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Tillage and Crop Rotation Effects on Mechanical Properties and Structural Stability of a Sandy Loam Soil in a Semi-arid Environment

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Tillage has strong influence on soil architecture and thus modifies soil matrix-pore system. Short-term (7 years) changes in soil mechanical properties (macro- and micro-level) were evaluated in pigeon pea-wheat (P-W), cotton-wheat (C-W) and maize-wheat (M-W) cropping systems (CS). Tillage systems were: no tillage (NT) and conventional tillage (CT) with or without crop residue retention (+R/-R). Soil bulk density didn't change appreciably. Soil resistance to penetration at 10-20 cm layer reduced under NT system with residue retention (NT+R), owing to greater soil water content. Maintaining residue, irrespective of tillage, improved soil aggregation and bulk soil organic carbon content (total, particulate and $KMnO_4$-oxidizable C), promoting a better root-zone hydro-physical regime in all CS. Effect of tillage on water-stability of aggregates was observed at 0-7.5 cm layer only, in air-dried, compared to field-moist samples. The tillage-CS interactions had impact on mean weight diameter (MWD) of air-dried aggregates at 0-7.5 cm layer. The MWD was higher in NT+R under P-W than any other tillage/residue-CS combination. Residue incorporation in CT also resulted in greater macro-aggregates (>0.25 mm), and thereby larger MWD. Disruption of aggregates through different energy inputs was the least under NT+R, indicating predominantly higher amount of water-stable aggregates, providing a better soil structure.

Key words: No tillage, cropping system, mean weight diameter, organic carbon

The effort to sustain food security comes through accepting the challenge of increasing crop productivity. However, we must also preserve the quality of the environment and natural ecosystems through sustainable approach. Conservation agriculture (CA) has the potential to achieve yield sustainability, and has proven role in facilitating soil aggregation, promoting root growth, conserving residual soil water and better nutrient cycling (Ghosh *et al*. 2010; Jemai *et al*. 2013). The fundamental essence of CA relies on residue retention and reduced tillage, aiming to minimize mechanical soil disturbance (de Moraes Sa *et al*. 2014) and permanent organic soil cover with suitable crop diversification options (FAO 2008), that promotes soil organic carbon (SOC) stabilization under the tropical soils of semi-arid India (Ghosh *et al*. 2010; Kumari *et al*. 2011; Choudhury *et al*. 2014).

Soils managed under no-tillage (NT) offers a number of benefits compared with soils under conventional tillage (CT) and thus it has the potential to restrict soil degradation (Salvo *et al*. 2010; Jemai *et al*. 2013; Choudhury *et al*. 2014). Adaptation of NT in legume (chickpea/ fababean/ pea) – wheat (López-Bellido *et al*. 2012) or legume (soybean/ alfalfa) – maize rotations (Karlen *et al*. 2006) over variable periods (3 to 20 years) improved soil quality parameters and yield response, than either continuous mono-cropping and/or CT practices. However, the

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effect of tillage and crop rotation interaction on soil properties varies with duration of NT adaptation and quantity of residue added into soil. Eight years of NT operations increased bulk density, reduced air filled porosity, and increased penetration resistance of the silt loam soils under corn-soybean (Hussain *et al*. 1999) or corn-winter wheat (Hu *et al*. 2007) rotation. In contrast, 6-8 years of continuous NT adaptation reduced bulk density, increased total porosity and improved soil hydraulic properties of the loam soils under maize–mustard/pea (Ghosh *et al*. 2010), wheat-sulla (*Sulla coronaria* L.) / wheat-fava bean (Jemai *et al*. 2013) and *Avena sativa* L. / *X Triticosecale Wit.* / *Vicia sativa* L. / *Brassica napus* L. combinations (Gómez-Paccard *et al*. 2015) under semi-arid Mediterranean climate. Inclusions of C_4 species in C_3 cereal based crop rotation were reported to promote the formation and stabilization of macro-aggregate fractions (Salvo *et al*. 2010). Continuous adoption of NT with crop residue retained on soil surface as mulch increased the proportion of water stable macro-aggregates in rice (direct seeded/ transplanted)-wheat system (Kumari *et al*. 2011; Choudhury *et al*. 2014). Increase in SOC, especially the particulate organic matter C (POM-C) fraction was reported in top layer over a wide range of soil textural classes (Mishra *et al*., 2010; de Moraes Sa *et al*. 2014; Dikgwatlhe *et al*. 2014) and also in C_3 cereal based cropping systems under semi-arid Mediterranean to dry sub-humid warm climatic conditions (Jemai *et al*. 2013). However, the accumulation of SOC under NT practice was limited under boreal agroecosystems (Sheehy *et al*. 2015).

Tillage and crop rotation modifies soil aggregation and SOC dynamics, and is often governed by residue management in a wide range of soil textural classes (Choudhury *et al*. 2014; Sheehy *et al*. 2015). Residue retention on surface promotes macroporosity, accelerates structural development and stability of macroaggregates (Choudhury *et al*. 2014; Mazumdar *et al*. 2015), thereby ensures the physical protection of aggregates against high rainfall energy, helps in conserving soil water and promotes higher yield (Das *et al*. 2013). However, crop residue removal is a common practice in Indian subcontinent, where the demand of crop residues as fodder or grazed *in-situ* is very high. This may lead to decline the SOC and may have adverse impact on crop yield.

Literature is replete with effect of alternate tillage practices on soil properties, but the conjoint tillage-cropping system effects have limited reports. Limited studies have been reported on the impact on soil mechanical properties at both bulk soil and soil aggregate level. In addition, majority of these literatures emphasized on C_3 cereal-based (preferably rice-wheat) cropping systems (Kumari *et al*. 2011; Choudhury *et al*. 2014). In view of problems related with rice-wheat rotations, diversifications of cropping systems are suggested. Effect of three cropping systems (CS), pigeon pea-wheat (P-W), cotton-wheat (C-W) and maize-wheat (M-W) were evaluated under CT and NT with two residue management (retention, +R and removal, -R) options for soil mechanical strength and structural stability, at the end of 7 years in a sandy loam soils of semi-arid India. Furthermore, we measured the oxidizable organic carbon ($KMnO_4$-C) as the labile pool and particulate organic matter C (POM-C) to support our results. The hypotheses tested were (1) soil hydro mechanical properties improved through no tillage practice; (2) crop residue had greater impact than tillage per se; and (3) cropping systems significantly altered the tillage and crop residue interactions.

Materials and Methods

Site description

The present study was conducted at the experimental farm of the ICAR-Indian Agricultural Research Institute, New Delhi (28°37' N, 77°09' E, 228.7 m above mean sea level). The climate is semi-arid with hot and extended summer (32-35 °C) and mild and short winter (13-15 °C). The mean annual rainfall is 750-800 mm, 2/3rd of which occurs during south-west monsoon period (July-September). The soil (0-15 cm) is Typic Haplustept, non-calcareous, mild alkaline in reaction (pH 8.0), sandy loam in texture (sand, silt and clay content vary as 74.0-75.4, 8.4-10.0 and 15.3-17.5%, respectively) and low in soluble salts (EC 0.21 dS m^{-1}).

The experiment was maintained in a split-plot design since *kharif* 2004, with tillage and residue management as main plots and three cropping systems, P-W, C-W and M-W, as sub-plots. The main plot treatments were (1) conventional tillage with residue incorporation (CT+R), (2) no-tillage with residues retention (NT+R), (3) conventional tillage with residue removal (CT-R), and (4) no-tillage with complete residue removal (NT-R). All the treatments were replicated thrice with individual plot size of 6 m × 3 m. During *kharif* season, crops were planted manually by opening furrows and placing seeds, while in *rabi* a multi-crop planter was used for sowing of wheat. All crops were grown with recommended practice of fertilizer and irrigation. The growth duration of rainy sown crops differed with maize (mid-July to mid-October), pigeon pea (early-June to mid-November) and cotton (May-end to November-end). Following harvest of these crops, wheat was grown uniformly from November-end to mid-April. Rainy season crops were sown manually along with 50% basal fertilization, while wheat was sown with no-tillage seed-cum-fertilizer drill. All crops were harvested manually and threshed in the field. A known quantity of residues (3 t ha^{-1}) was returned to the respective plots. This was incorporated into the soil with disc harrow and rotavator under CT and retained as mulch under NT, which almost covered the soil surface. Observations were recorded after 7 years of experimentation during March 2011.

Soil sampling and analysis

Bulk density, penetration resistance and soil water

Bulk density (BD), penetration resistance (PR), and gravimetric water content (θm) were determined in the standing wheat crop during 2011. The PR was measured by using Rimik cone penetrometer (model no. CP20) at intervals of 15 mm to a maximum depth of 45 cm. The measurements were synchronized with θm following irrigation on 74 days after sowing (DAS) and continued till the next irrigation on 95 DAS. All together 5 observations on PR were taken along with θm (0-7.5, 7.5-15, 15-30 and 30-45 cm depths) and the values were averaged (plot- and depth-wise). Soil BD was determined using core method in two replicates per plot (Blake and Hartge 1986) for all the above depths. The θm was converted to volumetric water content (θv) by multiplying with the BD values.

Water stability of soil aggregates

The surface (0-7.5 cm) and sub-surface (7.5-15 cm) layers of the soil were sampled for soil aggregation and organic C content analysis in triplicate from each plot. Field-moist samples were thoroughly mixed, passed through an 8.0 mm sieve by gently breaking up the clods along the natural plane of weakness, and stored at 4 °C in plastic bags till the analysis. Aggregate stability was measured by two methods: (1) wet sieving by Yoder method (Yoder 1936) and (2) fast wetting (FW), slow wetting (SW), and mechanical breakdown (MB) by Le Bissonnais method (Le Bissonnais 1996).

A portion of the collected soil samples was wet-sieved using Yoder apparatus. Both the field-moist (17-21%, g g^{-1}) and air-dried (at room temperature for 7 days) soils were used for the present analysis. Fifty g of the aggregate mass (3-5 mm) was wet-sieved through a set of 2 and 0.25 mm sieves, aiming to separate the large (>2 mm) and small (0.25-2.0 mm) macro-aggregates, and micro-aggregate+clay-and-silt size particles (<0.25 mm). Le Bissonnais method combined three disruptive tests (pre-treatment) corresponding to various wetting conditions and energies: (a) fast wetting (FW), (b) slow wetting (SW), and (c) mechanical breakdown (MB). To obtain uniform dryness, aggregate mass was oven-dried overnight at 40 °C immediately prior to pre-treatment. In FW test, approximately 5 g of aggregates was gently immersed in 50 mL of deionized water for 10 min, while in slow wetting test, aggregates were capillary-wetted at -0.3 kPa suction on a tension table for 30 min, and then gently immersed in water (50 mL). In mechanical breakdown test, 5 g of aggregates were immersed in methanol for 10 min, then transferred into a volumetric flask with 200 mL water, and agitated end-to-end 20 times by hand and left for settling. After these pre-treatments, the samples were transferred into a 0.053 mm sieve previously immersed in methanol and the sieve was moved gently. Aggregates on the 0.053 mm sieve were collected, oven-dried at 105 °C, and dry-sieved using a column of 6 sieves: 2, 1, 0.5, 0.2, 0.1 and 0.053 mm. Four replicates were performed for each pre-treatment. For each of these methods, aggregate mass on each sieve was recorded and aggregate stability was expressed as mean weight diameter (MWD).

Soil carbon fractions

Soil samples were analyzed for total organic carbon (TOC) using the elemental analyzer (Vario EL, Elementar Analysen Systeme GmbH, Germany). The POM fraction was isolated by following the method (Cambardella and Elliott 1992). Briefly here, 10 g of soil (<2 mm) was dispersed in 30 mL of sodium hexametaphosphate solution (5 g L^{-1}) on a reciprocating shaker for 18 h (180 rpm). The suspension was poured onto a 0.053 mm sieve and rinsed thoroughly with distilled water until the silt+clay fractions (<0.053 mm) were completely washed away. The retained fraction was transferred onto a glass beaker and dried at 50 °C. Carbon of the dried fraction (POM-C) was determined by wet digestion with potassium dichromate along with 3:2 H_2SO_4:85%H_3PO_4 digestion mixture in a digestion block set at 120 °C for 2 h (Snyder and Trofymow 1984). Labile C in soil was extracted by 0.33 *M* $KMnO_4$ and determined by adopting Blair method (Blair *et al*. 1995).

Statistical analysis

The statistical analysis was performed using the split-factorial design analysis in SAS 9.4 (Indian NARS Statistical Computing Portal). The design layout was factorial RBD, and results were obtained by ANOVA in split-factorial RBD. Least significant difference (LSD) was used for separation of means and the 95% probability level was taken for statistical significance. Interaction effects among sub-plots and between main plots and sub-plots were obtained.

Results and Discussion

Bulk density (BD) values did not differ either among the tillage-residue options or the cropping systems, irrespective of soil depth (Fig. 1). Marginal decrease in BD (1-2%) was recorded in NT+R at 7.5-15 and 15-30 cm layers compared to NT-R, and the effect of residue was evident. Cropping systems did not register any appreciable change in BD either at surface or at sub-surface layers. Irrespective of tillage or CS, the 15-30 cm layer recorded significantly higher BD (1.72±0.05 Mg m^{-3}), compared to 1.44 (±0.03) and 1.60 (±0.05) Mg m^{-3} at 0-7.5 and 7.5-15 cm layer, respectively, indicating the compaction at sub-surface.

The effect of tillage in reducing BD is transient and reduces with rainfall or irrigation events and with intercultural operations. Similar or lower BD under NT to a depth of 30 cm in short- (4 years) in a Typic Ustochrept and long-term (21 years) experiment in a Eutric Luvisol soil was reported (Shekhawat *et al*. 2016; Zhang *et al*. 2016). In contrast, many researchers have reported increased BD with NT practice due to absence of seasonal tillage and less intercultural operations (Celik 2011; Aikins and Afuakwa 2012). The present results indicated marginal decrease in soil BD across soil depths under NT (at end of 7 years NT practices), which implied that long-term adoption of NT might significantly reduce the sub-surface soil density to a desired level.

The soil resistance to penetration (PR) differed between tillage and residue options, predominantly at upper 0-15 cm layer, but was similar across the CS at all depths (Fig. 1). The PR profile indicated a distinct compact sub-surface layer (>1800 kPa). Significantly less PR was recorded at plough layer (0-15 cm) in NT+R, presumably due to higher average water content (17.6±2.4% during the period of observations, 74-95 DAS).

Compact sub-surface layers have been reported at IARI farm (Aggarwal *et al*. 2006), and other locations in the Indo-Gangetic alluvial plains (Amirinejad *et al*. 2011). Although the BD did not differ appreciably, NT with residue retention as mulch helped in maintaining a higher soil water level, which reduced the soil resistance just below the plough layer.

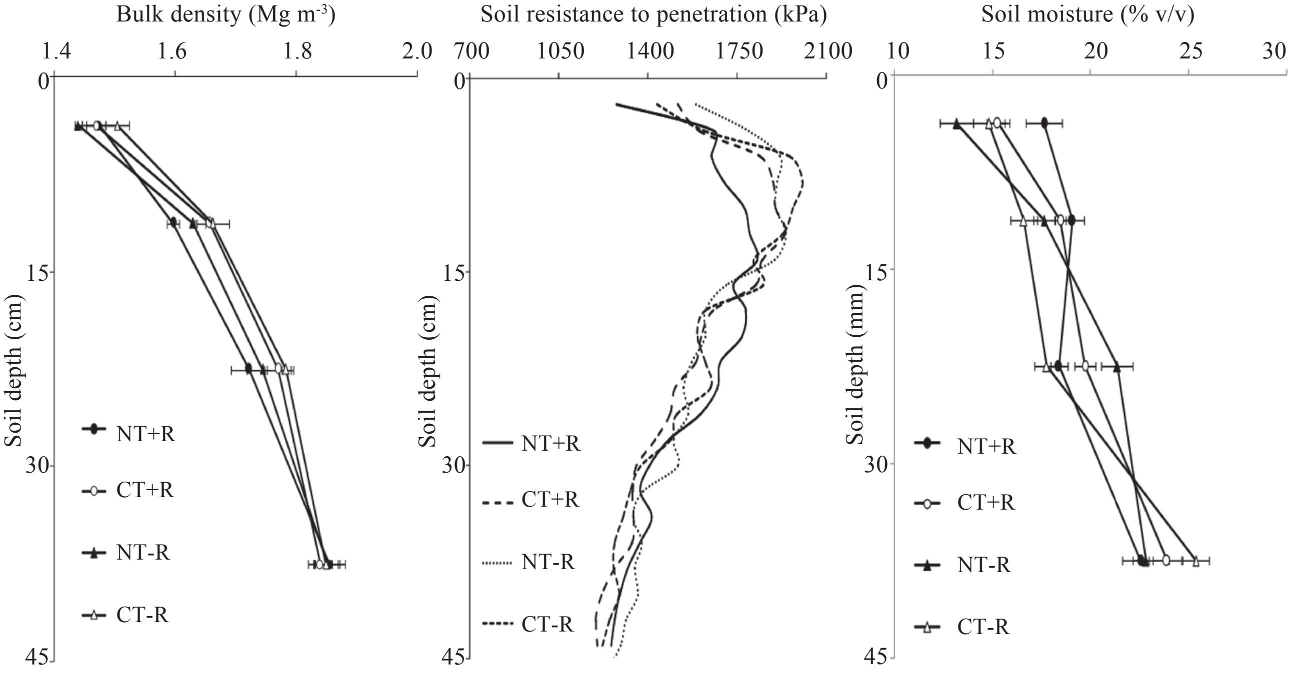

Fig. 1. Bulk density, soil resistance to penetration and soil water content (% v/v) profile under tillage and residue management practices

The crop residue on the surface acted as a barrier between soil surface and solar radiation that checked the evaporation loss. Marginal improvement in soil water content in CT+R could also be attributed to residue incorporation. Down the soil profile, the effect of tillage and residue reduced.

The tillage, CS and their interactions had significant impact on the distribution of soil aggregates, with larger impact on air-dried samples (Table 1). For field-moist samples, tillage, CS and their interactions had significant impacts on large (>2 mm) aggregate fraction. The CS and soil depth had significant interaction effect on large macroaggregate (LM, >2 mm) fraction, and greater amount were recorded in 0-7.5 cm layer across the CS. Across CS, NT+R had significantly higher LM fraction (8.47%) compared to NT-R (7.51%) and CT-R (7.38%), but it was similar with CT+R (8.04%). Other size fractions did not show any difference in either tillage practices or CS. Tillage impacted stability (MWD) of field-moist samples, and both the NT+R and CT+R recorded larger MWD of water-stable aggregates (0.82 mm) compared to NT-R (0.77 mm) and CT-R (0.76 mm), indicating that residue had larger impact than the tillage.

On air-dried samples, tillage, CS and their interactions on the LM fraction were clearly distinguished. Here, CT+R recorded higher LM (7.93%) and small microaggregates (SM, 2-0.25 mm; 42.40%) fraction, which was significantly higher than CT-R (7.39 and 40.55%) and NT-R (7.02 and 38.87%), but was comparable with NT+R (7.79 and 40.92%). Soil depth also showed significant interactions with tillage and CS. Across depths, CT+R had higher LM fractions, while M-W and P-W had greater amount of LM (7.81 and 7.69%) compared to C-W (7.10%) fraction. Tillage and CS also had impacts on SM fraction, but their interactions were non-significant. The water stability of air-dried aggregates was affected by tillage, CS, depths and their interactions. It was higher with NT+R and P-W system, and also in larger amount at 0-7.5 cm layer.

Residue incorporation in CT and retention in NT had clear benefits in stabilizing soil aggregates, and thereby improving soil structure (Mondal *et al.* 2013; Choudhury *et al.* 2014). The NT+R treatment in P-W system had the largest MWD of air-dried aggregates than any other tillage-CS combination and it could be attributed by more leaf foliage and deep root system of peagon pea in P-W system. However, irrespective of aggregates being either field-moist or air-dried, the stability was higher in NT+R and CT+R. This again suggests a larger role of crop residues in formation and imparting the stability of aggregates than the tillage operation per se. The higher amount of macro-aggregate (>0.25 mm) resulting higher MWD in NT+R was likely due to minimum tillage operations, high amount of organic matter content from the addition of crop residue as mulch that protects the soil surface from direct impact of rain drop. In CT+R, the residue incorporation and subsequently the higher TOC may be a major factor for larger aggregate stability. Overall TOC was positively correlated with MWD-FM (r = 0.57, $p < 0.001$) and MWD-AD (r = 0.37, $p = 0.001$) (Mondal *et al.* 2013; Choudhury *et al.* 2014).

The TOC content in soil was significantly impacted by tillage, but the CS had no effect. The data on TOC were therefore averaged over the CS. Averaged over depths, the NT+R had higher TOC (5.84 g kg^{-1}) content than NT-R (4.95 g kg^{-1}) and CT-R (5.43 g kg^{-1}), but it was at par with CT+R treatment (5.79 g kg^{-1}). Surface layers (0-7.5 and 7.5-15 cm) had higher TOC (6.65 g kg^{-1}) compared to the sub-surface layers (4.31 g kg^{-1}).

Table 1. Probability values of the analysis of variance for the effect of tillage and residue management, cropping system, depth and their interactions on relative size distribution of aggregates

Source	Field-moist sample				Air-dry sample				Total organic C
	LM	SM	Mi	MWD	LM	SM	Mi	MWD	
Tillage (T)	0.027	0.249	0.079	0.005	0.005	0.008	0.001	<0.001	0.004
Cropping system (CS)	0.062	0.572	0.824	0.650	<0.001	0.029	0.201	0.718	0.129
T × CS	0.026	0.387	0.182	0.027	<0.001	0.512	0.256	0.005	0.218
Depth (D)	0.004	0.855	0.595	0.069	<0.001	0.520	0.087	<0.001	0.026
T × D	0.498	0.251	0.342	0.625	0.035	0.033	0.020	0.008	0.008
CS × D	<0.001	0.246	0.345	0.033	<0.001	0.069	0.255	0.002	0.759
T × CS × D	0.523	0.886	0.817	0.602	0.736	0.003	0.001	<0.001	0.611

[LM = large (>2 mm) and SM = small (2-0.25 mm) macroaggregates, Mi=microaggregates+clay and silt size aggregates (<0.025 mm)], mean weight diameter (MWD) of water stable aggregates, and total bulk soil organic C

The TOC content decreases with intensive cultivation, which corresponds to a decrease in aggregate stability (Król *et al*. 2013). Similarly, in second layer, residue treated plots registered significantly higher TOC content in comparison to untreated plots. Further down the profile, no change in TOC was observed among the treatments. Effect of CS on TOC was non-significant irrespective of depth of soil. It is apparent that higher TOC in NT+R and CT+R, might be due to residue retention and incorporation, respectively, while continuous residue removal in NT-R and CT-R resulted in lower organic C content. Results also suggested that higher dependency on crop residue addition for build-up of TOC than the tillage alone.

Tillage and residue management had significant impact on MWDs of aggregates which were subjected to variable disruptive energies (Table 2). Soil aggregates were more stable and gave resistance to breakdown under slow wetting. The lowest MWD of soil sample were recorded under fast wetting due to rapid rupture and destruction of aggregates through entrapped air and rapid slaking in water. The slow wetting refers to disruption of aggregates when the water slowly moves in (capillary wetting), while only mechanical forces (motion of aggregates in water and not the entry of water in aggregates) are responsible for aggregate disruption in the mechanical breakdown test. The NT+R treatment resulted in higher aggregate-MWD under all three stability tests (p = 0.002, 0.006, and 0.008 in FW, SW and MB tests, respectively). Effect of crop residue was larger than that of tillage as indicated by the MWD (mean of three stability tests) of aggregates which followed the order: NT+R (0.69 mm) > CT+R (0.66 mm) > NT-R (0.62 mm) > CT-R (0.57) (*LSD = 0.05; p = 0.002*).

The higher MWD in NT+R and CT+R were due to crop residue either retained as mulch or incorporated into the soil, which resulted in higher C in soil and subsequently helped in aggregates stabilization (Bandyopadhyay *et al*. 2010; Karami *et al*. 2012). Crop residue therefore facilitated a better

Table 2. Mean weight diameter (MWD) (mm) of soil aggregates (0-7.5 cm) under three stability tests (FW-Fast wetting; SW-Slow wetting; MB-Mechanical breakdown) and soil carbon pools (g kg^{-1}) under the tillage and cropping systems

Tillage	Cropping systems (CS)	Mean weight diameter (mm)				$KMnO_4$-C	POM-C
		FW	SW	MB	Mean	(g kg^{-1} soil)	
CT+R	P-W	0.63	0.73	0.68	0.68	1.98	1.23
	C-W	0.60	0.72	0.69	0.67	1.88	1.26
	M-W	0.59	0.68	0.61	0.63	1.59	1.06
NT+R	P-W	0.66	0.72	0.67	0.68	1.85	1.21
	C-W	0.62	0.74	0.70	0.69	1.90	1.19
	M-W	0.66	0.72	0.68	0.69	1.58	1.18
CT-R	P-W	0.51	0.65	0.53	0.56	1.81	1.16
	C-W	0.60	0.58	0.56	0.58	1.64	0.84
	M-W	0.51	0.65	0.58	0.58	1.60	0.97
NT-R	P-W	0.59	0.68	0.59	0.62	1.41	0.84
	C-W	0.58	0.71	0.57	0.62	1.41	0.98
	M-W	0.53	0.66	0.63	0.62	1.42	1.09
Mean							
	CT+R	0.60	0.71	0.66	0.66	1.82	1.18
	NT+R	0.65	0.73	0.68	0.69	1.78	1.20
	CT-R	0.54	0.62	0.55	0.57	1.68	0.99
	NT-R	0.58	0.68	0.60	0.62	1.37	0.84
	P-W	0.60	0.70	0.62	0.64	1.76	1.11
	C-W	0.60	0.69	0.63	0.64	1.71	1.03
	M-W	0.58	0.68	0.63	0.63	1.52	1.01
LSD (P=0.05)	Tillage	0.06	0.11	0.10	0.05	0.19	0.24
		(0.002)	(0.006)	(0.008)	(0.002)	(0.005)	(0.004)
	CS	NS	NS	NS	NS	0.22	NS
		(0.59)	(0.28)	(0.76)	(0.94)	(0.02)	(0.51)
	Interaction	NS	NS	NS	NS	NS	NS
		(0.25)	(0.18)	(0.29)	(0.72)	(0.74)	(0.73)

soil hydromechanical regime at the bulk and/or aggregate scales, which could promote root growth and its distribution in wheat in the same soil, reported elsewhere (Mondal *et al*. 2014). The CS had no impact on aggregate stability, and tillage-CS interactions were also non-significant.

The effect of tillage and residue management on C pools ($KMnO_4$- and POM-C) was evident. Residue incorporation or retention increased the $KMnO_4$-C and POM-C by 8-29 per cent (*p=0.005*) and 19-42 per cent (*p=0.004*) compared to residue removal, respectively. However, CT+R, NT+R and CT-R had similar $KMnO_4$-C levels. Significantly lower $KMnO_4$-C was recorded in NT-R (1.37 g kg^{-1}). In NT-R, soil was undisturbed and the residue was removed, giving limited option of oxidization of readily available organic matter, and therefore, evolution of $KMnO_4$-C. The $KMnO_4$-C is the labile form of soil C, and we observe a significant reduction (4-31%; $p = 0.005$) in this soil C fraction under NT-R after 7 years irrespective of the cropping systems. The P-W and C-W had higher $KMnO_4$-C compared to M-W system. The POM-C content in NT+R was significantly higher than NT-R and marginally higher than CT-R but was at par with CT+R ($p = 0.004$).

Both the C pools ($KMnO_4$-C and POM-C) clearly explain that NT without crop residue can significantly reduce soil C and could have been worse than the conventional tillage without residue. There are reports on higher amounts of POM-C under NT than CT due to crop residue retention, particularly in the surface layer (Duval *et al*. 2013; Liu *et al*. 2014). Cropping system effect on $KMnO_4$-C was significant, while on POM-C, the effect was non-significant. Both the C pools ($KMnO_4$-C and POM-C) contents were the highest in legume-based CS (P-W). High amount of C in soils of P-W system can be attributed to greater residue accumulation from pigeon pea and the ability of the crop to fix atmospheric N and thereby maintain higher soil C (Drinkwater *et al*. 1998).

Tillage and crop residue management had impact on soil mechanical strength and stability of aggregates under various cropping systems. No-tillage with crop residue as mulch improved soil water content and reduced the sub-surface compaction. Crop residue retention in either CT or NT systems maintained soil aggregation and organic C content. Effect of NT with crop residue in different cropping systems with different quantities of crop residue addition vary and need extensive study.

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