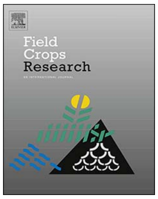
Field Crops Research 215 (2018) 222–231

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr



Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize-wheat cropping system in the North-western Indo-Gangetic Plains

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ARTICLE INFO

Keywords:
Conventional and zero tillage
Maize and wheat productivity
Permanent narrow and broad beds
Residue retention
Soil organic carbon

ABSTRACT

The Indo-Gangetic Plains (IGP) of India is dominated with rice − wheat cropping system that occupies almost 10.5 million ha area. The sustainability of rice-wheat system is under threat due to numerous water-, nutrients-, weeds- and environment-related problems, mainly, due to the cultivation of rice. Suitable crop and soil management practices with a bias to conservation agriculture (CA) that can sustain soil and environmental health as well as improve crop and water productivity, are required for the Indian IGP. Maize can be a viable alternative to rice and a potential driver for diversification of rice-wheat system. The acreage of maize is on the increase in conventional and conservation agriculture-based cereal systems of India in recent years. Therefore, a field experiment, involving a maize (*Zea mays* L.)-wheat cropping system was undertaken on a sandy clay loam soil for three years (2010–11 to 2012-13) in New Delhi to evaluate the impacts of CA on crop and water productivity, profitability and soil organic carbon (SOC) accumulation. There were five CA-based treatments in first year, and two treatments were introduced in second year (2011-12) onwards. The experiment was laid out in a randomized complete block design with three replications. In all the residue retention plots, wheat residue was retained in maize crop and maize residue was retained in wheat crop under zero till conditions. Results showed that the plots under permanent broad bed with residue (PBB + R) and without residue (PBB) resulted in ∼29 and ∼26% higher maize grain yield, respectively than conventional tillage (CT) (2.6 t ha^{-1}), but wheat grain yields were comparable in all the treatments in first year. Maize grain yield in second year under PBB + R and zero tillage with residue (ZT + R) were 55 and 43% higher than CT plots (2.8 t ha^{-1}). Three-year mean maize yields due to PBB + R and permanent narrow bed with residue (PNB + R) were 28 and 15% higher than that in CT plots (3.3 t ha^{-1}). The PBB + R resulted in 11% higher two-year mean water productivity in maize than PBB (∼without residue), but both these treatments were comparable in this regard in wheat. The ZT + R plots resulted in 14% and 22% higher two-year mean water productivity, respectively in maize and wheat than ZT plots. Overall, the plots under PBB + R had 57% and 19% higher mean water productivities in maize and wheat, respectively compared with CT plots. Again, the PBB + R plots gave 12% higher two-year mean net returns compared with CT plots. With regard to net returns, the plots under permanent narrow bed with and without residue (PNB + R; PNB) were inferior to PBB, PBB + R, ZT and ZT + R plots. Retention of both-season crop residues could significantly improve SOC concentration in surface (0–5 cm) soil. The PBB + R resulted in highest SOC pool at 0–30 cm soil layer, which was significantly higher than that in CT. This system showed maximum carbon sequestration potential. Thus, this CA practice, which involves PBB + R is superior to other practice. This would save water through higher water-use efficiency, and lead to accumulation of more carbon in soil with higher sequestration potential, besides giving sustainable production through maize-wheat system over the years. This can be adopted across the IGP regions of India, where irrigated rice-wheat system is in practice, and in similar agro-ecologies of the tropics and sub-tropics under irrigated conditions.

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http://dx.doi.org/10.1016/j.fcr.2017.10.021
Received 22 March 2017; Received in revised form 23 May 2017; Accepted 30 October 2017

1. Introduction

In the last few decades, high growth rates of cereal crops (wheat 3.0% and rice 2.3%) have kept pace with population growth in South Asia (Fischer et al., 2002; FAO, 2005). The past high growth rates in the intensively cultivated cropping systems has occurred at the costs of over-exploitations of natural resources, degradation of soil health and enhanced global warming (Jat et al., 2013). In India, rice (*Oryza sativa* L.) − wheat (*Triticum aestivum* L. emend Fiori & Paol) cropping system that occupies almost 10.5 million ha area has become the most dominant cropping system (Chaudhary and Harrington, 1993), followed by a major chunk of farmers in the Indo-Gangetic Plains (IGP). Several problems such as nutrients imbalances/deficiencies and low nutrient-use efficiency, high energy and labour demands, high emissions of greenhouse gases, and weed shift and resistance (Bhushan et al., 2007; Gupta and Seth, 2007; Ladha et al., 2009; Pathak et al., 2011; Ram et al., 2012) that have cropped up recently, threaten the sustainability of rice-wheat system. Continuous pumping of groundwater over the years to meet high water requirement of rice has resulted in a drastic decline in groundwater tables (Humphreys et al., 2010). Overall, traditional production management systems are leading to plateau of rice-wheat system productivity and fatigued natural resource base (Gathala et al., 2013). Thus, the region's food security is being continuously threatened and the problem is further complicated by the global environmental changes (Fischer et al., 2002; FAO, 2005; Gupta et al., 2016). These detrimental factors have given impetus to pursue alternative crops and cropping systems, which are more environment-friendly and efficient in utilizing natural resources (Aulakh and Grant, 2008).

Maize (*Zea mays* L.), cotton (*Gossypium* spp) (Das et al., 2014) and pigeonpea [*Cajanus cajan* (L.) Millsp.] (Singh et al., 2005) are suitable alternative crops to replace rice in the *kharif* (rainy) season. Maize is grown in an area of 9.5 million hectares with 24.5 million tonnes annual production (USDA, 2017) and ranks as third most important food crop after rice and wheat in India. Karnataka, Rajasthan, Bihar, Andhra Pradesh, Madhya Pradesh, Maharashtra, Uttar Pradesh, Punjab, Haryana are major maize-growing States in India. The adaptability of maize to diverse agro-ecologies and seasons is unmatched to any other crop. It can be a viable alternative to rice and a potential driver for crop diversification of the rice-wheat system in IGP of India (Hobbs and Gupta, 2003; Sayre and Hobbs, 2004; Humphreys et al., 2010; Saharawat et al., 2010; Das et al., 2013; Saad et al., 2016) and can ensure food and nutritional security. Around 85% of maize produced in India is consumed as human food (Singh et al., 2011) in the form of grains, green cobs, sweet corn, baby corn and pop corn. Besides, maize provides feed, fodder and serves as a source of basic raw materials for more than 3500 value-added industrial products for food (25%), animal feed (12%), poultry feed (49%), starch (12%), brewery (1%) and seed (1%) (Dass et al., 2008), including specialized maize like quality protein maize (QPM), baby corn, sweet corn, pop corn, high starch corn and high oil corn. It has immense potential for employment generation through post-harvest processing and value addition. A good quantity of maize is also exported to different countries from India. Maize is endowed with an assured minimum support price (MSP), which gets revised/increased every year by the Government of India (GOI, 2017). The MSP has been substantially increased to INR 13650 per tonne of maize grains in 2016-17, which is almost equal to the MSP of rice. Maize with significantly lower irrigation requirement (~400–600 mm in wet rainy season and ~700–800 mm in dry winter season) than transplanted (~2000–2100 mm) and direct-seeded (~1300–1400 mm) rice, can enhance system productivity, sustain soil health and environment quality (Meelu et al., 1979). Potential productivity, assured high returns and nutritional security could be realized from the maize–wheat system (especially after introduction of quality protein maize), thereby improving the livelihood and nutrition of the farmers and saving water. In IGP, traditionally maize and wheat are sown by broadcasting seed after intensive dry tillage (3–4 passes of harrow, 1–2 cultivators and 1planking) operations and with flood irrigation. The traditional production practices not only increase the input cost, but also are input inefficient. The intensive tillage and crop establishment account to around 25% of the total production cost, leading to reduced net income (Hobbs et al., 2008). Thus, the major challenge for researcher is to develop an alternate production system that is water efficient, as well as can help to sustain crop productivity, and produce more at less cost (Gathala et al., 2011).

Recently, conservation agriculture (CA) is being promoted and adopted for sustainable crop intensification (Kassam et al., 2009; FAO, 2011; Saad et al., 2016). It along with other best management practices like raised bed planting for water-saving and better crop establishment offer opportunities for maize and wheat in South Asia (Friedrich and Gustafson, 2007). Some of the CA-based component technologies such as laser-aided land leveling, zero tillage (ZT), raised bed planting, crop residue retention on the soil surface, and crop diversification have been evaluated in the IGP as alternatives to conventional practices (Harrington and Hobbs, 2009; Bhattacharyya et al., 2013, 2015; Das et al., 2014). The no-till raised bed system has gained importance in recent past in upland cropping system of South Asia to save irrigation water and reduce adverse impact of excess water on crop production (Connor et al., 2003; Sayre and Hobbs, 2004; Govaerts et al., 2005; Sayre et al., 2005). Superficial reshaping of beds done in the permanent raised beds once in a year, particularly before planting of rainy season crops reduces the cost of tillage as well as enhances water-use efficiency and sustainability of the maize-wheat system (Govaerts et al., 2005). Moreover, it controls machine traffic, limiting compaction to furrow bottoms, allows the use of lower seeding rates than with conventional planting and reduces crop lodging (Sayre and Moreno-Ramos, 1997). Moreover, the conservation agriculture practices lead to improvement in soil carbon sequestration (Bhattacharyya et al., 2012, 2015) and soil health due to less soil disturbance and retention of crop residues. Paustian et al. (1997) reported that the SOC content in no-till was significantly higher than that in conventional tillage due to reduced litter decomposition and less soil disturbance in no-till system. The reduced rate of litter decomposition may be due to the micro-climate less conducive to microbial activity in the surface layer and less soil to residue contact. Adoption of these alternative tillage and crop establishment practices helps in timely seeding of both crops, hence, leads to increased productivity. From a four-year study on sandy clay loam soil in Pakistan, Hassan et al. (2005) reported 30 and 65% increase in grain yield and water productivity of maize, respectively, under no-till raised bed system compared to traditional practice. Ram et al. (2012) reported similar productivity but higher economic returns from maize-wheat system under no-till raised bed system compared to CT on a coarse-textured loamy sand soil. However, limited information is available related to the comparative performances (on crop and water productivities) of maize and wheat sown in CT and no-till raised beds of different dimensions. Moreover, information on the impacts of bed width (narrow versus broad beds) with residue retention compared with farmers' practice is scarce. Such evidence-based studies are critical to promote a package of best practice to enhance and sustain productivity.

Therefore, a CA experiment on maize-wheat system was designed and executed in the western IGP. The specific objectives of this study were: (i) to evaluate the impacts of bed planting on crop yield, aboveground biomass productivity, water productivity and carbon sequestration under a maize-wheat system, and (ii) to evaluate the performance of residue retention *vis-a-vis* residue removal and narrow versus broad beds on the maize-wheat grain yields, water productivity and carbon sequestration. The hypotheses were: (i) ZT with permanent bed planting (both narrow and broad beds) would result in larger crop productivity and system water productivity compared with farmers' practice (conventional tillage; CT), (ii) residue retention would improve yield, system water productivity and carbon sequestration over the residue removal and (iii) permanent broad beds would have higher crop productivity, water productivity and carbon sequestration compared with permanent narrow beds.

2. Materials and methods

2.1. Experimental site

A field experiment was initiated at the ICAR-Indian Agricultural Research Institute (ICAR-IARI), New Delhi, India in 2010. Before 2010, the experimental field was under rice-wheat cropping system with recommended mineral fertilization for both crops for many years. The climate of the research farm is semi-arid with dry hot summer and cold winter. Annual rainfall is 710 mm of which 80% is received during the southwest monsoon from July to September, and rest is received through the 'Western Disturbances' from December to February. Pan evaporation varies from 3.5 to 13.5 mm d^{-1} and reference evapotranspiration from 9 to 15 mm d^{-1}. Daily mean values of weather parameters during the rainy (*kharif)* and winter (*rabi)* seasons in 2012–13 were same as reported by Das et al. (2014) for another experiment at IARI research farm, adjacent to this experiment.

The soil (0–15 cm layer) of experimental field was sandy clay loam in texture with pH 7.7, Walkley & Black C (oxidizable SOC) 5.2 g kg^{-1}, EC 0.64 dS m^{-1}, $KMnO_4$ oxidizable N 182.3 kg ha^{-1}, 0.5 M $NaHCO_3$ extractable P 23.3 kg ha^{-1} and 1 N NH_4OAc extractable K 250.5 kg ha^{-1}. It contained sufficient amounts of $CaCl_2$ extractable S and DTPA extractable micronutrients as all of these were above the critical deficiency limits.

2.2. Experimental details

In first year (2010-11), the field experiment was conducted with five treatments (Table 1), laid out in a randomized complete block design (RCBD) with three replications to compare conventional tillage (CT) with zero tillage (ZT) on narrow and broad beds with and without residue. From second year onwards, two additional treatments, zero tillage with residue retention (ZT + R) and without residue retention (ZT) were employed on usual flat/even land. For convenience in tractor operation (for sowing, fertilization, harvesting) and irrigation, each treatment was assigned on a 30.0 m long and 8.4 m wide strip (~252.0 m^2), which was sub-divided into three plots of 9.0 m x 8.4 m (~75.6 m^2) each, representing replications. There were 1.5 m wide gaps between the plots. Each plot/strip was surrounded by bunds/embankments for irrigation purposes.

The experimental field was laser-levelled in 2009. It was ploughed to a fine tilth during May-June 2010 for conducting this experiment. The narrow and broad bed plots of required dimensions were made with the help of a ridge/bed maker, and were continued as permanent narrow (PNB) and broad (PBB) beds in the subsequent years. In CT plots, one ploughing each with a tractor-drawn disk plough, cultivator and harrow, followed by leveling was done in every season for preparing pulverized soil with fine tilth. No ploughing was done in ZT, PBB and PNB plots with and without residue. In PBB and PNB plots, furrows were renovated and beds were reshaped once in a year before sowing of rainy-season maize crop.

The entire amounts of above-ground biomass of maize and wheat were not retained as the residue of these crops are used by the farmers of this region for livestock feed. About 40% of maize stover and wheat straw yields were retained as residue. Wheat straw yield of 2009–10 (the immediate previous crop) was nearly 6.5 t ha^{-1}. Therefore, at the beginning of experiment in first year (2010-11), an estimated 2.6 t ha^{-1} (i.e. 40% of 6.5 t ha^{-1}) *ex-situ* wheat residue was collected and applied on the PNB + R and PBB + R plots in maize crop. Anchored maize and wheat residue were kept in all the residue retention plots (i.e. ZT + R, PNB + R, PBB + R) from *in-situ* crop residue, which was available from the winter season (i.e. wheat crop) of first year onwards. For residue removal and CT plots, maize and wheat crops were harvested manually by cutting the bases of plants at around 3–4 cm above soil surface as the farmers usually do in IGP regions. By doing this, an estimated amount of about 4.5% of wheat straw was left as stubble in CT and other residue removal plots in all the years. For residue retention plots, the standing maize plants were cut manually at 40 cm height from the base and left *in situ* as anchored residue and estimated. Remaining amount of residue if at all required for making 40% residue of particular plot was applied uniformly as loose residue. Similarly, wheat plants were harvested with a combine harvester at 40 cm height from the base of plants for grains, and rest was retained as stubble. The cumulative (in three years) estimated amounts of residues returned to the maize-wheat system were 0.92, 0.86, 13.45, 0.90, 14.90, 1.20 and 10.90 Mg ha^{-1} in the plots under CT, PNB, PNB + R, PBB, PBB + R, ZT and ZT + R, respectively.

2.3. Crop sowing and management

Maize 'HQPM 1' seeds were sown on 30.06.2010, 07.07.2011 and 05.07.2012 in both CT and ZT conditions at 70 × 30 cm spacing and grown all through the rainy season (July-October) and harvested in the end of October every year. Enough time (April – June) was available after harvest of wheat for land preparation in CT, and maize could be sown on the same day under both CT and ZT plots. But, wheat (cv. HD

Table 1
Treatments adopted in the experiment.

Treatment	Treatment description					
	Maize crop			Wheat crop		
	Tillage	Type of bed	Residue retention	Tillage	Type of bed	Residue retention
CT	Conventional tillage	Plain/flat land	No	Conventional tillage	Plain/flat land	No
PNB	Zero tillage	Permanent narrow bed (40 cm bed and 30 cm furrow)	No	Zero tillage	Permanent narrow bed (40 cm bed and 30 cm furrow)	No
PNB + R	Zero tillage	Permanent narrow bed (40 cm bed and 30 cm furrow)	Yes; wheat residue	Zero tillage	Permanent narrow bed (40 cm bed and 30 cm furrow)	Yes; maize residue
PBB	Zero tillage	Permanent broad bed (110 cm bed and 30 cm furrow)	No	Zero tillage	Permanent broad bed (110 cm bed and 30 cm furrow)	No
PBB + R	Zero tillage	Permanent broad bed (110 cm bed and 30 cm furrow)	Yes; wheat residue	Zero tillage	Permanent broad bed (110 cm bed and 30 cm furrow)	Yes; maize residue
*ZT + R	Zero tillage	Plain/flat land	Yes; wheat residue	Zero tillage	Plain/flat land	Yes; maize residue
*ZT	Zero tillage	Plain/flat land	No	Zero tillage	Plain/flat land	No

*Introduced from the second year (2011-12) of the experiment.

2932) was sown on 01.11.2010, 05.11.2011 & 02.11.2012 under ZT, and on 12.11.2010, 15.11.2011 & 15.11.2012 under CT conditions, which indicates that the sowing of wheat under CT was delayed by almost 10-15 days.

A treatment/plot of PNB and PBB had 12 and 6 raised beds, respectively. There were 12 rows of maize on 12 narrow beds at 70 cm row-space ($\sim 12 \times 0.7 = 8.4$ m) in each plot of PNB; and 12 rows of maize on 6 broad beds ($6 \times 1.4 = 8.4$m) in each plot of PBB. But, there were 36 rows of wheat on 12 narrow beds in each plot of PNB (with spacing 14 cm between 3 rows in each narrow bed), and 30 rows of wheat on 6 broad beds at 20 cm row-space in each plot of PBB. In CT and ZT plots, there were 12 rows of maize at 70 cm, and 42 rows of wheat at 20 cm row-space. Both maize and wheat crops were sown using a turbo seeder (for PBB, PBB + R, ZT & ZT + R plots), a bed planter (for PNB & PNB + R plots), and a seed drill (for CT plots). The turbo seeder and bed planter had a fertilizer box attached for placing fertilizer in soil, and the fertilizers required for basal application were placed. A common dose of 120 kg N, 60 kg P_2O_5, 40 kg K_2O ha^{-1} was applied to both maize and wheat crops. In both crops, the full dose of P and K and half dose of N were applied as basal at the time of sowing using turbo seeder/bed planter (in PNB, PBB, ZT) and by broadcasting (in CT). Remaining N was top-dressed in two equal splits (at 30 and 60 DAS in maize; after first and second irrigation in wheat). During top-dressing, fertilizers were broadcasted, and care was taken to apply fertilizers along the crop rows and on the beds, leaving the furrows.

Herbicide glyphosate [N-(phosphonomethyl) glycine] was sprayed at 1.0 kg ha^{-1} in ZT plots about a week before sowing of maize and wheat crops for controlling existing weeds. Further, an application of the tank-mixture of atrazine (2-chloro, 4-isopropylamino, 6-ethylamino-1,3,5-*s*-triazine) at 0.75 kg ha^{-1} and pendimethalin (N-(1-ethylpropyl)-2,6-dinitro-3,4-xylidine) at 0.75 kg ha^{-1} was made in maize within 2–3 days of sowing for controlling annual weeds that might be germinating after maize was sown (Das, 2008). In wheat, isoproturon (N,N-dimethyl-N'-[4-(1-methylethyl)phenyl]urea) at 1.0 kg ha^{-1} was applied at 30 days after sowing for broad-spectrum weed control. No fungicide, but insecticide carbofuran 3G @ 25 kg ha^{-1} was used to control stem borer and shoot fly in maize. No fungicides/insecticide was applied to wheat.

2.4. Measurement of grain, stover/straw yield and system productivity

Grain yields of maize and wheat were recorded at 12% moisture. Maize stover and wheat straw yields were determined after oven-drying the stover/straw samples at 70 °C to a constant weight and expressed on an oven dry-weight basis. In every year, matured maize and wheat plants were harvested manually from the net plot areas (after discarding the border rows) in second week of October and second week of April, respectively, for determining grain and stover/straw yields. The net plot area was equal for every treatment, but the number of rows of crops that were harvested varied, depending on crops and land configuration/planting geometry. For measuring maize yield, central four rows/narrow beds up to a 5 m length (4×0.7 m $\times 5$ m $= 14$ m^2) were harvested manually from the PNB plots; and central four rows/two broad beds up to a 5 m length (14 m^2) from the PBB plots. For measuring wheat yield, four central narrow beds (2.8 m × 5.0 m) with 3 wheat rows in each bed (i.e. 12 wheat rows) were harvested manually from the PNB plots; and two central broad beds with 5 wheat rows in each bed (i.e. 10 wheat rows) from the PBB plots. But, for ZT and CT plots, maize (4 rows) and wheat (14 rows) were harvested from 2.8 m × 5.0 m area for yield measurement. Then, in all residue retention plots, maize crop was cut manually at about 40 cm height, and wheat crop was harvested with a combine harvester about 40 cm above the ground level. For residue removal and CT plots, maize and wheat crops were harvested manually by cutting the bases of plants at around 3–4 cm above soil. Maize grains after shelling, and wheat grains after threshing, were cleaned and weighed for their yields. Maize yield was converted into wheat equivalent yield (WEY) using Eq. (1). The minimum support prices of maize and wheat, declared by the Government of India (GOI, 2017) were used to determine the WEY of maize. The sum of wheat yield and WEY of maize was the system productivity.

$$\text{WEY} = [(\text{Maize yield} \times \text{Price of maize})/(\text{Price of wheat})] \quad (1)$$

2.5. Measurement of irrigation water, total water applied and water productivity

In 2011-12, five irrigations for maize and five irrigations for wheat, excluding the pre-sowing irrigation, were applied, whereas, in 2012-13, six irrigations for maize and five irrigations for wheat were applied. The irrigation water depth applied to each experimental plot was measured on an average four times during each irrigation period using a digital velocity meter and the wetted area of the field channel. A rating curve was generated at the beginning of the experiment, showing the relationship between flow depth and discharge in the main channel. Then, an exponential equation was developed. Afterwards, flow depth was measured at the time of irrigation in the channel and corresponding discharge was determined using the rating curve.

Soil moisture contents up to crop root zone were monitored periodically for deciding the date and quantity of irrigation water during the crop growth period. Soil moisture was measured periodically before the date of irrigation application up to the effective root zone. Root zone depth was taken as per the standard information available in literature at different growth stages. The date of irrigation was decided when the soil moisture of the root zone was reached at 50% of the total available water. Irrigation water depth in each treatment was calculated using soil moisture content before irrigation and root zone depth of plants using Eq. (2) (Michael, 2008).

$$\text{SMD} = (\theta_{Fc} - \theta_i) \times D_{RZ} \times B_d \quad (2)$$

where, SMD: soil moisture deficit (mm), θ_{Fc}: soil water content at field capacity (%), θ_i: soil water content before irrigation (%), D_{RZ}: root zone depth (mm), B_d: soil bulk density (Mg m^{-3}). Soil moisture content at any time was measured by a Time Domain Reflectometer (TDR) that was calibrated previously using the gravimetric method. Daily rainfall data were collected from a rain gauge located at about 500 m away from the experimental plots. Effective rainfall was calculated using standard methods (given by FAO) and then total amount of water applied was computed as the sum of water applied through irrigations and effective rainfall. Water productivity (kg grains ha^{-1}mm^{-1} of water) was computed using Eq. (3) as given by Bhushan et al. (2007):

$$\text{Total water productivity} = [\text{Grain yield}(\text{kg ha}^{-1}) / \text{Total water applied}(\text{mm})] \quad (3)$$

2.6. Estimation of crop evapo-transpiration

Soil water budget method was used to estimate actual crop evapo-transpiration (ETa). The components of water balance equation for a control volume of soil profile up to root zone depth were measured using Eq. 4.

$$ET_c = P + IR + C_p - D_p - R_o \pm \Delta W \quad (4)$$

where, ET_c is crop evapo-transpiration (mm), P is precipitation (mm), IR is total irrigation depth (mm), C_p is capillary contribution from ground water table to the crop root zone (mm), D_p is deep percolation losses (mm), R_o is runoff (mm) and ΔW is the change in soil water content (mm). The experimental plots were surrounded by bunds and the water table depth was below 4 m from the soil surface. Therefore, the surface runoff and vertical/upward seepage or the capillary flow to the root zone was assumed negligible in the calculation of ET using Eq. (4). Besides, the drainage below root zone, after a number of soil-water

Table 2
Productivity of maize and wheat as affected by conservation agriculture-based practices in maize-wheat cropping system.

Treatment†	2010 – 11		2011 – 12		2012 – 13	
	Maize grain yield (t ha^{-1})	Wheat grain yield (t ha^{-1})	Maize grain yield (t ha^{-1})	Wheat grain yield (t ha^{-1})	Maize grain yield (t ha^{-1})	Wheat grain yield (t ha^{-1})
CT	2.64c	5.14a	2.76d	4.84ab	4.52b	4.88ab
PNB	2.92bc	4.70a	2.93 cd	4.49b	4.98ab	4.72b
PNB + R	3.06ab	4.85a	3.12c	4.68ab	5.21a	5.02ab
PBB	3.33a	5.09a	3.63b	4.55b	5.08ab	4.93ab
PBB + R	3.40a	5.11a	3.95ab	4.98a	5.36a	4.88ab
*ZT + R	–	–	4.28a	4.84ab	4.84b	5.18a
*ZT	–	–	4.04a	4.62ab	4.61b	4.87ab

†See Table 1 for treatment details. Means followed by a similar letter within a column are not significantly different at $P < 0.05$ according to Tukey's HSD test. *Introduced from the second year of the experiment

content measurements, was considered to be negligible. Therefore, Eq. (4) was modified to Eq. (5) given below:

$$ETc = P + IR \pm \Delta W \tag{5}$$

The mentioned field water budgeting is commonly used to measure actual water use or crop evapo-transpiration when lysimetric facilities are not available (Farahani et al., 2009).

2.7. Estimation of soil organic carbon pool

The C pools of soil in 0–5, 5–15 and 15–30 cm soil layers were computed on equivalent mass basis using the following equation (Whalen et al., 2008; Wendt and Hauser, 2013).

$$\text{SOC pool } (\text{Mg ha}^{-1}) = [\text{SOC}_{con} \times \rho_b \times (T + T_{add}) \times 10000 \times 0.001]\ \text{mg kg}^{-1} \tag{6}$$

Where, SOC_{con} (concentration) was expressed as kg C Mg^{-1} soil; T, thickness of soil layer (m); T_{add}, additional thickness (m); ρ_b, bulk density of soil layer (Mg m^{-3})

The C concentration was measured by a TOC analyzer. Additional thickness of sampling required for a treatment (Tadd) was determined using the following equation

$$T_{add} = (\text{Msoil, equivalent} - \text{Msoil, sample}) \times 0.0001\ \text{ha m}^{-2} / \rho_{b,sample} \tag{7}$$

Where, Msoil, sample (i.e. the actual mass of the sample soil computed using its bulk density

$$(\text{Mg ha}^{-1}) = \text{depth (m)} \times \rho_{b\ sample}(\text{Mg m}^{-3}) \times 10000 \tag{8}$$

Msoil, equivalent = the equivalent mass of the reference soil (Mg ha^{-1})

The carbon sequestration potential was computed based on the differences in SOC pool between the CA treatments and CT (~control)

2.8. Crop production economics

Machine and human labour uses were recorded in both maize and wheat crops for various field operations like tillage (for CT), sowing, irrigation, fertilization, pesticide/herbicide application, harvesting, and threshing. Eight working hours were considered equivalent to 1 manday for calculating the cost of human labourers. In case of tractor-drawn machines, time taken to complete a field operation, such as tillage, sowing, harvesting was recorded to determine hiring cost. The costs of cultivation of treatments were estimated based on prevailing market costs of inputs/operations, which included seeds, fertilizers, pesticides, hiring charges of human labourers and machines for irrigation, fertilizers and pesticides application, harvesting, threshing, etc. Measurement also included the cost of residues for residue retention treatments. The minimum support prices (MSP) of maize and wheat grains, declared by the Government of India (GOI, 2017) were used for calculating the gross returns. The net returns ha^{-1} was worked out by deducting the total cost of cultivation from the gross returns. The costs/prices (Rs ha^{-1}) were converted to USD ($) ha^{-1} in respective years.

2.9. Statistical analyses

In this study, the objective was to compare the performances of different CA-based systems, involving tillage, residue and land configuration with that of a CT system. Individual components within the CA systems such as tillage (CT vs. ZT), residue (Retention vs. removal) and land configuration (raised bed planting vs. flat planting) were not analyzed as there were no sufficient equally-replicated data for contrast analysis. Therefore, data on grain and stover/straw yields of maize and wheat crops, water productivity, carbon accumulation, economics were analyzed using the analysis of variance (ANOVA) for randomized complete block design, involving 5 (in first year) and 7 (in second and third year) treatments (Gomez and Gomez, 1984). The significance of difference between treatment means was tested by the variance ratio (~F-value) at $P < 0.05$. Tukey's honestly significant difference (HSD) test was used as a post hoc mean separation test ($P < 0.05$) using SAS 9.1 (SAS Institute, Cary, NC). The Tukey's procedure was used where the ANOVAs of variables studied were significant. The year x treatment interactions were significant for the variables studied. Therefore, mean effects are presented year-wise and discussed.

3. Results

3.1. Maize and wheat crop productivity and system productivity

There was significant effect of CA on maize yield in all the three years of study (Table 2), but the effect was significant from the second year onwards in wheat crop. In first year, significantly higher maize yield was recorded in PBB + R (3.40 t ha^{-1}) compared to CT (2.64 t ha^{-1}). The increases in maize grain yields due to the PBB + R and PNB + R were 28.8 and 15.9%, respectively, than CT (farmers' practice) in this year. The ZT and ZT + R treatments were adopted from the second year. In second year, the ZT (with and without residue), PBB (with and without residue) and PNB (with residue) treatments resulted in significantly higher maize grain yields than CT plots (Table 2), and the increases in yields were 51, 37 and 13%, respectively in ZT (with and without residue), PBB (with and without residue) and PNB (with residue), respectively. Whereas, in the third year, PBB plots (with and without residue) resulted in higher maize yield by 16% compared to farmers' practice, followed by 13% higher yield obtained under ZT (with and without residue). Residue retention enhanced grain yield by 12% in second year over residue removal treatments. On an average, ZT plots recorded 39 and 11% higher maize grain yield than CT in second and third year, respectively. All ZT raised beds or flat planting plots resulted in significantly higher maize straw yields than CT plots, except PNB in 2011-12, and PBB in 2012–12 (Table 3).

Wheat grain and straw yields (Tables 2 and 3) did not follow a similar trend over the years. Highest grain yield was recorded in PBB + R (4.98 t ha^{-1}) followed by CT and ZT + R (4.84 t ha^{-1}) in second year, but in third year, highest grain yield was recorded in ZT + R (5.18 t ha^{-1}). Highest wheat straw yield was recorded in PNB + R in second year, but in third year, straw yield was highest in ZT. Wheat grain and straw yields in first year were similar in all the treatments, i.e. PNB (with and without residue), PBB (with and without residue), ZT (with and without residue) and CT (farmers' practice). Similarly, averaged over last two years, wheat yield/productivity (Fig. 1) was non-significant between tillage and bed planting methods. But, two-

Table 3
Stover/straw yields of maize and wheat as affected by conservation agriculture-based practices in maize-wheat cropping system.

Treatment[†]	2010 – 11		2011 – 12		2012 – 13	
	Maize stover yield ($t\ ha^{-1}$)	Wheat straw yield ($t\ ha^{-1}$)	Maize stover yield ($t\ ha^{-1}$)	Wheat straw yield ($t\ ha^{-1}$)	Maize stover yield ($t\ ha^{-1}$)	Wheat straw yield ($t\ ha^{-1}$)
CT	6.47c	7.95a	8.48c	7.50b	8.28c	8.75b
PNB	6.56c	7.02a	9.16c	7.03b	6.81d	8.14bc
PNB + R	8.38b	7.14a	11.11ab	8.37a	9.99b	7.30c
PBB	7.90ab	7.71a	10.84b	7.40b	8.61c	7.45c
PBB + R	9.10a	7.81a	12.01a	8.21a	11.41a	7.95bc
*ZT + R	–	–	11.96a	7.33b	12.05a	10.19a
*ZT	–	–	10.76b	7.38b	9.93b	10.03a

[†] See Table 1 for treatment details. Means followed by a similar letter within a column are not significantly different at $P < 0.05$ according to Tukey's HSD test. *Introduced from the second year of the experiment

year mean maize productivity differed significantly between them, and the PBB + R treatment resulted in significantly higher maize productivity than CT and PNB (with and without residue) treatments (Fig. 1). This led to significantly higher two-year mean maize-wheat system productivity in PBB + R treatments than in CT and PNB plots.

3.2. Water application and productivities in maize and wheat

Total irrigation water productivity of both crops varied significantly across treatments and years (Tables 4 and 5). The plots under PBB + R resulted in reduction in two-year mean irrigation water application by 14% (130 mm ha^{-1} in two years), and increased two-year mean water productivity of maize crop by 57% than CT. Averaged among residue management treatments, residue retention improved water productivity by 9% and reduced irrigation water requirement by 62 mm ha^{-1} in two years in maize. In wheat, two-year mean water applied in the plots under CT and ZT were similar and all other plots received significantly less water, with 14% water saving. Plots with PBB + R had about 16% higher mean water productivity in wheat crop than CT plots (Table 5). The partial residue retention (~40% of both maize and wheat) significantly improved two-year mean total water productivity in wheat crop under ZT plots (Table 5).

3.3. Economics

The cost of cultivation in the maize-wheat system was significantly affected by tillage and residue management practices in both years (Table 6). The cost of cultivation was lowest in ZT in both years (703–704 US$ ha^{-1}) followed by PNB and PBB (713–714 US$ ha^{-1}). The costs of cultivation were lower in these production systems compared to conventional farmers' practice, due to saving in cost of tillage and irrigation water. The cost of cultivation in maize-wheat system was higher in residue retained (879–938 US$ ha^{-1}) than residue removal plots. On an average, the cost of cultivation of residue-retained plots was 28 and 20% higher than ZT and CT plots, respectively. Considering maize-wheat system as a whole, higher net returns were obtained in ZT, ZT + R and PBB plots compared with CT. The net returns varied from (622- 2050 US$ ha^{-1}), and were recorded higher in the third year than the second year, due to increase in the minimum support price (MSP) in India. Two-year mean net returns were significantly higher in ZT compared to CT, PNB and PNB + R plots. The net returns accrued from ZT + R, PBB and PBB + R treatments were comparable with this. The ZT treatment recorded 18% higher two-year mean net returns than CT.

3.4. Soil organic carbon pool

The tillage, residue and bed planting significantly influenced soil organic carbon (SOC) concentration and soil organic carbon pool (on equivalent mass basis) at 0–5, 5–15 and 15–30 cm soil depths (Table 7). There was decline in SOC concentration with the increase in soil depth. Retention of crop residues has significantly improved the SOC concentration in the top 0–5 cm soil layer by ~4.6%. The total SOC pool in the 0–30 cm soil layer improved by ~4.5% in plots with residue retention compared to residue removal plots. Maximum SOC pool was registered under PBB + R treatment (34.4 Mg ha^{-1}), which was significantly higher than the conventional tillage system (28.8 Mg ha^{-1}) by 19.4%. Permanent narrow bed and permanent broad bed systems registered higher SOC pool than that of the conventional tillage system but were at par with the zero tillage system. Conservation agricultural practices registered significantly higher SOC concentration and SOC pool than that of the conventional tillage system. The carbon sequestration potential ranged from 2.54 Mg ha^{-1} (PNB) to 5.59 Mg ha^{-1} (PBB + R). Application of crop residue mulch has improved the carbon sequestration potential both in the permanent narrow bed and broad bed system. Permanent broad bed system was superior to permanent narrow bed system with respect to carbon sequestration potential irrespective of the residue retention.

4. Discussion

Continuous rice-wheat cropping system in the IGP has resulted in the deterioration of soil health and decline in factor productivity (Chaudhary and Harrington, 1993). In the North-western IGP, rice-wheat is the pre-dominant cropping systems. But over the last six decades, this cropping system has led to over-exploitations of natural resources, degradation of soil health and enhanced global warming

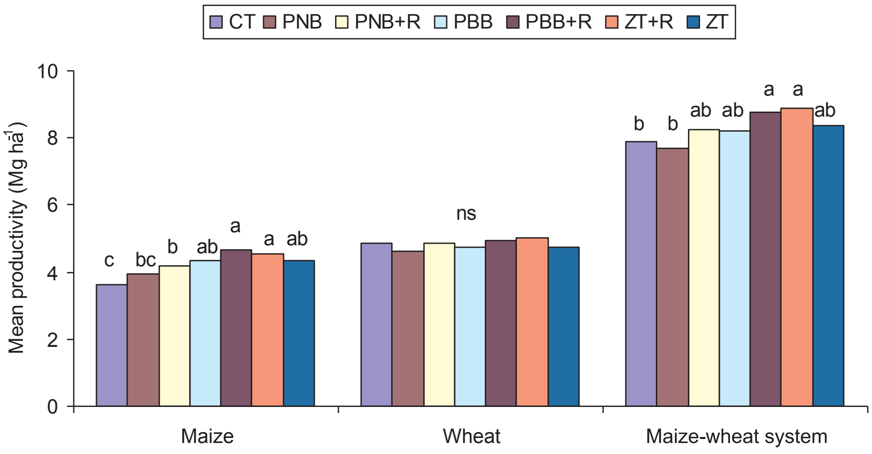

Fig. 1. Conservation agriculture effects on mean productivities (of 2011–12 and 2012–13) of maize, wheat and maize-wheat system. The maize-wheat system productivity was expressed in wheat-equivalent yield ($t\ ha^{-1}$). See Table 1 for treatment details; treatment bars followed by a different letter within a group are significantly different at $P < 0.05$ according to Tukey's HSD test; ns = non-significant at $P < 0.05$).

Table 4
Impacts of conservation agriculture on irrigation water productivity in maize crop under a maize-wheat system.

Treatment[†]	2011 – 12		2012 – 13		Mean of two years	
	Irrigation water (mm) applied	Water productivity (kgha^{-1}mm^{-1})	Irrigation water applied (mm)	Water productivity (kg ha^{-1}mm^{-1})	Irrigation water applied (mm)	Water productivity (kg ha^{-1}mm^{-1})
CT	556.4a	4.96d	506.6a	8.92d	531.5a	6.94d
PNB	523.4ab	5.60 cd	470.6ab	10.58bc	497.0ab	8.09c
PNB + R	517.4ab	6.03c	462.6ab	11.26b	490.0ab	8.65abc
PBB	511.4ab	7.10b	454.6b	11.17b	483.0b	9.14b
PBB + R	499.4b	7.91a	434.6b	12.33a	467.0b	10.12a
ZT + R	532.4ab	8.04a	478.6ab	10.11c	505.5ab	9.08b
ZT	541.4ab	7.46ab	490.6ab	9.40 cd	516.0ab	8.43abc

[†] See Table 1 for treatment details. Means followed by a similar letter within a column are not significantly different at $P < 0.05$ according to Tukey's HSD test.

Table 5
Impacts of conservation agriculture on irrigation water productivity in wheat crop under a maize-wheat system.

Treatment*	2011 – 12		2012 – 13		Mean of two years	
	Irrigation water applied (mm)	Water productivity (kg ha^{-1}mm^{-1})	Irrigation water applied (mm)	Water productivity (kg ha^{-1}mm^{-1})	Irrigation water applied (mm)	Water productivity (kg ha^{-1}mm^{-1})
CT	454ab	10.66c	552a	8.84c	503.0a	9.75bc
PNB	398b	11.28bc	488bc	9.67b	443.0b	10.48b
PNB + R	405b	11.56bc	480bc	10.46a	442.5b	11.01ab
PBB	391c	11.64b	468bc	10.53a	429.5b	11.09ab
PBB + R	405b	12.30ab	448c	10.89a	426.5b	11.60a
ZT + R	384c	12.60a	520ab	9.96ab	452.0b	11.28a
ZT	489a	9.45d	536a	9.09c	512.5a	9.27c

*See Table 1 for treatment details. Means followed by a similar letter within a column are not significantly different at $P < 0.05$ according to Tukey's HSD test.

Table 6
The cost of cultivation and net returns (US$ ha^{-1}) due to different conservation agriculture-based treatments under an irrigated maize-wheat system.

Treatment*	2011–12 **		2012–13**		Mean of two years	
	Cost of cultivation (US $ ha^{-1})	Net returns (US $ ha^{-1})	Cost of cultivation (US $ ha^{-1})	Net returns (US $ ha^{-1})	Cost of cultivation (US $ ha^{-1})	Net returns (US $ ha^{-1})
CT	744b	742c	769b	1757b	757b	1250c
PNB	714b	725c	713b	1955ab	713b	1340bc
PNB + R	889a	622d	938a	2050a	913a	1336bc
PBB	714b	853b	713b	2028a	713b	1440a
PBB + R	889a	821b	938a	1981ab	913a	1401ab
ZT + R	879a	856b	928a	2033a	903a	1445a
ZT	704b	945a	703b	1999ab	703b	1472a

*See Table 1 for treatment details. Means followed by a similar letter within a column are not significantly different at $P < 0.05$ according to Tukey's HSD test. **60 INR (Indian Rupee) = 1US$ in 2012-13; 55 INR (Indian Rupee) = 1US$ in 2011–12.

Table 7
Impacts of conservation agriculture on total organic carbon content, total soil organic carbon pool (equivalent mass basis) and C-sequestration potential in a maize-wheat system (after three years).

Treatment*	Total organic carbon (g kg^{-1})			Total soil organic carbon pool (Mg ha^{-1})				C-sequestration potential (0–30 cm) (Mg ha^{-1})
	0–5 cm	5–15 cm	15–30 cm	0–5 cm	5–15 cm	15–30 cm	0–30 cm	
CT	7.02c	5.88c	4.73b	5.82c	10.66c	12.36c	28.84c	–
PNB	7.37b	6.79b	4.95b	6.12b	12.32b	12.94b	31.38b	2.54c
PNB + R	7.50ab	7.18ab	5.57a	6.22b	13.02ab	14.56a	33.80ab	4.96ab
PBB	7.53ab	7.16ab	5.46a	6.25b	12.99ab	14.27ab	33.51ab	4.67ab
PBB + R	7.75ab	7.58a	5.45a	6.43a	13.75a	14.25ab	34.43a	5.59a
ZT + R	8.28a	7.10ab	5.54a	6.87a	12.88ab	14.48a	34.23a	5.39a
ZT	7.58ab	6.66b	5.67a	6.29ab	12.08b	14.82a	33.19ab	4.35b

*See Table 1 for treatment details. Means followed by a similar letter within a column are not significantly different at $P < 0.05$ according to Tukey's HSD test.

(Saharawat et al., 2010; Das et al., 2013, 2014). In the rice-wheat system, wheat straw is mostly removed from the fields as a dry fodder for the livestock, whereas rice straw is burnt in the fields due to short time lapse between rice harvest and wheat seeding (Gupta and Seth, 2007). Maize is a high input-responsive crop with higher yield potential. It requires much less irrigation water than both direct-seeded and puddled transplanted rice. Puddling in rice and entire biomass removal with intensive tillage cause loss of carbon and other nutrients (Beri et al., 2003) and development of water repellency in soil (Passioura, 2002; Singh et al., 2005). Moreover, continuous pumping of groundwater over the years to meet the high water requirement of 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. To address these issues, this long-term field experiment was initiated on a sandy clay loam soil of western IGP under different CA practices in the maize-wheat cropping system, where all the three principles of CA (zero tillage, residue retention and crop rotation) along with raised bed and flat planting were evaluated. Thus, crop residues were recycled with the specific aim for soil and water conservation and improved crop productivity.

In accordance to the envisioned hypothesis, maize-wheat system may potentially replace the rice-wheat system with the adoption of CA, particularly ZT and permanent beds with residue retention. These practices enhanced maize productivity alternatively leading to higher maize-wheat system productivity compared with conventional farmers' practice and residue removal condition for all three years. Wheat grain yield also improved gradually under CA practices, but varied over the years. Although not a consistently significant variation, in this study, PBB + R plot was superior to PNB + R on maize and wheat yields. Under PBB + R, two rows of maize having been sown on the edges of beds/near to the furrows, might not have experienced water stress. Supplemental occasional rainfall could mitigate the stress, if at all observed. Residue retention was better under PBB through even distribution of residue on top of the broad beds compared to PNB. This led to better infiltration and conservation of water on beds, less run-off and erosion, better temperature moderation, weed control, and higher soil microbial activity leading to biological tillage under PBB compared to PNB. This led to higher numbers of tillers of wheat per unit area in permanent broad beds (data not shown) than narrow beds. Further studies on photosynthesis, light interception, root water uptake, nutrient load and radiation-use efficiency *vis-a-vis* crop geometry under different bed configurations would help understand the crop productivity better (Das et al., 2014).

Three rows of wheat were sown at around 14 cm spacing on each narrow bed by a bed planter, specially designed for this purpose, called DWR Planter, developed by Indian Institute of Wheat and Barley Research (IIWBR), Karnal, Haryana, India (previously Directorate of Wheat Research (DWR). This might have led to over-crowding of wheat plants due to narrower row-spacing and considerable reduction in tillering (Das and Yaduraju, 2012). This has, however, better smothering ability of weeds that exist on the beds. Recently, two-row system of narrow-bed planting has been found to be better (Sayre et al., 2005). This should be studied and validated in the IGP of India. However, contrasting results were obtained under conventional till flat-sown conditions. Das and Yaduraju (2011) observed that sowing two rows and then providing gaps of one unsown row of wheat (i.e. missing one row from sowing after every two rows of wheat sown) was inferior to the treatments of missing one row after every four rows of wheat sown, and normal-sown wheat (without any missing row), due to significant reduction in number of rows of wheat sown per ha. The border effect was not enough to compensate this.

Earlier Das et al. (2014) observed that the best treatment, PBB + R required 14% less water, but produced 48% higher system productivity and 36% higher net returns than CT plots in the cotton-wheat system. Under the maize-wheat system also, the PBB + R plots resulted in 10% higher two-year mean system productivity (Fig. 1) and 29% higher water productivity (mean of two crops) and 12% higher net returns compared with CT plots. Plots under ZT + R also resulted in 24 and 16% higher water productivity and economic profitability, respectively, than CT plots. Thus, long term performance analysis of the PBB + R versus ZT + R management practice is a researchable issue in the maize-wheat system. Five rows of wheat were sown using a turbo seeder on each of the broad beds at 20 cm spacing. The central third row of wheat on the broad bed from either furrow usually experiences mild water stress (Authors' visual observations), depending on rainfall received, and how furrows are irrigated. Intermittent rainfall received during winter can mitigate the water stress. Full furrow irrigation, instead of ¾ full furrow irrigation (as usually suggested), can reduce this effect. Water stress effect on wheat plants of the central third row was hardly distinguishable from the plants of adjacent rows under residue-retained broad beds (PBB + R), but was noticeable under PBB plots without residue. Lower wheat yields obtained in PBB than PBB + R plots (Table 2) is a proof. Upon using tractor with broad tyres, the outermost one row of wheat on either side of the beds are subject to slight compaction under PBB and PNB plots, and wheat germination/emergence is slightly affected. The compaction effect on wheat germination can be minimized to a large extent by providing anchored residue, and maintaining optimum soil moisture at sowing time.

We observed that the increase in water productivity was the resultant of both increases in maize/wheat yields and savings in irrigation water. Under the broad beds treatments, the numbers of beds and furrows were 6 and 7, respectively per plot, whereas in case of narrow beds, the numbers of beds and furrows were 12 and 13, respectively per plot (~9.0 m × 8.4 m). The dimension of furrows being equal, the total amount of water applied in a given plot area was higher in narrow beds than broad beds. This, combined with higher yields of maize and wheat, contributed to higher water productivity under PBB plots than PNB plots. The mean water productivity of both crops with residue retention plots (~PNB + R, PBB + R and ZT + R) was higher than the residue removal treatments (~PNB, PBB and ZT). This was mainly attributed to less irrigation water use with residue retention than residue removal, and higher productivity with residue retention compared with the residue removal plots. With respect to net returns, it was observed that, the CA-based ZT + R, PBB + R, and PNB + R had slightly lower net returns than that accrued from their respective no-residue plots (i.e., ZT, PBB and PNB). The residue, which was retained involved cost and increased the cost of production and, thereby, reduced the net returns. However, higher biomass (stover/straw) yields under the CA-based ZT + R, PBB + R, and PNB + R plots compared to their respective no-residue plots could greatly compensate for the cost of residue, and the net returns was insignificantly reduced, indicating the second hypothesis that residue retention would improve yield, water productivity and net returns over the residue removal plots was partially accepted.

Retention of crop residues significantly improved the SOC concentration in the top 0–5 cm soil layer, could be due to addition of carbon through both-season crops residue. All the CA-based practices significantly improved the SOC pool at 0–30 cm soil depth than conventional till system or farmers' practice. But, the PBB + R treatment was most superior and resulted in significantly higher SOC pool than CT. This had higher carbon sequestration potential than even the zero till permanent narrow bed with residue (PNB + R). Mikha et al. (2013) observed that the SOC concentration in 0–30 cm depth increased by 19.7% in a Weld silt loam soil under CA after seven years (2001–2008). Standardizing the soil mass of 2001 to the equivalent soil mass (ESM) of 2008 for each treatment showed an average gain in SOC by 5.8 Mg C ha^{-1} (range 3.3 for mixed red and broad-leaved crops under chisel phoughing to 9.8 Mg C ha^{-1} for continuous corn crop under no tllage). The gain in SOC pool reported in this experiment is agreement with the present study (mean gain of 4.58 Mg C ha^{-1}). Retention of residues significantly improved the carbon sequestration potential in the permanent narrow bed, permanent broad bed, and zero-till planting (ZT + R). This supports our third hypothesis that conservation agriculture practices can lead to carbon sequestration and improve soil health, which, in turn, cause improved crop productivity and water productivity under conservation agriculture than conventional agriculture practice. We included three basic principles of CA: minimum soil disturbance, permanent soil cover, and crop rotation, involving maize and wheat. However, horizontal crop intensification of the maize-wheat rotation with inclusion of a legume (for cover crops, green or brown manures) could have been an ideal CA in this clay loam soil. In a sandy loam soil in the western IGP of India, Saad et al. (2015) reported that crop intensification through maize-wheat-green gram rotation was more remunerative. Besides, vertical intensification through inter-cropping of legumes (green gram, soybean, cowpea, blackgram) with maize (having wider spacing) can be studied for a more sustainable CA-based maize-wheat production system in the IGP of India.

5. Conclusion

This study shows that conservation agriculture-based permanent beds with residue retention or zero tillage with residue retention resulted in higher water productivity and crop & system productivities than conventional tillage (farmers' practice) in maize-wheat rotation. These practices led to more carbon sequestration and augment soil organic carbon build-up compared to residue removal plots under zero till raised beds (broad and narrow), and conventional tillage. The permanent broad bed and zero tillage with residue, on net returns, were superior to conventional tillage and permanent narrow beds with and without residue, despite the fact that residue involved cost. These results are novel and can be of immense importance to the IGP of India, which, being dominated with rice-wheat cropping system, suffers from multiple problems of yield stagnation, low input-use efficiencies, declining ground water table, depleting soil organic carbon and deterioration of soil health. These practices can be recommended for adoption under the maize-wheat cropping system in Indian IGP and similar agro-ecologies of the tropics and sub-tropics under irrigated conditions. Adopting permanent broad bed and zero tillage with residue can be an important adaptation-led mitigation strategy to climate change in Indian IGP. Possible synergies between planting geometry, zero tillage, permanent bed, residue (characterization and quantification) and cropping systems needs further studies across locations for site-specific alterations/refinement in CA practices. However, the long-term impact on productivity, profitability and soil health of these practices under this cropping system is a researchable issue. Horizontal crop intensification with inclusion of legume, particularly summer green gram, cowpea in between wheat and maize cropping seasons (not studied here) or vertical intensification through inter-cropping of green gram, soybean, cowpea, black gram with maize (having wider spacing) need to be studied for developing a more sustainable CA-based maize-wheat production system.

Acknowledgements

The authors gratefully acknowledge the supports and services received from the ICAR-Indian Agricultural Research Institute, New Delhi for successful conduct of this research work under the 'Challenge Programme on Conservation Agriculture'.

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