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Long term effect of conservation agriculture in maize rotations on total organic carbon, physical and biological properties of a sandy loam soil in north-western Indo-Gangetic Plains

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ABSTRACT

Maize-based crop rotations are advocated as alternate to rice-based systems in South Asia due to better suitability for diverse ecologies, higher yields with less water use and more palatable maize fodder compared to rice, and increased demand of maize from piggery and poultry industries. Alternate tillage and crop establishment practices are important management strategies for tackling the issues of soil health deterioration and over exploitation of underground water resources, particularly in rice based intensive crop rotations. The conservation agriculture (CA) based tillage and crop establishment practices such as zero tillage (ZT) and permanent raised beds (PB) hold potential to enhance soil organic carbon (SOC), physical and biological properties for sustainability of soil health. Therefore, a long term study was conducted to evaluate the twelve combinations of tillage practices (03) and irrigated intensive maize based crop rotations (04) on organic carbon, physical properties and microbial biomass and enzymatic activities of a sandy loam (Typic Haplustept) soil in north-western India. The tillage practices consisted of ZT, PB and conventional tillage (CT) in main plots and four diversified intensive maize based crop rotations (MWMb: Maize-Wheat-Mungbean, MCS: Maize-Chickpea-*Sesbaina*, MMuMb: Maize-Mustard-Mungbean, MMS: Maize-Maize-*Sesbania*) in sub plots. In this study we analysed the SOC, physical and biological properties of soil at various depths after 7 years of continuous ZT, PB and CT in diversified maize rotations. Compared to CT plots, the soil physical properties like water stable aggregates (WSA) > 250 μm were 16.1-32.5% higher, and bulk density (BD) and penetration resistance (PR) showed significant ($P < 0.05$) decline (11.0–14.3 and 11.2–12.0%) in ZT and PB plots at 0–15 and 15–30 cm soil layers. The soil organic carbon (SOC) increased by 34.6-35.3% at 0–15 cm, and 23.6-26.5% at 15–30 cm soil depths with conservation agriculture (ZT and PB) based crop establishment techniques over CT. Similarly, the soil microbial biomass carbon (MBC) under CA based systems increased by 45–48.9% in 0–30 cm profile depth of a sandy loam (Typic Haplustept) soil. Significant ($P < 0.05$) improvement in soil enzymatic activities i.e., Fluorescein diacetate, dehydrogenase, βGlucosidase and Alkaline phosphatase was also recorded in the CA based treatments. Significant ($P < 0.05$) synergistic effects of summer legumes (mungbean and *Sesbania*) with winter legume/cereal in crop rotations were observed on SOC, WSA, BD, PR and K_{sat} at 0–15 and 15–30 cm depths. Interaction between tillage and crop rotations were significant ($P < 0.05$) for soil organic carbon, physical properties and enzymatic activities. Thus our long-term study suggests that CA based crop management

Abbreviations ALP alkaline phosphatase activity; BD bulk density; BG ß Glucosidase activity; CA conservation agriculture; CT conventional tillage; DHA dehydrogenase activity; FDA Fluorescein diacetate hydrolysis activity; GMD geometric mean diameter; ICAR Indian Council of Agricultural Research; IGP Indo-Gangetic Plains; K_{sat} saturated hydraulic conductivity; MBC microbial biomass carbon; MCS maize (*Zea mays* L.)-chickpea (*Cicer arietinum* L.)-sesbaina (*Sesbania acculata*); MMuMb maize (*Zea mays* L.)-mustard (*Brassica juncea*)-mungbean [*Vigna radiata* (L.) Wilczek]; MMS maize (*Zea mays* L.)-maize (*Zea mays* L.)-sesbania (*Sesbania acculata*); MWMb maize (*Zea mays* L.)-wheat (*Triticum aestivum* L.)-mungbean [*Vigna radiata* (L.) Wilczek]; MWD mean weight diameter; PB permanent raised bed; PR soil penetration resistance; SCL sandy clay loam; SOC total soil organic carbon; SL sandy loam (Typic Haplustept); WSA water stable aggregates; ZT zero tillage

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1. Introduction

Tillage is an important management practice involving physical manipulation of soil for crop establishment. Optimization of tillage practices lead to improvement in soil health. Soil health is a dynamic and complex system, and its functions are mainly mediated by agricultural management practices (Doran and Zeiss, 2000). Intensive agricultural practices often leads to changes in soil health governing properties like, soil structure, aggregation, porosity, strength, hydraulic conductivity, infiltration, bulk density, soil moisture content, soil carbon content, microbial biomass and their activities (Osunbitan et al., 2005; Allen et al., 2011). Soil with better health and quality will be able to produce higher crop yield under favourable as well as extreme climatic conditions (Congreves et al., 2015), and soil health acts as a critical component for adaptation and mitigation of climate change effects by the crops (Congreves et al., 2015). Therefore, long

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with selected diversified maize based rotations (MCS and MWMb) can be advocated as sustainable intensification strategy in light textured soils of north-western India and other similar agro-ecologies of South Asia.

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term study (>5 years) on effect of tillage practices for maintaining or enhancing soil physical, chemical and biological characteristics of sandy loam (Typic Haplustept) soil are needed (Singh et al., 2016). However, measurement and demonstrations of soil health related properties (physical, chemical and biological), and their interactions are very complex (Karlen et al., 2003).

Sandy loam (Typic Haplustept) soil is the most dominant soil texture of Indo Gangetic Plains. The main production constraints of this type of soil are higher bulk density, poor water retention capacity, higher hydraulic conductivity, lower soil organic carbon and lower biological activities (Singh et al., 2016). The low organic carbon content in sandy loam (Typic Haplustept) soils is one of the major reasons for declining in soil health resulting in low and unsustainable productivity of intensified irrigated rice-wheat cropping systems of this region (Dwivedi et al., 2003; Singh et al., 2005). However, the other drivers for replacing of rice-wheat system with maize based crop rotations are (i) better adaptability of maize crop because of its C_4 nature, (ii) increasing demand of maize for poultry, piggery and fishery sectors, (iii) narrowing export market for rice (Dass et al., 2012; Pandey et al., 2008), (iv) higher productivity potential with more palatable fodder of maize. These factors recently compelled the Government of India to put a major emphasis on diversification of rice with maize especially in dark zones (areas where water table is declining due to overexploitation of ground water resources) of the rice-wheat rotation across north-western Indo-Gangetic Plains (IGP). However, as a futuristic strategy, there is a need to study the long-term consequence of contrasting tillage & crop establishment practices in diverse maize rotations on soil health for designing future action plan in these ecologies.

Crop management practices (tillage systems or cropping sequences) can affect soil health. Karlen et al. (2013) observed that deep soil ploughing with mouldboard plow had significant negative impact on soil health and quality parameters. Some studies showed encouraging findings of increasing soil organic matter, soil structure due to maintenance of soil aggregates, reduced oxidation of soil organic matter with minimum tilling of soil compared to conventional tillage (Beare et al., 1994; Halvorson et al., 2002). Similarly, diversification in crop rotations can also affects soil health by affecting carbon contents, due to the difference in chemical composition of different crop residues that are added to soil (Srinivasarao et al., 2013). These effects of either tillage or cropping systems on soil physical and chemical properties affect the microbial biomass and their activities and some other important processes such as organic matter decomposition and mediation of plant nutrient availability (Dick, 1992; Balota et al., 2003). However, precise information on the long term effects of different tillage practices and intensified maize based crop rotations on soil health in the IGP region of South Asia is lacking. The research findings of this region and elsewhere presents an opportunity to investigate the effect of long term agricultural management systems on soil health parameters.

It is hypothesized that conservation agriculture based tillage practices (ZT and PB) and diversified maize based crop rotations improve soil physical, chemical and biological properties and overall soil health, compared to conventional tillage and existing dominant rice-wheat cropping system of the region. Identification of best tillage practice and/or crop rotation to maintain or enhance soil health can help the farmer/grower to plan their crop management strategies. In this backdrop, the objectives of present study were to determine the long term effects of different tillage practices and intensive maize based crop rotations on physical properties, organic carbon content and biological activities in sandy loam (Typic Haplustept) soil of north-western IGP.

2. Materials and methods

2.1. Experimental site

The long term field experiment was initiated in the wet (*Kharif*) season of 2008 at the research farm of the Indian Institute of Maize Research, Pusa Campus, New Delhi, India (28°40′ N, 77°12′ E and 229 m elevation). The region has a semi-arid climate, with an average (mean of last 30 years) annual rainfall of 650 mm (70–80% of which received during July-September) with the mean annual evaporation of 850 mm. Rainfall along the period of the cropping cycle (July to June) ranged from 533 to 1507 mm. The mean daily minimum temperature of 0–4 °C in January, mean daily maximum temperature of 40–46 °C in May-June and mean daily relative humidity of 67–83% during the experimentation years (The detail meteorological data are also provided in Supplementary Table 1). The soil of experimental site was sandy loam (Typic Haplustept) in texture with pH 7.8; EC 0.32 dSm^{-1}, and the initial physical, chemical and biological properties of the soil is depicted in Table 1.

2.2. Experimental details

The experiment was laid out in split-plot design with tillage practices [zero tillage (ZT), permanent raised bed (PB) and conventional tillage (CT)] as main plot treatment and intensified crop rotations as subplot [maize-wheat-mungbean (MWMb), maize-chickpea-*Sesbania* (MCS), maize-mustard-mungbean (MMuMb) and maize-maize-Sesbania (MMS)] treatment, replicated three times. The sub plot size was 16.5 m x 4.0 m and was fixed throughout the experimentation. The field was deep tilled (to 30 cm depth) using chisel plough to break the hard pan below the plough layer and then laser leveled before start of the experiment. The CT involved one ploughing each with disc harrow followed by spring-tyne cultivator and rotavator. In ZT, different crops were direct drilled using ZT planter with inverted ‘T’ tynes. In the first year (July 2008), raised beds were fresh whereas in subsequent seasons they were kept as permanent beds (PB). The width of the beds (mid-furrow to mid-furrow) was 67 cm, with 37 cm wide flat tops, and 15 cm furrow depth. Reshaping of PB was done with disc coulter at the end of every cropping cycle without significantly bury of residues in one-go simultaneous while planting of crops were done by using raised bed multi-crop planter.

2.3. Crop establishment and management

In the first *kharif* 2008 season, mungbean and *Sesbania* residues (1.5 Mg ha^{-1}, dry weight basis) were applied, which were grown on the adjoining non-experimental field. In the subsequent years, about 30% of the residues of maize, wheat, mustard and mungbean were retained in the plots and the remaining amounts of residues were removed for use as fodder for cattle and fuel. Quality protein maize hybrid HQPM-1 was sown with seed rate of 20 kg ha^{-1} during first fortnight of July in *kharif* season and from last week of October to first week of November in winter season of every study year. The maize crop was planted at a row spacing of 67 cm with plant to plant spacing maintained at 25 cm in *kharif* and 20 cm in *rabi* season in all the

Table 1.
Initial status (prior to wet season, 2008) of soil properties at f the experimental site.

A. Soil Physical properties

Soil Properties	Depth (cm)					
	0–10	10–20	20–30	30–40	40–50	50–60
BD (Mg m^{-3})	1.58	1.64	1.73	1.73	1.73	1.72
PR (kPa)	805	1600	1810	2060	2049	1965

B. Carbon and aggregation

Depth (cm)	SOC (g kg^{-1} of soil)	WSA (%)	MWD (mm)	GMD (mm)	K_{sat} (cm h^{-1})	Particle size distribution			Soil Texture
						Sand (%)	Silt (%)	Clay (%)	
0–15	4.40	55	0.830	0.595	0.919	64.10	16.84	19.25	SL
15–30	4.21	51	0.700	0.539	0.875	64.45	10.75	24.84	SCL
30–45	3.70	48	0.598	0.528	0.703	63.89	10.15	26.24	SCL

C. Soil biological properties

Depth (cm)	MBC µg C g^{-1} soil	FDA µg Florescein g^{-1} h^{-1}	Dehydrogenase µg TPF Rel g^{-1} day^{-1}	ß Glucosidase µg *p*-NP Rel g^{-1} 24 h^{-1}	Alkaline Phosphatase µg *p*-NP Rel g^{-1} 24 h^{-1}
0–30 cm	340	0.445	22.38	1.56	39.0

plots. The maize crop was harvested in the last week of October and first week of May during *kharif* and *rabi* seasons of each year, respectively. The wheat was sown with a seed rate of 100 kg ha^{-1}in the 2nd to 3rd week of November at a row spacing of 22.5 cm under CT and ZT treatments, while two rows of wheat were planted on the on top of the PB keeping a row spacing of 18.5 cm. The chickpea (cultivar P 362 in the first 3 years, and cultivar Pusa 547 thereafter) was sowed in the last week of October using a seed rate of 80 kg ha^{-1} in 30 cm wide rows keeping 20 cm distance between plant to plant in CT and ZT plots, and two rows 18.5 cm apart were planted on the PB. The mustard crop (cultivar Pusa Bold in the initial 3 years and NRCDR-2 thereafter) was sown in the month of October by using a seed rate of 5 kg ha^{-1} at row spacing of 30 cm in CT and ZT plots. The mungbean (cultivar Pusa Vishal) was sown using a seed rate of 25 kg ha^{-1} with a row spacing of 30 cm in the first fortnight of April in ZT and CT plots. In PB treatment, like wheat and chickpea, two rows of mustard and mungbean were planted at a distance of 18.5 cm on each PB. The maize, wheat, chickpea, mustard and mungbean crops were sown by zero–till multi crop bed planter in PB, zero-till multi-crop planter in ZT and multi-crop planter in CT plots. The *Sesbania* (local cultivar) was sown in the second fortnight of April after the harvest of *rabi* crops by broadcasting using a seed rate of 35 kg ha^{-1}. The exact date of sowing and harvesting of each crop in every year is mentioned in Supplementary Table 2.

Kharif maize received a common fertilizer dose of 150 kg N + 60 kg P_2O_5 + 40 kg K_2O + 25 kg $ZnSO_4$ ha^{-1} and *rabi* maize was fertilized with 180 kg N + 80 kg P_2O_5 + 60 kg K_2O + 25 kg $ZnSO_4$ ha^{-1} In both the seasons 1/3rd N and whole P_2O_5, K_2O and $ZnSO_4$ were applied as basal at sowing, while remaining 2/3rd N was top dressed by broadcasting as urea in two equal splits at V_5 and V_T vegetative growth phases of maize. Wheat received a general fertilizer dose of 120 kg N + 60 kg P_2O_5 + 40 kg K_2O ha^{-1}. Half of the N and full dose of P_2O_5 and K_2O as basal were applied at the time of sowing, while the remaining N was top-dressed in two equal splits before first and 3rd irrigation. Mustard was fertilized with a basal dose of 90 kg N + 40 kg P_2O_5 + 30 kg K_2O ha^{-1}. Whole amount of P and K along with 50% of N were applied at planting, while the remaining N was top dressed at the time of first irrigation. In chickpea, whole of the 30 kg N + 40 kg P_2O_5 + 40 kg K_2O ha^{-1} were applied at seeding. Similarly, in summer mungbean a basal dose 30 kg N + 40 kg P_2O_5 ha^{-1} was applied at the time of sowing.

For managing weeds, herbicide gylphosate was sprayed @ 1.0 kg ha^{-1} in the ZT and PB plots about two days before sowing of each crop. However, in case of CT plots Atrazine @ 1.0 kg ha^{-1} as pre-emergence(PE) in maize, Pendimethalin @ 1.0 kg ha^{-1} as PE in chickpea, mungbean, wheat and mustard and Cladinofop @ 60 g ha^{-1} at 28–32 days after seeding in wheat was applied. In addition to chemical weed management, one hand weeding was also done in all the CT plots only at 30–40 days after sowing.

2.4. Soil sampling and processing

The soil was sampled in 2008 (prior to establishing the experiment) and 2014 (after harvest of summer season crop of 7th years) from fixed plots. The soil samples for bulk density of soil profile (0–10, 10–20, 20–30, 30–40, 40–50 and 50–60 cm) were collected in triplicate from each experimental unit by a core sampler with core of 5 cm height and 5 cm diameter. Soil samples from 0 to 15, 15–30 and 30–45 cm layers were collected using hand shovel for aggregate analysis. After drying in shade, they were broken by giving gentle stroke in a wooden hammer and only aggregates of 4–8 mm size were used for aggregate analysis. For microbial analysis, the soil samples of 0–30 cm depth were collected using tube augur from each experimental plot. The gentle sieving was done through 4 mm mesh sieve to eliminate stones, plants roots and large organic substances. After sieving the field moist samples were passed through a 2-mm sieve and stored at 4 °C until used for assaying of microbial biomass carbon and various other soil enzyme activities (dehydrogenase, flourescein diacetate, alkaline phosphatase, and ß Glucosidase)

2.5. Analytical methods

2.5.1. Total soil organic carbon

The total organic carbon content from different soil layers (0–15, 15–30 and 30–45 cm) was determined using finely ground (250 µm sieved) soil with Elementar^{R} dry combustion analyzer in triplicates.

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2.5.2. Soil physical properties

The bulk density of soil was determined upto the depth of 60 cm (at 10 cm interval) in triplicate from each replication by a core sampler with core of 5 cm height and 5 cm diameter. The saturated hydraulic conductivity was determined by constant head method (Mishra and Ahmad, 1987). The saturated hydraulic conductivity (K_{sat}) was calculated by using the formula as given in Eq. (1):

$$K_{sat} = \frac{QL}{HAT} \quad (1)$$

where;

K_{sat} = Saturated hydraulic conductivity (cm h^{-1})
Q = Quantity of water collected (cc)
L = Flow length/length of sample (cm)
H = Loss in head (cm)
A = Cross sectional area of sample (cm^2)
T = Time interval (minute)

Soil strength (cone penetration resistance) was measured at harvesting of the crop in the 7th year when the profile moisture content was near field capacity using a hand held recording penetrometer (Rimik make CP40II penetrometer, Australia) fitted with a cone of 12.8 mm diameter with area of 130 square mm, having maximum cone index of 5600 kPa, which recorded soil penetration resistance at 10 mm interval down to 700 mm soil depth (Anderson et al., 1980). Resistance data from three same positions (between rows) in each treatment per plot were averaged for every depth and mean was expressed in kilo pascals (kPa). But in the present experiment the average value for 100 mm is presented upto 600 mm.

The aggregate size distribution of soil was determined by wet sieving method using Yodders apparatus (Yodder, 1936). For this purpose, 50 g of air dried soil passed through 8 mm sieve and retained in 4 mm sieve was transferred to the upper most set of sieves having diameter of 4, 2, 1, 0.5, 0.25 and 0.125 mm. It was soaked for 10 min for capillary rewetting. After that, the set of sieves were shaken in water drum for a period of 10 min with amplitude of 3 cm with the oscillation frequency of 30 cycles per minute. Then soil samples from each sieve and also from the drum were collected. This resulted in distribution of aggregates into following classes, *i.e.,* (i) 4000–8000 µm, (ii) 2000–4000 µm, (iii) 1000–2000 µm, (iv) 500–1000 µm, (v) 250–500 µm, (vi) 125–250 µm, (vii) 0–125 µm. The aggregates retained in each classes were collected in beaker and oven dried at 65–70 °C till constant weight is achieved. Water stable aggregation was expressed as the percentage of aggregates greater than 250 µm, diameter. Mean weight diameter (MWD) of aggregates was estimated (Kemper and Rosenau, 1986) using the formula of Eq. (2):

$$\mathrm{MWD(mm)} = \sum_{i=1}^{i=n} (X_i W_i) / \sum_{i=1}^{i=n} W_i \quad (2)$$

where, W_i, is the proportion of aggregates retained on each sieves in relation to the whole, X_i is the mean diameter of the sieve (mm). The geometric mean diameter (GMD) was determined by using the following formula of Eq. (3):

$$\mathrm{GMD(mm)} = \exp\left(\left(\sum_{i=1}^{i=n} W_i \log X_i\right) / \left(\sum_{i=1}^{i=n} W_i\right)\right) \quad (3)$$

2.5.3. Soil biological properties

Soil microbial biomass carbon (MBC) was estimated using the method described by Nunan et al. (1998). Soil sample of 17.5 g was taken from every treatment in a closed-capped bottle and 1.0 ml of chloroform was added and then fumigated. One non-fumigated set was also prepared in a 250 ml flask. Then these samples were incubated in dark for 24 h. After incubation, chloroform was evaporated at 50 °C in BOD *i.e.,* caps were opened for next 20–24 h. After that, 70 ml 0.5 M K_2SO_4 was added into these samples and put the samples on shaker for 30 min. Supernatant was taken out with filtering of the samples by Whatman No. 42 filter paper. Absorbance of supernatant was recorded immediately form both fumigated and non-fumigated samples at 280 nm. MBC of Soil samples was calculated by using the formula given below in Eq. (4):

$$\mathrm{MBC}(\mu\mathrm{g/g\ of\ soil}) = \frac{\begin{pmatrix}\mathrm{O.D\ of\ fumigated\ soil} - \mathrm{O.} \\ \mathrm{D\ of\ nonfumigated\ soil}\end{pmatrix} \times 15487}{\mathrm{Amount\ of\ soil\ used}} \quad (4)$$

Soil microbial activity in terms of fluoresein diacetate (FDA) hydrolysis was determined using the procedure given by Green et al. (2006). Soil sample of 1 g weight was taken in a test tube containing 5 ml of 60 mM potassium phosphate buffer (7.6 pH) and 10 µl FDA stock solutions and then incubated at 37 °C for two hours. One control test tube was prepared for each sample without adding FDA solution. The reaction was terminated by adding 0.2 ml (5% v/v) acetone reagent. Then it was filtered through Whatman No. 2 filter paper and absorbance of samples was recorded at 490 nm. The FDA hydrolysis was calculated in terms of A490 units "µg of Fluorescein released gram $soil^{-1}hr^{-1}$".

The dehydrogenase activity was estimated using the procedure suggested by Casida et al. (1964). The enzyme activity was estimated through the production of triphenyl formazan from triphenyl tetrazolum chloride which was used as an acceptor of hydrogen atoms. Air dried 1 g soil was weighed and placed in a 15 ml screw cap tube (three replications were maintained for every experimental treatment, then 0.2 ml of 3% w/v 2, 3, 5 triphenyl tetrazolium chloride was added. To ensure a thin layer of water above the soil surface, 0.5 ml of 1% glucose solution was added. The tubes were incubated at 30 °C ± 1 °C temperature. After 24 h of incubation, 10 ml of methanol was added into it and the tubes were hand shaken for one minute. These tubes were allowed to stand in dark for six hours. The colour intensity developed was measured spectrophotometrically at 485 nm. The dehydrogenase activity was expressed in terms of mg Triphenyl formazon (TPF) produced hr^{-1} g^{-1} of air dry soil. The standard curve was drawn with a range of 0.005 mg TPF to 0.4 mg per 10 ml of methanol.

ß Glucosidase activity was determined using the procedure described by Eivazi and Tabatabai (1988). In this method 0.2 ml of toluene, 4 ml of Modified universal buffer (MUB) and 1 ml of *p*-nitrophenyl β D glucoside solution were incubated with 1 g soil at 37 °C for one hour. After that 1 ml of 0.5 M $CaCl_2$ and 4 ml of 0.1 M THAM (Trishydroxy methyl amino methane**)** were added and the soil solution obtained was filtered using Whatman No 1 filter paper. Yellow colour intensities of the solutions obtained were measured spectrophotometrically at 490 nm and compared with a calibration graph plotted from the result obtained with standards containing 0, 10, 20,

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30, 40, and 50 μg of *p*-nitrophenol released g^{-1} soil 24 hr^{-1} observed at 490 nm by applying standard readings.

The Alkaline phosphatise activity was determined spectrophotometrically using the method described by Tabatabai and Bremner (1969). Soil samples of two sets each of 1.0 g soil were taken in 50 ml conical flasks. Out of these two sets, one set was used as control. Then, 0.2 ml toluene and 4 ml of modified universal buffer (MUB) adjusted at pH 11.0 were added to all flasks. After that 1 ml of substrate, *p*-nitrophenyl phosphate (0.025 M) was added to one set of the samples. The flasks of both the sets were swirled for few seconds to mix the contents and incubated at 37 °C for 1 h. After incubation, 1 ml of 0.05 M $CaCl_2$ and 4 ml of 0.5 M NaOH was added and swirled for few seconds. Then, 1 ml of *p*-nitrophenyl phosphate (0.025 M) was added to the remaining set of samples. All the suspensions were filtered quickly through Whatman No. 1 filter paper. The yellow colour intensity was measured at 440 nm wavelength (blue filter). The amounts of *p*-nitrophenol formed in each sample were calculated from the standard curve drawn. Alkaline phosphatase activity was expressed in terms of μg *p*-nitrophenol released g^{-1} soil 24 hr^{-1}.

2.6. Statistical analysis

All data recorded for different soil properties were analysed with the help of analysis of variance (ANOVA) technique (Gomez and Gomez, 1984) for split-plot design using SAS 9.3 software (SAS Institute, Cary, NC). The least significant difference test was used to decipher the main and interaction effects of treatments at 5% level of significance ($P < 0.05$) by using least significant test. Correlation and regression analysis was performed using data analysis tool pack of Ms Excel (2007).

3. Results and discussion

3.1. Total soil organic carbon

The long-term conservation agriculture (CA) practices (PB and ZT) had significant ($P < 0.05$) effect on SOC content of different soil layers (Table 2). The SOC content in PB and ZT plots were significantly ($P < 0.05$) higher (23.6 to 35.3%) than the CT plots for the soil depths 0–15 and 15–30 cm. However, the SOC content of PB, ZT and CT plots were statistically at par for the soil depth of 30–45 cm. The soil tilling increases organic matter decomposition and decreases carbon content by increasing organic matter oxidation (Six et al., 1999; Balasdent et al., 2001; Balota et al., 2003; Thomas et al., 2007). Moreover, the crop roots remains intact in the root zone due to non-disturbance of the soil under CA, which might facilitate enhancement of organic carbon input in deeper root zones (up to 30 cm) through their decay. However, this improvement might not cause significant effect in much deeper soil layers (30–45 cm) due to absence of sufficient root biomass. Aziz et al. (2015) had observed that NT enhanced the total carbon by 30% and active carbon by 10% in corn-soybean-wheat-cowpea rotation over CT. The enhancements in soil carbon content due to CA practices were also reported by Baker et al. (2007), Thomas et al. (2007) and Kaiser et al. (2014).

The effect of diversified maize based crop rotations on SOC contents were significant ($P < 0.05$) for 0–15 and 15–30 cm soil depths (Table 2). Maximum SOC contents in both the soil depths was recorded in MCS sequence, which were 18.9 and 20.4% higher compared to MMuMb and MMS crop rotations, respectively. In all the soil depths MCS plots recorded higher carbon content over other crop rotations, this might be due to differences in quantity and chemical composition of crop residue biomass and/or root exudates among the crop rotations (Congreves et al., 2015). The narrow C:N ratio of legume residue caused rapid decomposition and hence higher SOC compared to other cropping sequences. Further, tap roots of the legume resulted higher SOC content in deeper layers. Generally, across the tillage and crop rotations SOC content decreased in sub-surface soil layers.

Table 2.
Effect of long term (after seven years) tillage practices and diversified crop rotations on soil organic carbon in different soil layers.

Treatment	Soil Organic Carbon (g kg^{-1} of soil)		
	0–15 cm	15–30 cm	30–45 cm
Tillage practices			
PB	6.54^{a}	5.53^{a}	4.27^{a}
ZT-flat	6.51^{a}	5.66^{a}	4.34^{a}
CT-flat	4.83^{b}	4.47^{b}	4.09^{a}
Cropping systems			
MWMb	6.33^{a}	5.53^{a}	4.32^{a}
MCS	6.56^{a}	5.66^{a}	4.41^{a}
MMuMb	5.45^{b}	4.56^{c}	4.07^{a}
MMS	5.51^{b}	5.13^{b}	4.12^{a}
Tillage × cropping systems			
PB-MWMb	7.19^{a}	5.98^{a}	4.46^{a}
PB-MCS	7.15^{a}	6.31^{a}	4.53^{a}
PB-MMuMb	5.45^{b}	4.50^{d}	4.03^{a}
PB-MMS	6.37^{a}	5.31^{bc}	4.07^{a}
ZT-MWMb	6.88^{a}	5.98^{a}	4.47^{a}
ZT-MCS	7.15^{a}	6.02^{a}	4.52^{a}
ZT-MMuMb	6.44^{a}	4.88^{cd}	4.15^{a}
ZT-MMS	5.58^{b}	5.75^{ab}	4.21^{a}
CT-MWMb	4.91^{bcd}	4.63^{d}	4.03^{a}
CT-MCS	5.37^{bc}	4.64^{d}	4.19^{a}
CT-MMuMb	4.46^{d}	4.29^{d}	4.03^{a}
CT-MMS	4.59^{cd}	4.33^{d}	4.09^{a}

Note: PB: Permanent bed; ZT: Zero tillage flat; CT: Conventional tillage flat; MWMb: Maize-Wheat-Mungbean; MCS: Maize-Chickpea-*Sesbaina*; MMuMb: Maize-Mustard-Mungbean; MMS: Maize-Maize-*Sesbania*. *Same letter within each column indicate no significant difference among the treatments (at $P < 0.05$) according to DunLSD test.

The tillage and crop rotations had significant ($P < 0.05$) interaction effect on SOC content of 0–15 and 15–30 cm soil layers (Table 2). However, the tillage and crop rotations interaction effect on SOC was not observed for 30–45 cm soil layers. The highest SOC content was found in PB-MWMb treatment for 0–15 cm soil depth and PB-MCS treatment for 15–30 cm soil layers. PB-MWMb and PB-MCS plot registered 61.3% and 47.2% higher SOC compared to CT-MMuMb for above soil layers, respectively. Thierfelder et al. (2012) found 31% greater soil carbon by inclusion of cowpea and sunhemp in maize based crop rotations. Saha and Ghosh (2013) also reported the positive effects of legume residue application in cereal cropping systems on soil carbon content.

3.2. Effect on soil physical properties

3.2.1. Soil aggregation

The tillage and crop rotations had significant ($P<0.05$) effect on water stable aggregates (>250 μm) for 0–15 and 15–30 cm soil depth (Fig. 1a). ZT and PB plots showed 23–32.5% and 16–20.6% higher water stable aggregates (WSA) compared to CT in 0–15 and 15–30 cm soil depth, respectively. Whereas, in 30–45 cm soil depth, WSA did not differed significantly ($P<0.05$) by different tillage practices. Our results of higher WSA in CA practices compared to CT are in agreement with other experimental findings (Gathala et al., 2011; Jat et al., 2013). The diversified crop rotations significantly ($P<0.05$) influenced the WSA and the highest values were found in MCS rotation plots which were 5–17.4% (0–15 cm) and 6.6–24.1%

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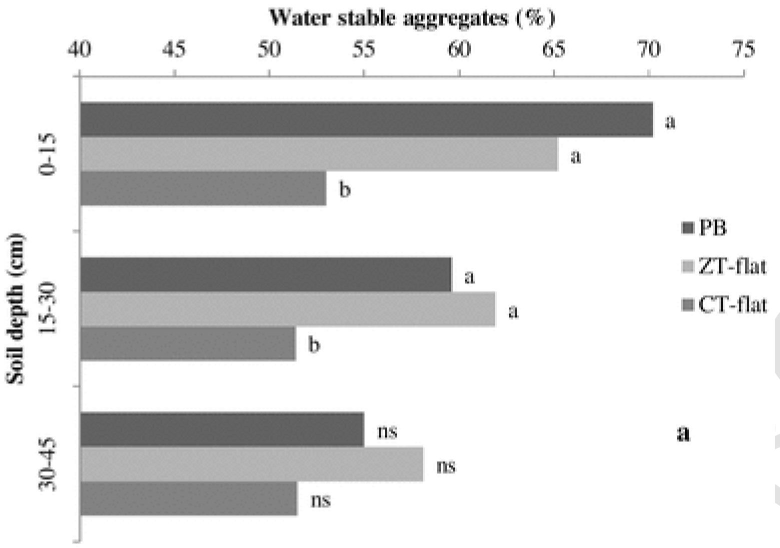

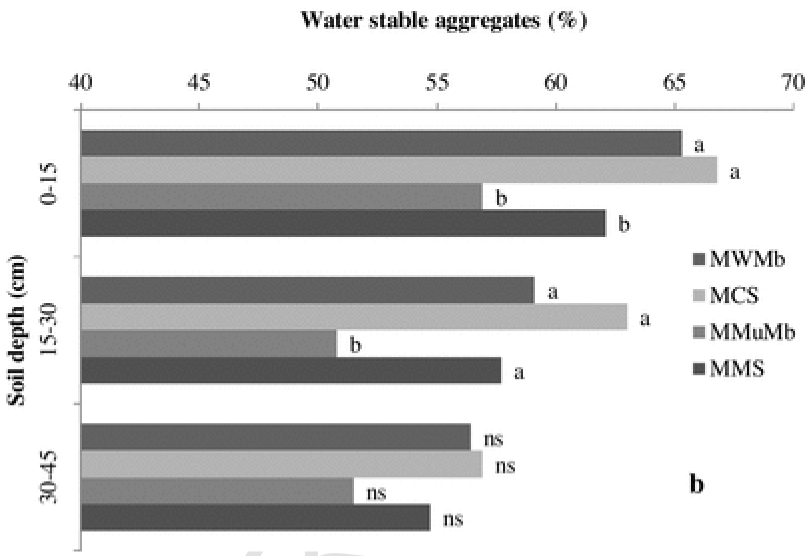

Fig. 1. Effect of long term (after seven years) tillage practices (a) and diversified crop rotations (b) on water stable aggregates. *The bars followed by a different letter within a depth are significantly different (at P < 0.05) according to LSD test.

(15–30 cm) higher compared to MWMb, MMS and MMuMb rotations (Fig. 1b). The WSA were recorded 67 and 63% higher in MCS crop rotation in 0–15 and 15–30 cm soil layers, respectively. The interaction effect of tillage and crop rotations were not significant (P>0.05) for WSA (data not given). The WSA were significantly and positively correlated with the SOC content (Table 3) of the soil (r=0.966***), this finding is in agreement with Six et al. (2002) and Biswas et al. (2009). The relation between SOC and WSA

Table 3.
Correlation matrix of soil physical properties with soil organic carbon.

Parameters	SOC	WSA	K_{sat}	GMD	MWD	PR
WSA	0.966***					
K_{sat}	0.928***	0.963***				
GMD	0.928***	0.951***	0.962***			
MWD	0.923***	0.953***	0.980***	0.976***		
PR	−0.788**	−0.873***	−0.891***	−0.837***	−0.875***	
BD	−0.858***	−0.898***	−0.952***	−0.947***	−0.964***	0.918***

** and *** indicate significance at 1 and 0.1% level of significance.
SOC: Soil organic carbon; WSA: Water stable aggregate; K_{sat}: Saturated hydraulic conductivity; GMD: Geometric mean diameter; MWD: Mean weight diameter; PR: Penetration resistance; BD: Bulk density.

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showed that about 93.2% variations in WSA can be explained by SOC as evident from Eq. (5):

$$WSA = 10.05SOC + 6.109;\ R^2 = 0.932^{***} \quad (5)$$

The statistical analysis showed that there was significant ($P < 0.05$) main effects of tillage and crop rotations on the mean weight diameter (MWD) and geometric mean diameter (GMD) upto 30 cm soil depth. It was observed that the ZT and PB plots have 47.1–53.4% and 24.5–37.3% higher MWD compared to CT in 0–15 and 15–30 cm soil depth, respectively (Fig. 2a). Similarly, GMD was increased in ZT and PB plots by 28.5–33.9% and 19.0–26.5% compared to CT in 0–15 and 15–30 cm soil depth, respectively (Fig. 3a). However, in sub soil layer (30–45 cm) the MWD and GMD did not differ significantly ($P < 0.05$) by different tillage practices. The diversified crop rotations significantly ($P < 0.05$) influenced the MWD and GMD, the highest were found in MCS rotation plots, which were 4.6–18.0% and 3.0–16.1% (0–15 cm) and 1.4–13.7% (15–30 cm) higher compared to MWMb, MMS and MMuMb rotations (Fig. 2b and 3b). However, both MWD and GMD were statistically at par in 30–45 cm soil layer across crop rotations. These findings are in agreement with the results of Hermawan and Bomke (1997). In general, we found that the treatments with higher soil organic carbon (SOC) content had significantly higher MWD and GMD. The lesser soil disturbance under CA practices (ZT and PB) reduces oxidation of organic matter and hence improves storage of SOC. Inclusion of two legumes in MCS compared to other crop rotations might result in higher SOC due to faster and easier decomposition of lower C:N ratio residues and root nodules (Srinivasarao et al., 2013). Consequently, ZT and PB were the best main plot treatment and MCS crop rotation as sub plot treatment. To further verify of this, we analysed the correlation (Table 3) of the SOC with soil aggregation and found that about 85.2% and 86.0% variations in MWD ($r = 0.923^{***}$) and GMD ($r = 0.928^{***}$) can be explained by SOC content (Eq. (6) and (7)). The similar relationships of SOC with soil aggregation properties were reported elsewhere (Filho et al., 2002; Six et al., 2002; Pinheiro et al., 2004; Verma and Sharma, 2007; Govaerts et al., 2009; Biswas

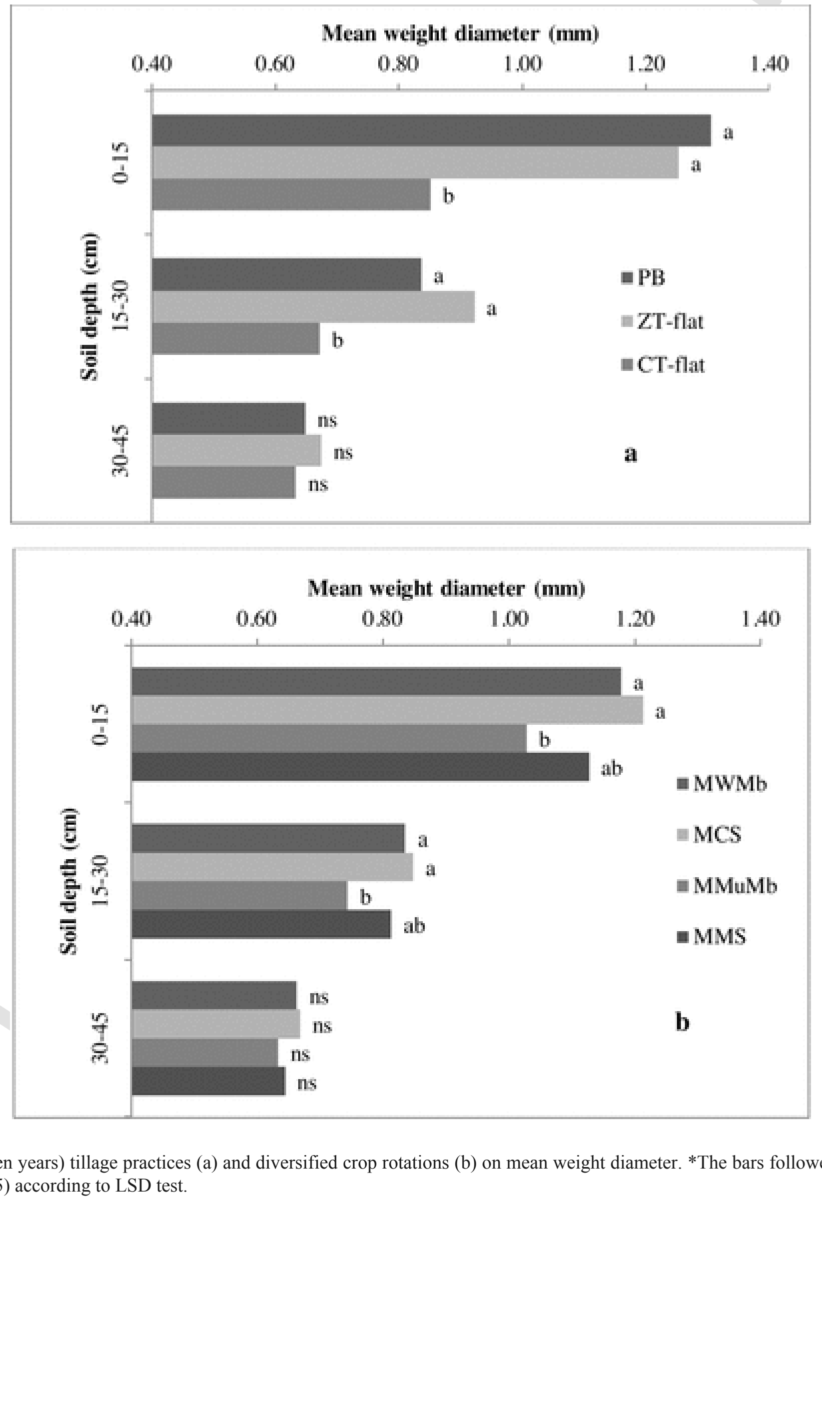

Fig. 2. Effect of long term (after seven years) tillage practices (a) and diversified crop rotations (b) on mean weight diameter. *The bars followed by a different letter within a depth are significantly different (at P < 0.05) according to LSD test.

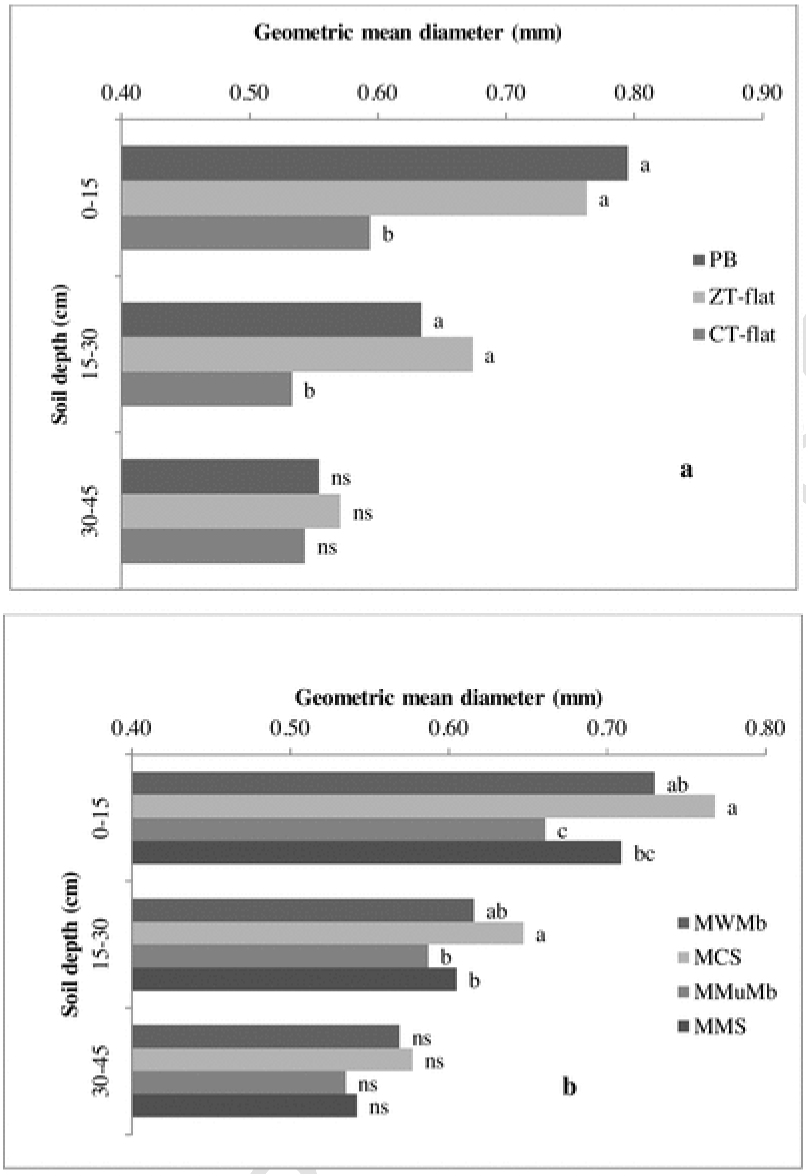

Fig. 3. Effect of long term (after seven years) tillage practices (a) and diversified crop rotations (b) on geometric mean diameter. *The bars followed by a different letter within a depth are significantly different (at $P < 0.05$) according to LSD test.

et al., 2009; Bandyopadhyay et al., 2010). Thus enhancement in SOC content is important for better soil aggregation.

$$MWD = 0.198\ SOC - 0.167;\ R^2 = 0.852^{***} \quad (6)$$

$$GMD = 0.098SOC + 0.118;\ R^2 = 0.860^{***} \quad (7)$$

3.2.2. Bulk density

The effects of tillage practices were significant ($P < 0.05$) on bulk density (BD) of 0–10, 10–20 and 20–30 cm soil depths, while in deeper soil layers (30–60 cm) it was non-significant (Fig. 4a). The BD under CA practices (ZT and PB) was lowered by 4.3–6.9% in 0–30 cm soil profile than CT plots after the harvest of 7th summer season crop. The decrease in BD under CA could be due to higher SOC content, better aggregation, increased root growth and biomass (Unger and Jones, 1998). Elsewhere, the similar findings of lower BD values under ZT were also reported by Yang and Wander (1999) and Salem et al. (2015). In contrast, some researchers reported higher BD values in clay/silty loam soil under ZT (Kumar et al., 2002; Wilkens et al., 2002).

The main effect of crop rotations and interaction effects of tillage and diversified crop rotations on soil BD were non-significant ($P < 0.05$) for all soil depths (0–60 cm). Unger and Jones (1998) also reported that soil BD did not differ significantly due to crop rotations effects. However, in our long-term study the BD values were lowest in MCS rotation plots and the maximum in MMuMb plots for all soil layers (Fig. 4b). So, in our study the higher BD values in MMuMb rotation plots might be due to lower SOC content compared to MCS plots (Table 2). Differential chemical composition of crop residues and root biomass brings out differential addition of SOC (Congreves et al., 2015). The similar findings of lower BD due to pulses inclusion were also reported by Verhulst et al. (2011) and Thierfelder et al. (2012). We also found significant ($P < 0.05$) and negative correlation (r=-0.858***, Table 3) between SOC and BD for 0–30 cm layers as

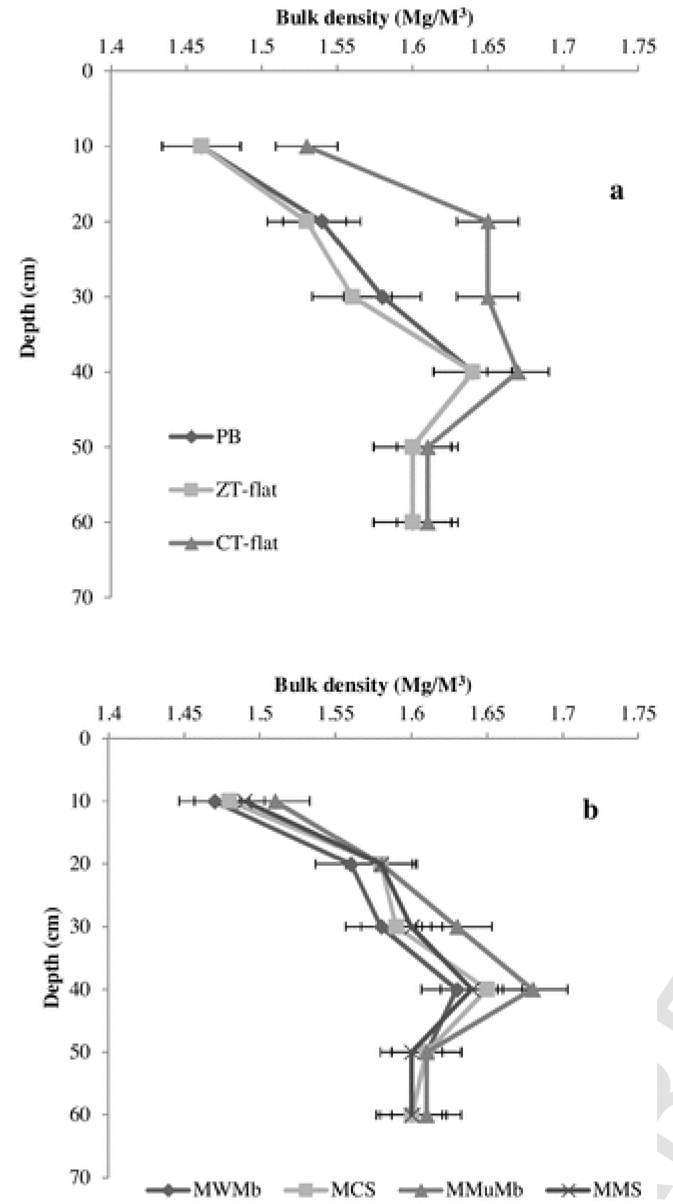

Fig. 4. Effect of long term (after seven years) tillage practices (a) and diversified crop rotations (b) on bulk density of soil.

evident from Eq. (8). The negative slope of SOC and BD for our experiment confirms that the increase in BD is associated with decrease in SOC content.

$$BD = -0.043SOC + 808; R^2 = 0.738^{***} \quad (8)$$

In our study, we found that generally across the tillage and crop rotations the BD of sandy loam (Typic Haplustept) soil was increased with depth and the maximum BD (1.64–1.67 Mg m^{-3}) were recorded in 30–40 cm soil layer but it was slightly lowered in subsequent layers.

3.2.3. Soil penetration resistance

The main effects of tillage practices and crop rotations were significant ($P < 0.05$) on PR up to 50 cm soil depth (Fig. 5a and b). The PR across tillage and crop rotations treatments increased with depth

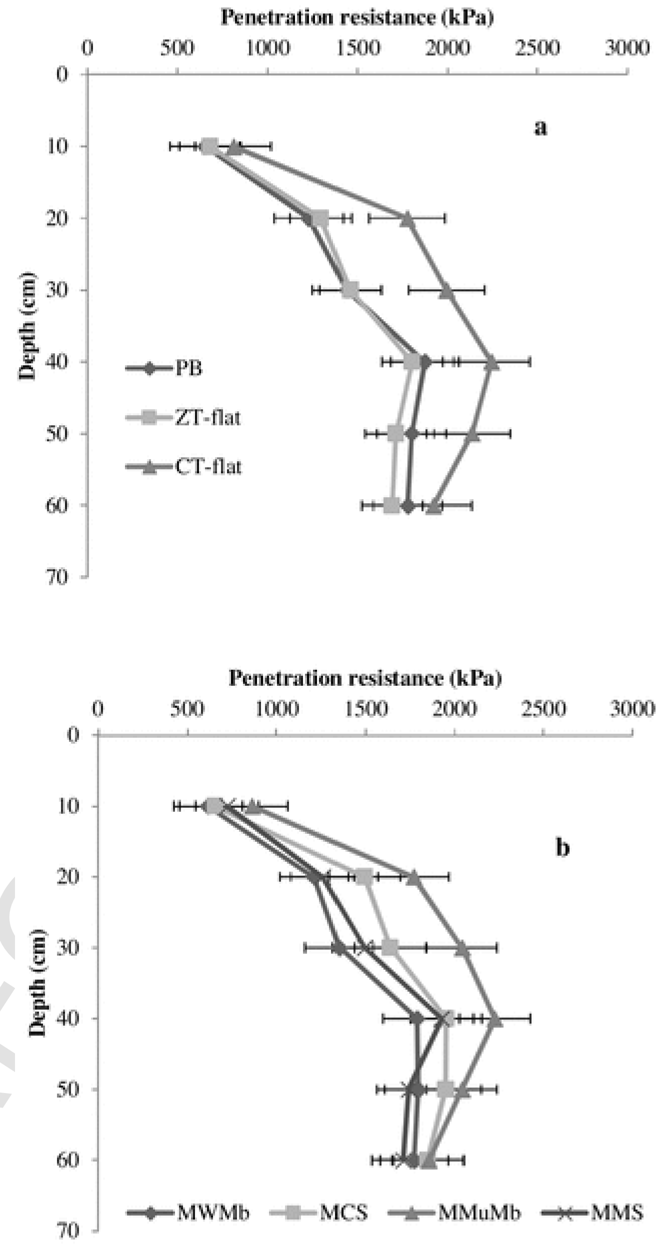

Fig. 5. Effect of long term (after seven years) tillage practices (a) and diversified crop rotations (b) on penetration resistance of soil.

(upto 40 cm) because of higher intrinsic BD in deeper soil layers (Unger and Jones, 1998). In our long term study, maximum PR (1804–2244 kPa) was recorded at 30–40 cm soil depth. Moreover, PR decreased under ZT plots by 15.9–27.1% and PB by 15.8–30.7% compared to CT in different layers of effective root zone (0–50 cm). The compaction caused by plough pan development under CT practices enhances the soil resistance which might contribute to higher PR in repeated tilled soil. Elsewhere, Yang and Wander (1999) and Saha et al. (2010) reported lower PR of soil under CA practices. Another reason of increased PR in CT practices could be due to increased BD (Fig. 4a and b) as evident from significant and high correlation (Table 3) between PR and BD. We found that 84% variation in PR could be explained through BD (Eq. (9)). Sharma and De Datta (1986) also re-

ported positive and significant relationship between PR and BD.

$$PR = 7398BD - 10182;\ R^2 = 0.841^{***} \quad (9)$$

Similar to tillage practices, diversified crop rotations also significantly influenced the PR in soil profiles upto 50 cm depth. In our study, after harvest of 7th year summer season crop, the maximum PR (864–2226 kPa) was recorded in MMuMb crop rotation at all the soil depths (0–50 cm), which was significantly ($P < 0.05$) higher than other crop rotations. However, in upper surface soil layers (up to 40 cm soil depths), the lowest penetration resistance (617–1789 kPa) was observed in MWMb sequence plots and below 40 cm depth the PR was lowest in MMS plots which might be due to addition of more underground biomass by two maize crops in deeper soil layers. Unger and Jones (1998) also reported that the PR differed due to crop rotations, being lower for continuous wheat (1.79 MPa) than for wheat-fallow (2.32 MPa) or wheat-sorghum-fallow (2.42 MPa).

The interaction effect of tillage and crop rotations on PR was significant ($P < 0.05$) only for 0–10 cm soil layers (Data not presented). The least ($P < 0.05$) PR was observed in MCS crop rotation of ZT tillage practices (428 kPa) concomitant to lowest BD of the same treatment. However, the same MCS crop rotation under CT tillage resulted in the highest ($P < 0.05$) PR (1006 kPa).

3.2.4. Saturated hydraulic conductivity (K_{sat})

Across the tillage and crop rotations, the K_{sat} decreased with increase in soil depth (Fig. 6a and b). Tillage treatments had significant effect on K_{sat} for 0–15 and 15–30 cm soil layers. However, the tillage effect on K_{sat} was not observed for 30–45 cm soil layers. The K_{sat} increased by 14.3 and 11.2% in PB plots and 11.1 and 12.0% in ZT plots for 0–15 and 15–30 cm soil layers, respectively, compared to CT plots. The increase in K_{sat} under conservation agriculture practices (PB and ZT) was mainly attributed to decrease in bulk density and increase in effective pore volume (Unger and Jones, 1998) because of better soil aggregation in these practices. Similar findings have also been reported (Osunbitan et al., 2005; Bhattacharya et al., 2006; Rasool et al., 2007; Li et al., 2011).

Similar to tillage effects, the diversified crop rotations also significantly ($P < 0.05$) affected the K_{sat} at 0–15 and 15–30 cm soil depths (Fig. 6b). However, K_{sat} was not affected ($P > 0.05$) by crop rotation

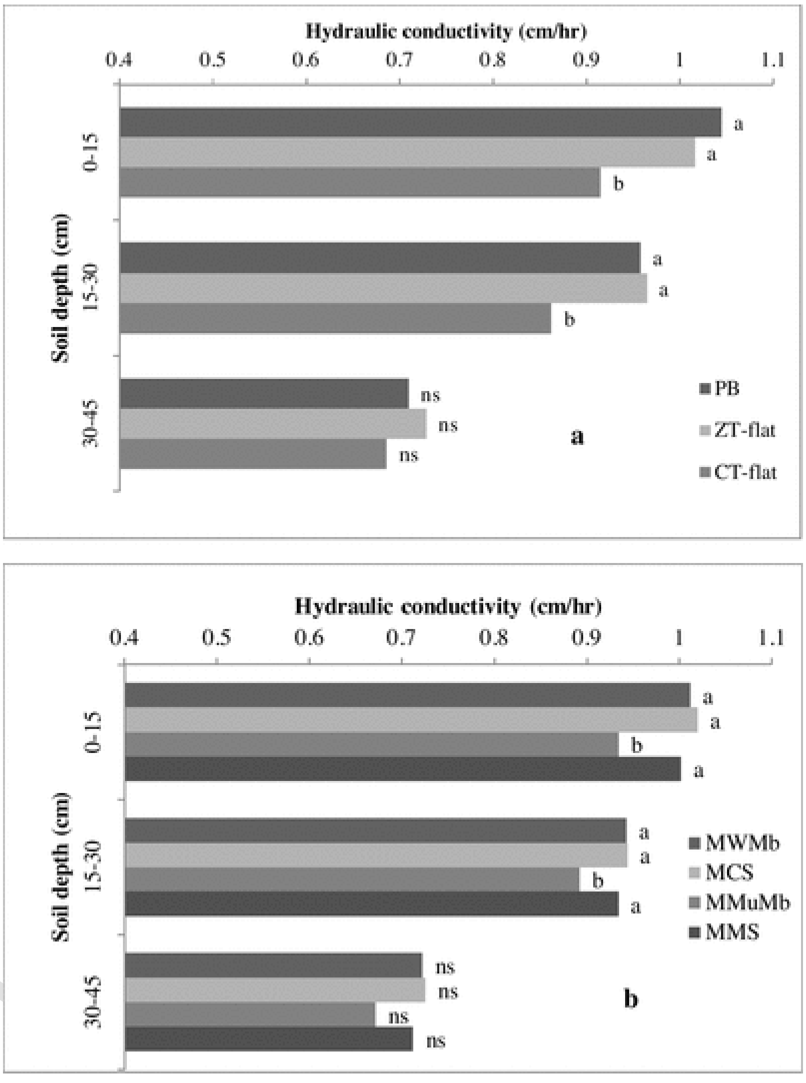

Fig. 6. Effect of long term (after seven years) tillage practices (a) and diversified crop rotations (b) on saturated hydraulic conductivity of soil. *The bars followed by a different letter within a depth are significantly different (at $P < 0.05$) according to LSD test.

at 30–45 cm soil depth. The K_{sat} increased by 9.3 and 5.9% in MCS; 8.4 and 5.7% in MWMb; 6.9 and 4.6% in MMS in 0–15 and 15–30 cm soil layer, respectively, compared to MMuMb crop rotation. The lowest K_{sat} in all the soil depths were recorded in MMuMb crop rotation due to higher BD (Fig. 4b) and lower aggregate stability (Figs. 1b, 2b and 3b) compared to other crop rotations. The interaction effect of tillage and crop rotations was non-significant ($P < 0.05$) on K_{sat} at all soil depths (data not presented). The K_{sat} of 0–30 cm soil layers was significantly negatively correlated (r = −0.952***) with BD (Table 3) as evident from Eq. (10):

$$K_{sat} = -2.108BD + 4.209;\ R^2 = 0.904^{***} \quad (10)$$

3.3. Effect on soil biological properties

3.3.1. Microbial biomass carbon

Tillage and crop rotations had significant ($P < 0.05$) effects on soil microbial biomass carbon (MBC) of 0–30 cm soil layer (Table 4). MBC was higher by 48.9 and 44.9% in ZT and PB compared to CT, respectively. However, the ZT and PB were statistically at par ($P < 0.05$) with respect to soil MBC. The highest ($P < 0.05$) soil MBC (436.1 μg g^{-1} soil) was recorded in MCS crop rotation followed by MWMb, MMuMb and MMS. The interaction of tillage and crop rotations were significant ($P < 0.05$) for soil MBC. Highest MBC was recorded in ZT-MCS (495.1 μg g^{-1} soil) treatment and least in CT-MMuMb (239.9 μg g^{-1} soil). Inclusion of two legumes (chickpea and *sesbania*) in CA practices (ZT-MCS) increased SOC (Table 2), which might have led to higher microbial activities, and hence higher MBC. The differential lignin composition and C:N ratio of cereals, oilseeds and legumes (Zita et al., 2012) resulted in differential microbial activities. The allelopathic effect of mustard residue also affects rate of residue decomposition. Mullen et al. (1998), Kandeler et al. (2006) and Singh et al. (2009) also observed higher MBC at higher SOC content. In our study, the MBC had significant and positive correlation (Table 5) with SOC (r = 0.974***) as evident from regression Eq. (11) which indicates that 94.8% variation of MBC can be explained by SOC.

$$MBC = 9SOC - 287.1;\ R^2 = 948^{***} \quad (11)$$

3.3.2. Fluorescein diacetate hydrolysis

Long-term tillage and crop rotations and their interactions had significant ($P < 0.05$) effect on soil Fluorescein diacetate hydrolysis (FDA) enzyme activity for 0–30 cm soil depth (Table 4). FDA hydrolysis is a measurement for contribution of several enzymes, involved in decomposition of soil organic matter. Similar to soil MBC, the FDA was higher by 40.9% in ZT and 37.1% in PB compared to CT, supporting the positive effect of CA practices on soil enzymatic activities. The diversified crop rotations also significantly influenced the activity of FDA hydrolysis. The MCS crop rotation resulted in 18.8% and 12.4% higher ($P < 0.05$) activity of FDA hydrolysis over MMuMb and MMS, respectively, but it was statistically at par with MWMb crop rotation. The interaction effect of tillage and crop rotations revealed that ZT-MCS had highest and CT-MMuMb had the lowest FDA activities. Gajda et al. (2013) and Perez-Brandan et al. (2012) also reported higher soil microbial enzymatic activities due to conservation agriculture or legumes. This can be attributed to enhanced MBC content in these treatments. The relationship between FDA and MBC showed that 85.8% variation in the FDA can be explained by MBC as evident from Eq. (12).

$$FDA = 0001MBC + 134;\ R^2 = 0.858^{***} \quad (12)$$

Table 4.
Effect of long term (after seven years) tillage practices and diversified crop rotations on soil microbial health.

Treatments	MBC (μg C g^{-1} soil)	FDA (μg Floresceing^{-1}hr^{-1})	Dehydrogenase (μg TPF Rel g^{-1} day^{-1})	ß Glucosidase (μg *p*-NP Rel g^{-1} 24 h^{-1})	Alkaline Phosphatase (μg *p*-NP Rel g^{-1} 24 h^{-1})
Tillage practices					
PB	419.7^{a}	0.507^{a}	30.4^{b}	1.94^{b}	40.46^{b}
ZT-flat	431.2^{a}	0.521^{a}	33.3^{a}	2.15^{a}	40.70^{a}
CT-flat	289.5^{b}	0.370^{b}	23.2^{c}	1.71^{c}	40.03^{c}
Cropping systems					
MWMb	417.2^{b}	0.486^{a}	31.4^{a}	2.02^{b}	40.63^{b}
MCS	436.1^{a}	0.504^{a}	32.8^{a}	2.17^{a}	40.90^{a}
MMuMb	315.8^{d}	0.424^{c}	23.6^{c}	1.71^{d}	30.74^{d}
MMS	351.6^{c}	0.448^{b}	27.9^{b}	1.82^{c}	40.33^{c}
Tillage x cropping systems					
PB-MWMb	467.4^{a}	0.518^{b}	32.4^{bcd}	2.04^{abc}	40.65^{b}
PB-MCS	470.9^{a}	0.536^{ab}	36.5^{ab}	2.16^{abc}	50.06^{a}
PB-MMuMb	352.3^{c}	0.479^{c}	22.0^{fg}	1.74^{bc}	30.65^{e}
PB-MMS	388.3^{b}	0.495^{c}	30.2^{cde}	1.83^{abc}	40.47^{b}
ZT-MWMb	479.8^{a}	0.527^{b}	35.1^{abc}	2.33^{ab}	50.06^{a}
ZT-MCS	495.1^{a}	0.552^{a}	39.0^{a}	2.46^{a}	50.23^{a}
ZT-MMuMb	355.3^{c}	0.488^{c}	27.8^{de}	1.82^{abc}	30.99^{d}
ZT-MMS	394.7^{b}	0.516^{b}	31.3^{cde}	1.97^{abc}	40.52^{b}
CT-MWMb	304.3^{d}	0.415^{d}	26.6^{ef}	1.70^{bc}	40.17^{cd}
CT-MCS	342.1^{c}	0.424^{d}	22.7^{fg}	1.89^{abc}	40.39^{bc}
CT-MMuMb	239.9^{f}	0.306^{f}	21.1^{g}	1.58^{c}	30.56^{e}
CT-MMS	271.9^{e}	0.334^{e}	22.4^{fg}	1.67^{c}	40.01^{d}

Note: PB: Permanent bed; ZT: Zero tillage flat; CT: Conventional tillage flat; MWMb: Maize-Wheat-Mungbean; MCS: Maize-Chickpea-*Sesbaina*; MMuMb: Maize-Mustard-Mungbean; MMS: Maize-Maize-*Sesbania.* *Same letter within each column indicate no significant difference among the treatments (at P < 0.05) according to LSD test.

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Table 5.
Correlation matrix of soil microbial activities with soil organic carbon.

Parameters	MBC	FDA	DHA	BG	ALP
FDA	0.927***				
DHA	0.917***	0.834***			
BG	0.928***	0.796**	0.905***		
ALP	0.890***	0.746**	0.924***	0.930***	
SOC	0.974***	0.888***	0.936***	0.887***	0.877***

** and *** indicate significance at 1 and 0.1% level of significance.
MBC: microbial biomass carbon; FDA: fluorescein diacetate; DHA: Dehydrogenase; BG: ß Glucosidase; ALP: Alkaline Phosphatase; SOC: Soil organic carbon.

3.3.3. Dehydrogenase activity

Similar to FDA enzyme activity, the dehydrogenase activity (DHA) was significantly (P < 0.05) affected by tillage and crop rotations and their interactions (Table 4). Higher DHA indicate higher microbial activity. The maximum soil DHA was recorded under ZT plots, which was significantly ($P < 0.05$) higher than CT plots and was statistically at par with PB treatment. The DHA in 0–30 cm soil layer was 43.5 and 30.6% higher in ZT and PB treatments compared to CT , respectively. The DHA increased under MCS crop rotation by 38.6, 17.3 and 4.4% over MMuMb, MMS and MWMb, respectively. The interaction effect of tillage and crop rotations revealed that ZT-MCS had highest and CT-MMuMb had the lowest DH activities. This can be attributed to the MBC content of the soil. Madejon et al. (2007) and Tao et al. (2009) have also observed higher DHA in conservation agriculture with legume crop. The relationship between DHA and MBC showed that 84.0% variation in the DHA can be explained by MBC as evident from Eq. (13).

$$DHA = 066MBC + 711; R^2 = 0.840^{***} \quad (13)$$

3.3.4. ß-Glucosidase activity

Soil ß-Glucosidase (BG) activity significantly ($P < 0.05$) varied with tillage practices, crop rotations and their interactions (Table 4). The maximum soil BG activity was recorded under ZT , which was 25.7% and 10.5% higher compared to CT and PB tillage, respectively. Similar findings of enhanced BG activity under CA practices were also reported byStott et al., 2009. The activities of BG increased by 26.6, 19.0 and 7.2% under MCS crop rotation over to MMuMb, MMS and MWMb, respectively. The interaction effect of tillage and crop rotations study revealed that ZT-MCS had highest (2.46 µg *p*-NP Rel g^{-1} 24 h^{-1}) and CT-MMuMb had the lowest (1.58 µg *p*-NP Rel g^{-1} 24 h^{-1}) BG activities. A significant and positive correlation (0.928***) was found between BG and MBC (Table 5). The relationship between BG and MBC showed that 86.1% variation in the BG can be explained by MBC as evident from Eq. (14).

$$BG = 003MBC + 800; R^2 = 0.861^{***} \quad (14)$$

3.3.5. Alkaline phosphatase activity

Soil alkaline phosphatase (ALP) activity was significantly ($P < 0.05$) different with tillage practices, diversified crop rotations and their interactions at 0–30 cm soil depth (Table 4). Among the tillage practices, the maximum activity of ALP was recorded under ZT, which was 16.6 and 10.6% higher over CT and PB, respectively. The minimum ALP activity was recorded under CT possibly due to lower MBC and SOC content. Amongst crop rotations, the MCS rotation had 31.1, 13.1 and 5.6% higher ALP activities compared to MMuMb, MMS and MWMb, respectively. The interaction effect of tillage and crop rotations study revealed that ZT-MCS had highest (50.23 µg *p*-NP Rel g^{-1} 24 h^{-1}) and CT-MMuMb (30.56 µg *p*-NP Rel g^{-1} 24 h^{-1}) had the lowest ALP activities. Dodor and Tabatabai (2003) observed differential activities of ALP under various crop rotations. They also found significant correlation of ALP with SOC. This is also evident from our study where we found positive and significant correlation (r=0.877***) of ALP with SOC (Table 5). The activities of ALP was significantly positively correlated (Table 5) with MBC content at 0–30 cm depth (r=0.890***) as evident from Eq. (15) and these were probably the force for enhancing ALP activities.

$$ALP = 062MBC + 71; R^2 = 0.792^{***} \quad (15)$$

3.4. Effect on system yield and economics

The TCE practices and cropping systems had significant ($P < 0.05$) effect on system productivity (maize equivalent yield, MEY) and economics. In first two years (2008–09 and 2009–10), the system productivity was higher in PB (8.23–8.52 Mg ha^{-1}) compared to ZT (8.03–8.33 Mg ha^{-1}) and CT (7.94–8.01 Mg ha^{-1}). Thereafter, MEY was significantly higher in ZT (11.22–12.85 Mg ha^{-1}) compared to PB (10.60–12.31 Mg ha^{-1}) and CT (9.28–10.69 Mg ha^{-1}). The higher system yield under CA based PB and ZT practices were also reported by Parihar et al. (2016).The MEY in first year of study was at par in MMuMb and MWMb systems, but significantly higher compared to other cropping systems. From 2nd to 4th year MWMb system turned out to be the highest yielder (10.29–12.63 Mg ha^{-1}) and thereafter (5th and 6th years), the MMuMb system produced significantly higher MEY (13.22–13.45 Mg ha^{-1}) compared to other maize based systems. The MEY was lowest under MCS system (6.83–10.30 Mg ha^{-1}). The cost of cultivation for different crops in maize-based systems was almost similar in PB and ZT but was lower than CT. Net returns were maximum in PB (US$ 1052–1196 ha^{-1}) for initial two years, while in subsequent years ZT (US$1712–2489 ha^{-1}) registered highest net returns. The lowest net returns were observed in CT for all the years (US$ 871–1839 ha^{-1}). Among the cropping systems, the MMuMb system gave significantly higher net returns in first (US$ 1182 ha^{-1}) and sixth year (US$ 2394 ha^{-1}) of study while in the rest years, MWMb system resulted highest net return (US$ 1268–2093 ha^{-1}).

4. Conclusions

In north-western India, maize-based rotations being advocated as sustainable intensification options and alternative to rice-based rotations to address the issues of declining water table, soil health deterioration particularly decline in organic carbon and microbial biomass and increased soil compaction which results in declining factor productivity and farm profits. Our results from long term (seven years) study demonstrated that establishment of diverse crops under maize based rotations with CA based systems (ZT and PB) resulted in significant improvement in the physical properties of sandy loam (Typic Haplustept) soil. We observed decrease in bulk density (4.3–6.9%) and penetration resistance (15.9–30.7%) and increase in organic carbon (23.6–35.3%), saturated hydraulic conductivity (11.1–21.3%) and water stable aggregates (16.1–32.5%) compared to conventional tillage based maize production. It was also observed that with ZT fol-

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lowed by PB led to significant improvement in soil biological health i.e. microbial biomass carbon (45–48.9%), fluorescein diacetate (37.1–40.9%), dehydrogenase (30.6–43.5%), ß-glucosidase (13.7–25.7%) and alkaline phosphatase (10.6–16.5%) over CT . Among the maize based crop rotations, maize-chickpea-*sesbania* proved to be best rotation for improving these soil physical and biological properties. Our study suggest that the CA (ZT and PB) with maize-chickpea-*sesbania* and maize-wheat-mungbean rotations provides an alternate to improving soil health in sandy loam (Typic Haplustept) soil of north-west IGP and other similar ago-ecologies of South Asia.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.still.2016.04.001.

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