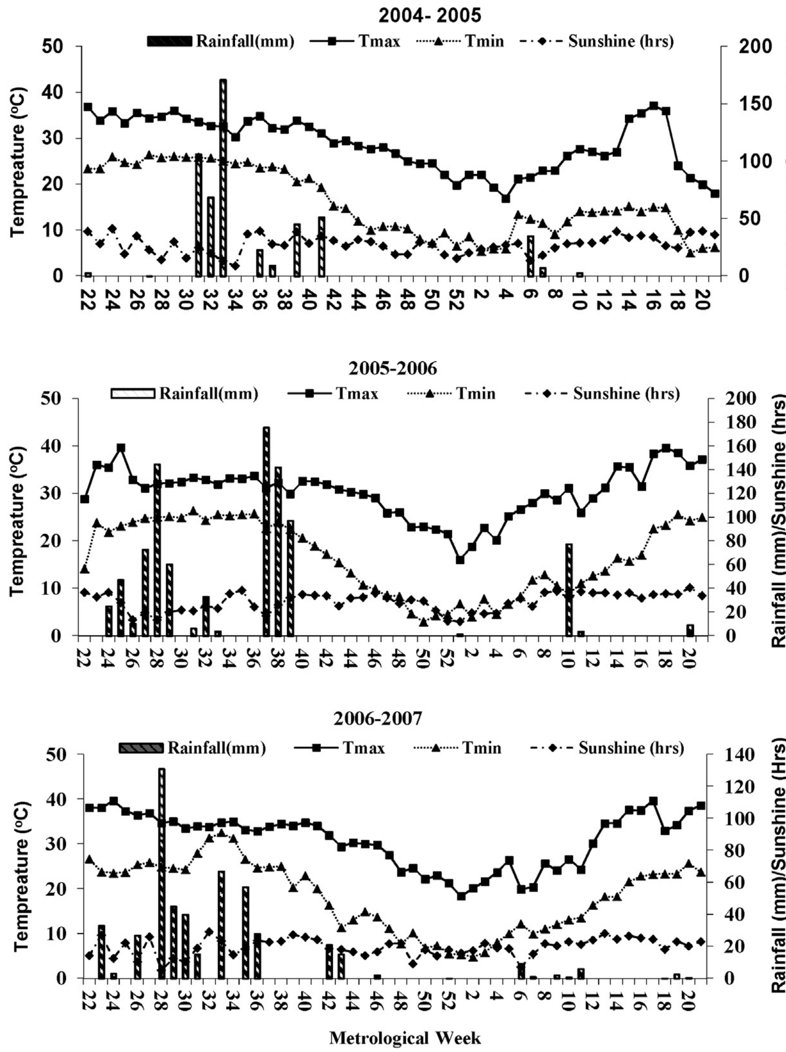

Fig. 1. Weekly maximum temperature, minimum temperature, sunshine hours and rainfall at the experimental site.

was maintained at 5-cm by adjusting the depth control wheels of the planter. Immediately after seeding, pre-emergence herbicide atrazine (1.0 kg a.i. ha^{-1}) was applied as spray to check weed germination.

Wheat (PBW-343) was seeded at 100 kg seed ha^{-1} at 20-cm row spacing in T1 and T2, and a seed rate of 80 kg ha^{-1} was used in NTB (T3). Two rows of the wheat were planted on both sides at the top of the raised beds spaced at 25-cm on the same bed in T3. To control weeds in wheat Arelon 75WP (isoproturon) at 1.25 kg ha^{-1} plus 2,4-D sodium salt (80%) at 0.625 kg ha^{-1} (35 days after sowing (DAS) were used to control grass and broadleaf weeds, respectively. Seeding was done on the same day in all the treatments.

2.4. Crop residue management

The crops were harvested manually with partial residue retention (10-cm high anchored wheat stubbles and 20-cm high anchored maize stems) in all the 3 treatments. While in conventional-tillage practices, stubbles were incorporated into the soil, the stubbles were retained at the soil surface under T2 and T3. Average load of stubbles was 2.5 Mg ha^{-1} for maize and 2.0 Mg ha^{-1} for wheat.

2.5. Fertilizer management

In both maize and wheat, all plots received 120 kg N, 26 kg P, and 50 kg K ha^{-1}. Half N and whole of P and K were applied as basal at sowing of both the crops. Both of P as diammonium phosphate (23 kg + 26 kg P ha^{-1}) and K as muriate of potash (50 kg K ha^{-1}) were drilled along with seed using seed-cum fertilizer planter in the all the treatments. Remaining portion of basal dose of N (37 kg N ha^{-1}) as urea was broadcast immediately prior to sowing. To maize, remaining half N was top dressed by broadcasting of urea in two equal split doses at V5 and V7 growth stages. In the event of the rains coinciding with the urea application, no irrigation was applied otherwise irrigation was applied immediately after the top dressing of urea. To wheat, remaining half N was top dressed in two equal split doses; first split before 1st post-sowing irrigation at crown root initiation stage and the second split before 3rd irrigation at pre-flowering stage.

2.6. Yield measurement

At maturity, grain yield of maize was determined on an area of 10.05 m^2 (3 beds × 5 m long) in the middle of each plot. Grain yield of wheat was determined on an area of 14 m^2 in CTF and NT plots,

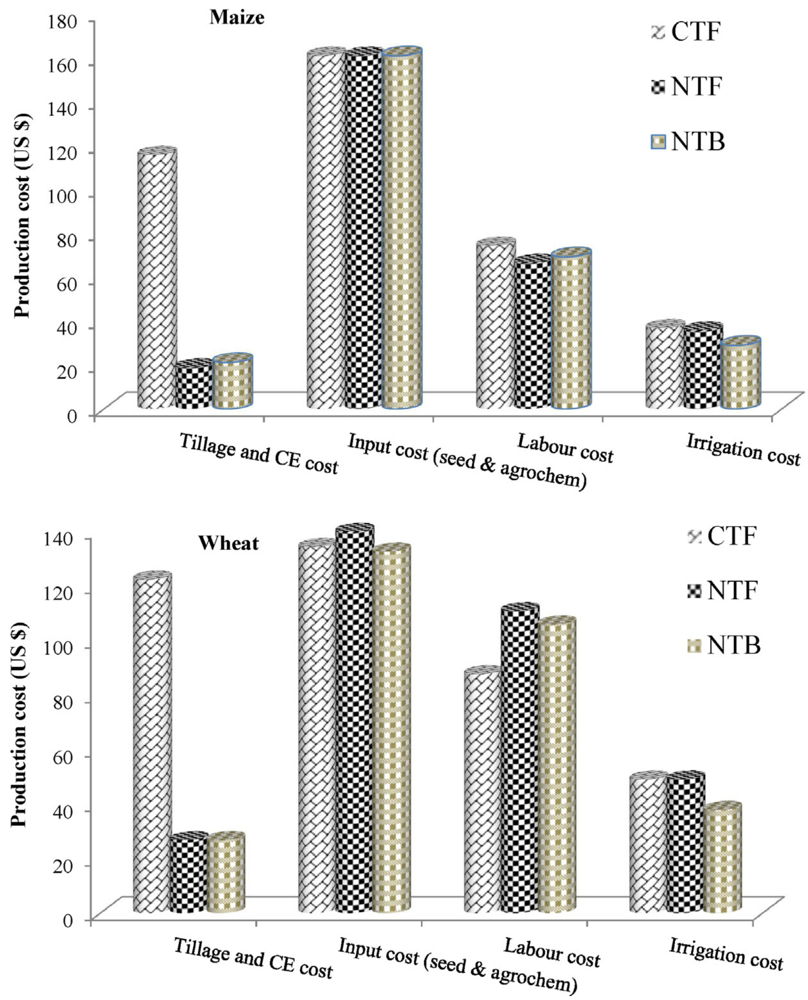

Fig. 2. Production costs involved in maize and wheat production under different tillage treatments.

and 14.07 m^2 in NTB plots. Grain yields of maize and wheat are reported at 14% and 12% grain moisture content, respectively.

2.7. *Water application and water productivity measurement*

Irrigation water was measured using a 'parshall flume'. All the treatments received same number of irrigations but the volume of irrigation water differed. The irrigation was applied to both maize and wheat as per the critical growth stages recommended in the region, but also depended on the rainfall event. The quantity of water applied and the depth of irrigation were computed using standard procedure. Rainfall data were recorded using a rain gauge installed at the experimental field and the total rainfall received during the crop seasons are given in Fig. 1. The input water productivity (WP_{I+R}) was computed as the ratio of grain yield to the total water input (irrigation + rainfall) and expressed as kg grain ha-mm^{-1}.

2.8. *Gross margin analysis*

Cost of cultivation under different treatments was estimated on the basis of approved market rates for inputs as fixed by the local Govt. Institution by taking into account costs of seed, fertilizers, biocide, and the hiring charges of human labour (minimum wage rate by Govt. of India) and machines for land preparation and seeding, irrigation, fertilizer application, plant protection, harvesting, and threshing, and the time (h) required per ha to complete an individual field operation (Jat et al., 2009). The cost of tillage and crop establishment, input (seed and agrochemicals), labour and irrigation in the production of maize and wheat are provided in Fig. 2. Gross returns were calculated on the basis of support price offered by Government of India for maize (US$ 172.2 Mg^{-1}) and wheat (US$ 214.2 Mg^{-1}). Net returns were calculated as the difference between gross income and total cost of cultivation. System productivity was calculated adding the grain yield of rice and wheat in each year, and the system net returns were calculated by adding the net return of maize and wheat for the individual year.

2.9. *Soil physical properties*

The soil physical properties were measured at the initiation of the experiment and after three cycles of MWS. The bulk density of oven-dried soil in the 0–30-cm layer at 5-cm interval was determined measured after the harvest of wheat in 2006–07 (after-3 crop cycles) using the core method as described by Blake and Hartage (1986). The cumulative infiltration of water through soil was measured using a double-ring infiltrometer from two spots within each plot. The infiltrometer consisted of an open outer ring consisted of 30-cm diameter steel pipe and an inner ring of 20-cm diameter. Both inner and outer rings were inserted about 10-cm into the soil. Water was added in both inner and outer rings using a straw deflector to minimize disturbance of soil surface. Cumulative infiltration from the inner ring was monitored for 545-min when the steady state was achieved for all the treatments. The fall in water depth in the inner ring was recorded after an interval of 5, 20, 35, 65, and constantly after every 60-min until steady state condition achieved. Soil aggregate size distribution and mean weight diameter (MWD) were determined using the wet-sieving method (Kemper and Rosenau, 1986). Penetration resistance in the 0–45-cm soil layer at 5-cm interval was measured using cone penetrometer. In the permanent beds, the bulk density and penetration resistance were recorded from centre of the top of the bed. The bulk density and penetration reading were recorded at the same time at moisture near to field capacity. To achieve almost similar moisture levels in all the plots, the field was irrigated after the harvest of the crop. For recording the infiltration rate, the infiltrometers were installed keeping centre of the double ring on centre of the top of the permanent beds. Similarly, the clods for analysis of aggregation and MWD were taken from the beds. The methodology for measurement of physical properties in permanent beds was adopted from Jat et al. (2009).

2.10. Data analysis

All the data on yield, water productivity, economic parameters and soil physical properties were analyzed with IRRISTAT for Windows for one-way ANOVA (IRRI, 2005). The pooled data were also analyzed keeping years as the main and TCE treatments as sub-effects using split-plot design. Duncan's multiple range test (DMRT) was used at the $P < 0.05$ level of probability to test the differences between the treatment means.

3. Results and discussion

Since there were significant year × treatment interactions in case al the parameters studied, simple effects (year-wise) are presented and discussed in the following subsections.

3.1. Weather analysis

The rainfall during maize season (June–October) was higher in 2006–07 (482-mm) than in 2004–05 and 2005–06 (378 and 482-mm, respectively) (Fig. 1). Rainfall during wheat season (November–April) was lower in 2004–05 (4-mm) and 2006–07 (12-mm) than in 2005–06 when crop received 80-mm of rain. Mean monthly minimum and maximum temperatures during the maize growing seasons (June–October) were nearly similar each year (Fig. 1). In the wheat season (November–April), minimum temperature during November–December was lower by an average of 3.3–3.6 °C in 2005–06 than in the other two years of study period. Sunshine hours were generally similar during the three years of the study.

3.2. Grain yield

There was a significant ($p < 0.05$) effect of tillage practices on maize yield during all the three years of the study (Table 1). Maize on NTB showed significant increases of 28.4%, 8.2% and 73.4% (with an average value of 30%) in yield compared to CTF in 2004–05, 2005–06 and 2006–07, respectively. NTF produced significantly higher maize yield than CTF in 2004–05 and 2006–07, but the yields were similar in 2005–06. Comparing NTF and NTB systems, maize yield was significantly higher under NTB than in NTF, except in 2006–07 when the yields were similar. Maize yield under CTF was markedly lower in 2006–07 compared with the 2004–05 due to heavy rains (131-mm during wks 29, 30 and 31) received at V4 to V5 growth stages that caused temporary flooding and adversely affected crop growth (Fig. 1). The infiltration rate in plots under CTF was markedly lower than in NTF and NTB (Figs. 5 and 6). Maize is known to be quite sensitive to excess water stress and yields poorly under water logged conditions (Dhillon et al., 1998; Lal et al., 1988). In earlier studies on fine-textured soils similar increases in maize yield on NTB compared with CTF were reported by Aggarwal et al. (2000) and Hassan et al. (2005) because maize under flat layout suffered from water logging. In contrast, Ram-Singh et al. (2012) obtained similar maize yield on NTB, NTF and CTF systems on coarse-textured loamy sand where no flooding occurred due to high rate of infiltration. Apart from less waterlogging experienced by maize on NTB, improvement in soil physical conditions (see next section) also contributed to higher maize yields recorded under NTB than flat layout. Maize yields declined over the year irrespective of the treatments, however, decline was maximum (48.2%) in CTF and minimum in NTF (34.1%). We are unable to find most plausible cause for this decline in maize yield except, much higher rains (131–144-mm) in 2005–06 and 2006–07 during V4 and V5 crop growth stages than in 2004–05 when crop received only 4-mm of rain. Heavy rain storms (415-mm) received during wks 37, 38 and 39 might have adversely affected the grain development in 2005–06. Wheat in NTF out-yielded CTF by 8.4% in 2004–05 and 16.1% in 2006–07, but the differences were non-significant in 2005–06 (Table 1).

Wheat yield in different treatments was generally similar in all three years of the study possibly due to similar weather conditions (Table 1). Wheat yields were significantly higher on NTF than on NTB in 2004–05 and 2006–07 (Table 1). However, wheat yield was similar under the three tillage systems in 2005–06. Ram-Singh et al. (2012) reported similar yields of wheat under NTF, NTB and CTF on a loamy sand soil under MWS. In contrast, Hassan et al. (2005) reported 13% increase in wheat yield on NTB compared with CTF in MWS. There are many reports of higher yields of NTF than CTF wheat sown after transplanted rice and this was mainly due to early sowing of wheat in the NTF system (Malik et al., 2004; Yadvinder-Singh Ladha, 2004; Jat et al., 2011a). Yadvinder-Singh et al. (2008) suggested that soil moisture at the time of planting on the beds is a critical factor in determining tilth on the medium to fine-textured soils, with cloddy soil and poor seed–soil contact, particularly when moisture was sub-optimal. Low spike density on beds may lead to poor wheat performance compared to CTF.

3.3. Total system productivity

Total productivity of MWS was significantly affected by tillage practices in all years of the study (Table 1). Total productivity across years was minimum under CTF (7.33–9.52 t ha^{-1}) and maximum under NTB (8.50–10.83 t ha^{-1}). While system productivity was significantly higher on NTB compared to NTF in 2004–05 and 2005–06, reverse was true in 2006–07. Total system productivity declined significantly in 2006–07 under CTF and NTB compared with that of 2005–06 but it did not change significantly in NTF.

3.4. Irrigation and total water use

The data pertaining to irrigation water use (W_I) and total water (irrigation + rainfall) use (W_{I+R}) are presented in Table 2. The W_I in maize was significantly lower in NTF (7.2–15.8%) and NTB (19.2–37.2%) systems compared to CTF and it was significantly lower under NTB than under NTF, except in 2006–07. The lower W_I under NTB than CTF was due lesser amount of irrigation water used in each irrigation as the number of irrigations applied was similar for the three tillage systems. Earlier studies (Gupta et al., 2003; Jat et al., 2009, 2011b; Hassan et al., 2005; Gathala et al., 2011a; Ram-Singh et al., 2012) showed that raised bed planting in rice–wheat and maize–wheat systems reduces irrigation water use by 12–60% and also improves drainage compared with CTF.

Like in maize, W_I in wheat was significantly lower under NTB and NTF compared with CTF in all the three years, except in 2006–07

Table 1
Effect of tillage practices on grain yield of maize–wheat system.

Tillage practices	Grain yield (Mg ha^{-1})								
	2004–05			2005–06			2006–07		
	Maize	Wheat	System	Maize	Wheat	System	Maize	Wheat	System
CTF	4.40c	5.12b	9.52c	3.78b	5.45a	9.23b	1.88b	5.35b	7.23c
NTF	4.75b	5.55a	10.30b	3.65b	5.62a	9.27b	3.13a	6.21a	9.34a
NTB	5.65a	5.18b	10.83a	4.12a	5.55a	9.67a	3.26a	5.24b	8.50b

when it was similar in NTF and CTF (Table 2). W_I in wheat was similar under NTF and NTB in 2004–05 but it was significantly lower under NTB compared to NTF in 2005–06 and 2006–07. Averaged across three years, NTF and NTB systems needed 10.8% and 24.7% of lesser W_I than CTF, respectively. Earlier studies by Aggarwal and Goswami (2003), Hassan et al. (2005) and Ram-Singh et al. (2012) showed 30–50% reductions in W_I on raised beds. The similar W_I under CTF and NTF in the third year could be due to increased rate of infiltration on NTF plots (see section on soil physical properties). The W_I in MWS was significantly lower under NTB than under NTF and CTF, and significantly higher under CTF than NTF, except in 2006–07 when it was similar under CTF and NTF.

W_{I+R} in maize differed significantly among 3 tillage practices in all the years (Table 2). The trend in W_{I+R} was generally similar to that in W_I because all the treatments received similar amount of rainfall during the cropping season. The W_{I+R} of maize across years and treatments ranged from 194–323-mm; with maximum under CTF and minimum under NTB. Like for W_I, W_{I+R} in wheat was significantly lower under NTF and NTB than CTF. W_{I+R} for the MWS under three tillage treatments varied significantly each year and was maximum during 2005–06 (1572-mm) and minimum during 2004–05 (847-mm). The net savings in W_{I+R} for MWS in NTB and NTF over CTF were similar to that reported for W_I.

3.5. Water productivity

Irrigation water productivity (WP_I) of maize varied significantly across treatments and years (Table 3). WP_I in maize was significantly higher with NTB (14.42–27.78 kg grain ha-mm^{-1} water) and NTF (12.04–17.46 kg grain ha-mm^{-1}) than in CTF (6.71–14.71 kg grain ha-mm^{-1}) (Table 3). In wheat, significantly higher WP_I for wheat was recorded for NTB and NTF systems than for CTF, except in 2006–07 when WP_I was similar in CTF and NTB (Table 3). The WP_I of the MWS was significantly higher for NTB and NTF than CTF system in all the three years. Averaged over three years WP_I of MWS was 26.2% and 51.7% higher for NTF and NTB than for CTF, respectively. The increase in WP_I is the resultant of both increase in yield and saving in irrigation water.

Like WP_I, WP_{I+R} varied significantly across treatments and years (Table 3). Total water productivity (WP_{I+R}) in maize and wheat generally followed the same trend as for WP_I. In maize, mean WP_{I+R} was 4.17, 5.00 and 6.17 kg grain ha-mm^{-1} for CTF, NTF and NTB, respectively (Table 3). Similarly, WP_{I+R} for wheat (averaged across 3 years) was higher for NTF and NTB (14.77–15.09 kg grain ha-mm^{-1}) than in CTF (11.92 kg grain ha-mm^{-1}) (Table 3). The values of WP_{I+R} are higher for wheat than maize due higher grain yield and lesser amount of rain received during the cropping season.

3.6. Economic analysis

The cost of cultivation in maize, wheat and MWS was significantly affected by tillage systems in all the years except for wheat in 2004–05 (Fig. 2 and Table 4). The cost of maize cultivation was significantly lower under NTB and NTF (US$ 265–291 ha^{-1}) systems than under CTF system (US$ 379–400 ha^{-1}); the cost of production was similar for NTB and NT systems. The lower cost of production under NTB and NTF systems compared to CTF was mainly due to saving in cost of tillage and irrigation water. The cost of cultivation in wheat was not influenced by the three tillage systems in the first year (2004–05) because all the plots were prepared using CTF before the imposition of the treatments. While cost of wheat production was significantly lower for NTB and NTF than CTF system during 2005–07, it was similar under three tillage systems in 2004–05. The total cost of MW cultivation followed a similar trend to that of maize.

Gross and net returns in maize were significantly higher in NTB and NTF systems compared to CTF in 2004–05 and 2006–07 but in 2005–06 gross returns were similar under NTF and CTF systems (Table 4). Gross and net returns in maize under NTB were significantly higher by US$ 116 ha^{-1} in 2004–05 and US$ 51 ha^{-1} in 2005–06 compared to NTF system, but no differences were observed in 2006–07. While gross returns from wheat were similar from the three tillage systems in 2005–06 and 2006–07, NTF system provided significantly higher gross returns than CTF and NTB in 2004–05. Considering MWS as a whole, significantly higher gross returns were obtained in NTB and NTF systems compared with CTF in 2004–05, and the differences were non-significant in 2005–06. NTF system provided significantly higher gross returns from MWS in 2006–07 compared to CTF but the gross returns from NTB and CTF were similar.

The net returns from maize in CTF ranged from net loss of US$ 165 ha^{-1} during 2006–07 to net returns of US$ 156 ha^{-1} during

Table 2
Effect of tillage practices on irrigation and total water input in maize–wheat system.

Irrigation water applied (mm)									
Tillage practices	2004–05			2005–06			2006–07		
	Maize	Wheat	System	Maize	Wheat	System	Maize	Wheat	System
CTF	323a	370a	693a	293a	480a	773a	280a	422a	702a
NTF	272b	293b	566b	262b	440b	702b	260a	407a	667b
NTB	203c	262b	465c	194c	366c	560c	226b	380b	606c
Rainfall (mm)	378	4	382	790	80	870	482	12	494
Total input water (irrigation + rainfall) mm									
CTF	701a	374a	1075a	1083a	560a	1643a	762a	434a	1196a
NTF	650b	297b	948b	1052b	520b	1572b	742a	419a	1161b
NTB	581c	266b	847c	984c	446c	1430c	708b	392b	1100c

Table 3
Effect of tillage practices on irrigation water and input water productivity in maize–wheat system.

Irrigation water productivity (kg grain ha-mm^{-1})									
Tillage practices	2004–05			2005–06			2006–07		
	Maize	Wheat	System	Maize	Wheat	System	Maize	Wheat	System
CTF	14.71c	13.84b	13.74c	12.90b	1135c	11.94c	6.71c	12.68b	10.30b
NTF	17.46b	18.94a	18.20b	13.93b	12.77b	13.21b	12.04b	15.26a	14.00a
NTB	27.78a	19.80a	23.29a	21.24a	15.16a	17.27a	14.42a	13.79b	14.03a
Total input water productivity (kg grain ha-mm^{-1})									
CTF	6.28c	13.69b	8.86c	3.49b	9.73c	5.62b	2.47b	12.33b	6.05b
NTF	7.31b	18.69a	10.86b	3.48b	10.81b	5.90b	4.22a	14.82a	7.81a
NTB	9.72a	19.47a	12.79a	4.19a	12.44a	6.76a	4.60a	13.37b	7.73a

2004–05. The net returns from wheat were significantly higher (US$ 93–245) in NTF compared to CTF system during all the years. The net returns were significantly higher in NTB compared to CTF in 2004–05 and 2005–06. Net returns from the MWS were significantly higher (US$ 59–510) in NTF and NTB than in CTF system. While NTB outperformed NTF during 2004–05 and 2005–06, NTF provided more net returns than NTB in 2006–07. Averaged across three years, NTB and NTF systems provided similar net returns which were about US$ 281 ha^{-1} higher compared to CTF system.

3.7. Soil physical properties

Soil bulk density increased with depth with highest values at 15–20-cm and then decreased to 30-cm. The bulk density in the 10–15-cm soil layers was significantly lower in the NTB and NTF compared to CTF (Fig. 3). In the 15–20-cm soil layer, bulk density under CTF and NTB was similar, but it was significantly lower in NTF than CTF (Fig. 4). The cone resistance followed a similar trend to that of bulk density.

The penetration resistance was least in upper 0–5-cm layer of the NTB due to loose soil on the top of raised beds, consistent with the bulk density data. The most likely reason for higher values of bulk density and soil resistance in CTF compared to NTF and NTB is the excessive use of tillage implements causing compaction in the plough layer. These results are in conformity with those reported earlier by Yang et al. (1999), Jat et al. (2005, 2009), Govaerts et al. (2009) and Gathala et al. (2011b). The cumulative infiltration for 545-min was about 3-times in NTF and more than 8-times in NTB of the values in CTF after three years of experimentation (Fig. 5). Similarly, steady state infiltration rate was maximum (2.70-cm h^{-1}) in NTB, followed by NTF (1.40-cm h^{-1}) and minimum (0.30-cm h^{-1}) in the CTF (Fig. 6). More infiltration in NTF and NTB plots might be due to the minimal disturbance of pore continuity. In an earlier study, Shaver et al. (2002), Jat et al. (2009), and Gathala et al. (2011b) reported higher infiltration in no-till and NTB than in CTF plots. Soil aggregation was improved in the both NTF and NTB treatments, more so in the NTF system. The proportion of soil aggregates > 0.25 mm was highest (78.5%) in NTF (Fig. 7) followed by the NTB (70.5%). MWD of aggregates was similar in NTF and NTB (3.25 and 3.27-mm, respectively) but significantly higher than in CTF (Fig. 8). The increase in soil aggregation under NTF and NTB was possibly due to higher levels of soil organic carbon (4.46-g kg^{-1})

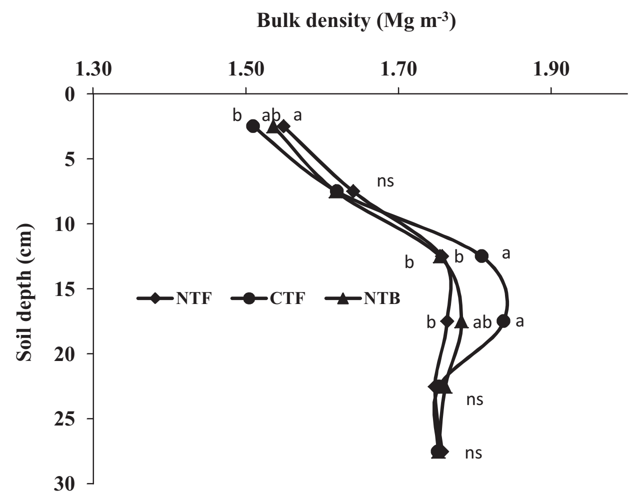

Fig. 3. Effect of tillage practices on soil bulk density after three years of maize–wheat system. CTF, conventional till flat, NTF, no tillage flat, NTB, permanent raised beds. Treatment means within a row followed by the same letter were not statistically different.

Table 4
Effect of tillage practices on cost of production, gross returns and net returns in maize–wheat system.

Tillage practices	2004–05			2005–06			2006–07		
	Maize	Wheat	System	Maize	Wheat	System	Maize	Wheat	System
	Cost of production (US$ha^{-1})								
CTF	383	375	758	379	393	772	400	410	810
NTF	291	310	601	265	328	593	291	340	631
NTB	285	279	564	270	309	579	285	320	605
LSD(*P* = *0.05*)	61.1	NS	98.7	31.9	19.3	44.0	31.6	45.1	64.7
	Gross returns (US$ ha^{-1})								
CTF	539	716	1255	451	929	1380	235	1098	1333
NTF	582	777	1359	435	957	1393	391	1273	1664
NTB	692	726	1418	491	946	1437	407	1075	1482
LSD(*P* = *0.05*)	26.5	20.4	40.3	31.4	NS	NS	65.5	NS	234.7
	Net returns (US$ ha^{-1})								
CTF	156	341	497	72	536	608	-165	688	523
NTF	291	467	758	170	629	800	100	933	1033
NTB	407	447	854	221	637	859	122	755	877
LSD(*P* = *0.05*)	26.5	20.4	40.2	31.4	21.9	46.3	65.5	181.5	234.7

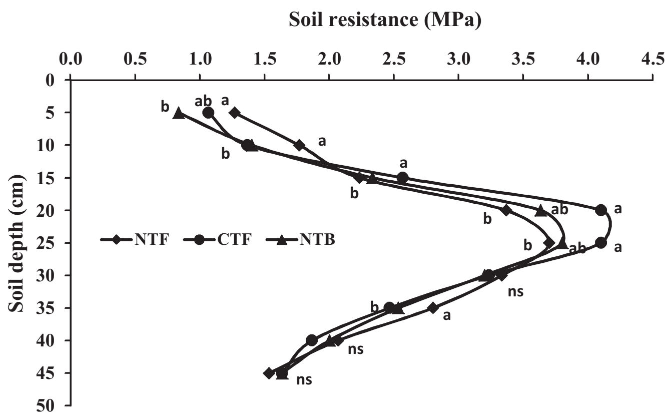

Fig. 4. Effect of tillage practices on soil resistance after three years of maize–wheat system. CTF, conventional till flat, NTF, no tillage flat, NTB, permanent raised beds. Treatment means within a row followed by the same letter were not statistically different.

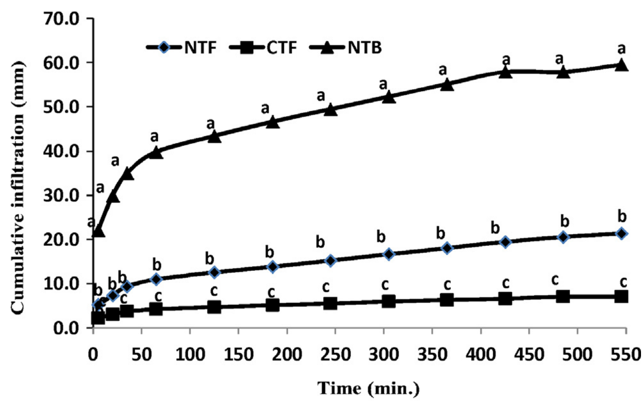

Fig. 5. Effect of tillage practices on cumulative infiltration after three years of maize–wheat system. CTF, conventional till flat; NTF, no tillage flat; NTB, permanent raised beds. Treatment means followed by the same letter were not statistically different.

than in CTF (4.09-g kg^{-1}) as a result of the least soil disturbance. In earlier studies, Jat et al. (2009) and Gathala et al. (2011b) have reported significant improvement in soil aggregation under NT and NTB systems.

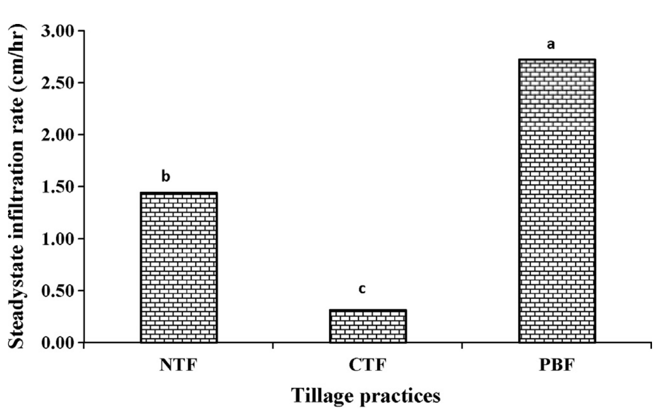

Fig. 6. Effect of tillage and crop establishment techniques on steady state infiltration after three years of maize–wheat system. CTF, conventional till flat; NTF, no tillage flat; NTB, permanent raised beds. Treatment means within a row followed by the same letter were not statistically different.

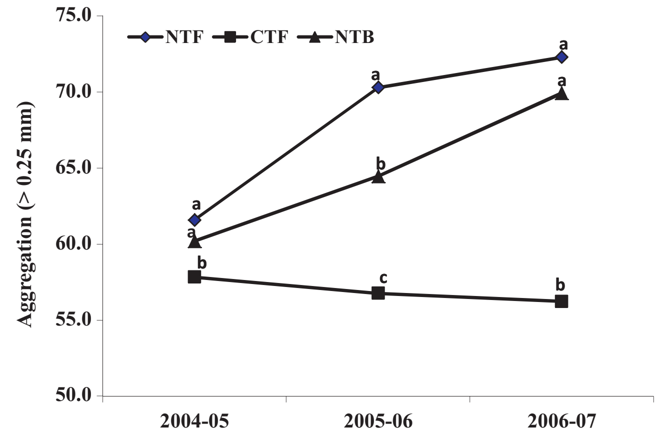

Fig. 7. Effect of tillage and crop establishment techniques on soil aggregation after three years of maize–wheat system. CTF, conventional till flat; NTF, no tillage flat; NTB, permanent raised beds. Treatment means within a column followed by the same letter were not statistically different.

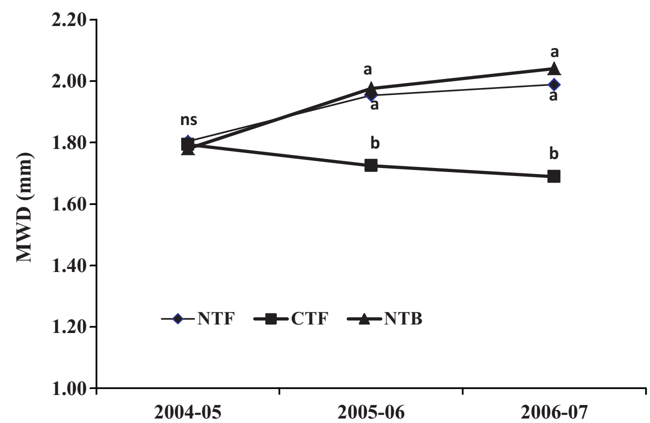

Fig. 8. Effect of tillage practices on mean weight diameter (MWD) of soil aggregates after three years of maize–wheat system. CTF,conventional till flat; NTF, no tillage flat; NTB, permanent raised beds. Treatment means within a column followed by the same letter were not statistically different.

4. Conclusion

The study showed that MW cultivation system both NTB and NTF systems are more economical than CTF system. The permanent raised bed planting (NTB) system was superior to other tillage methods when taking into account yield, water productivity, profitability and soil physical conditions in a sandy loam soil.

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