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Influence of sequential tillage and residue management practices on soil and root parameters in soybean (*Glycine max*) - wheat (*Triticum aestivum*) cropping system

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ABSTRACT

A field study was conducted in 2009-10 and 2010-11 at Indian Agricultural Research Institute, New Delhi to assess the effect of sequential tillage and crop establishment and residue management practices on soil health and root parameters in soybean [*Glycine max* (L.) Merr.] – wheat (*Triticum aestivum* L.) cropping system. The results pertaining to the experiments at the end of the two year study revealed that most of the soil properties except infiltration rate and microbial biomass carbon (MBC); and root parameters of both crops except root length density (RLD) and average root diameter of wheat were non-significant by the sequential tillage and crop establishment treatments. Unlike sequential tillage and crop establishment techniques, all soil properties except bulk density, pH, EC and root parameters of both soybean and wheat responded significantly to the residue management practices. The infiltration rate was significantly higher with skipping the sequence of CT-Flat by ZT-Flat. Skipping the sequence of CT-Flat and bed with ZT-Flat and bed recorded higher soil mean weight diameter (MWD) and grand mean diameter (GMD) at 0-10 cm soil depth than the counterpart by skipping of ZT-Flat and bed with CT-Flat and bed. The percentage of soil macro-aggregate was high by skipping ZT-Flat and bed with CT-flat and bed at all depths while the reverse was exhibited in case of percentage soil micro-aggregates by skipping CT-Flat and bed with ZT-Flat and bed. By skipping CT-flat and bed with ZT-flat and bed significantly higher soil MBC was recorded than the counterpart skipping tillage treatments. The same significant trend was also exhibited for soil MBC with residue management treatments, where the wheat + soybean residue application recorded 20.90 % higher than the control. Root parameters like RLD, root surface area (RSA), root volume density (RVD), average root diameter (ARD) in soybean while these were partly non-significant (RSD and RVD) in wheat with the sequential tillage and crop establishment treatments, whereas the residue management practices significantly influenced the root parameters of both the crops. Among the residue management practices, wheat + soybean residue obtained higher RLD (2.57 and 1.03 cm/cm^3); RSA (0.79 and 0.32 cm^2/cm^3); RVD (18.11 and 7.46×10^{-3} cm^3/cm^3) and average root diameter (1.04 and 0.85 mm) both in soybean and wheat crops than rest of the treatments. Thus, impact of short-term zero tillage is short lived for favourable soil health and root parameters when skipping with conventional tillage.

Key words: Bed and flat planting, Continuous tillage (CT), Soybean–wheat cropping system, Soil parameters, Zero tillage (ZT)

Soybean [*Glycine max* (L.) Merr]–wheat (*Triticum aestivum* L.) cropping system could be a more remunerative by adopting conservation tillage without affecting the system productivity (Chauhan 2007, Mishra and Singh 2009). Tillage is used for creating better environment for plant growth but the degree varies widely with the type of tillage method. Altering the tillage system by sequential tillage will influence the soil health, root morphology of the crop and weed species composition. The tillage sequence within a crop rotation is often unrecognized as a rotational component but like crop rotations, the sequence may reduce weeds, and other pests if managed properly in annual cropping systems (Carter 1994). Soil health (physical, chemical and biological properties) is an important criterion to maintain it under dynamic equilibrium so as to sustain the productivity, improve the resource use efficiency of soybean-wheat cropping system. While there is an abundance of field studies that support the beneficial impact on soil health (for examples on chemical, physical and biological properties, e.g. Lal 1997, Roldan *et al*. 2003, Brevault *et al*. 2007). To assure normal plant growth, the soil must be in such conditions that roots have enough air, water and nutrients (Husnjak *et al*. 2002). Root morphology of any crop is dependent on the soil environment which ultimately governed by the tillage practices. Soil management practices like tillage, bed formation and crop

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residue incorporation into soil enhanced root proliferation as evident from increase in RLD (Aggarwal and Goswami 2003). Much works were carried out on continuous zero tillage, for more than decades there is paucity of information in respect to sequential tillage impacts on changes in soil health and root growth for the system as a whole. Hence, the present investigation was undertaken to study the effect of tillage and residue management practices on soil physico-chemical properties and root parameters in soybean-wheat cropping system in NWPZ of India.

MATERIALS AND METHODS

The field experiment was conducted during *kharif* and *rabi* 2009-10 and 2010-11 at the research farm of Division of Agronomy, Indian Agricultural Research Institute, New Delhi, situated at 28.4°N latitude and 77.1°E longitude and at an altitude of 228.6 meters above mean sea level. The soil of the experimental field was a sandy clay loam in texture, neutral in reaction (pH 7.6), low in organic carbon (0.38 %), low in available N (150 kg/ha), medium in available P (11.2 kg/ha) and available K (245 kg/ha). The experiment was laid out in split plot design with three replications in a fixed lay out. The main plot treatments consisted of four sequential tillage and crop establishment techniques to soybean and wheat, viz. conventional tillage-flat–zero tillage-flat (CT-F–ZT-F); zero tillage-flat–conventional tillage-flat (ZT-F–CT-F); conventional tillage-bed–zero tillage-bed (CT-B–ZT-B) and zero tillage-bed–conventional tillage-bed (ZT-B–CT-B) while the sub plot treatments were four residue management practices, viz. control, wheat residue (3 tonnes/ha), soybean residue (3 tonnes/ha) and soybean + wheat residue (3 tonnes/ha each). The soybean variety DS 9814 during *kharif* (June to October) and wheat variety PBW 550 during *rabi* (November to April) were grown at row to row spacing of 35 cm and 20 cm, respectively. Well dried crop residues of wheat and soybean of previous season were applied @ 3 tonnes/ha to soybean and wheat crop, respectively, by spreading the material uniformly a week before preparation of the field for sowing. In conventional tillage–flat: After the harvest of previous crop the plots were ploughed with a disc harrow twice. Further cultivator was run twice followed by planking before sowing of soybean. In conventional tillage–bed: Soybean was sown with the help of bed planter after the land preparation. The beds were formed at a distance of 67.5 cm from bed to bed. In zero tillage–flat: No tillage operation was carried out after harvest of previous crop, soybean was sown with the help of zero-till seed drill. In zero tillage–bed: Soybean was sown with the help of bed planter without any tillage operation. The recommended practice of fertilizers application was followed to both the crops. The N, P and K were given in the form of urea, single super phosphate and muriate of potash, respectively in soybean @ 20:60:40 N, P_2O_5 and K_2O kg/ha and in wheat @ 120:60:40 N, P_2O_5 and K_2O kg/ha. In soybean Pendimethalin @ 0.75 kg a.i/ha was applied as pre-emergence followed by two hand weeding at 20 DAS and 40 DAS and in wheat one blanket spray of Paraquat was made before sowing of the crop only in zero tillage plots followed by application of Isoproturon and 2,4-D at 30-35 DAS to ZT and CT plots.

Soil bulk density of surface (0-15 cm) and sub surface (15-30 cm) soil was determined by the core sampler method (Piper 1950) from three randomly chosen areas of each plot. The procedure for determining bulk density was followed as described by Chopra and Kanwar (1991). Hydraulic conductivity is estimated by using the formula K =QL/HAT where, Q is the quantity of water collected, L is the length of sample (cm), H is the loss in head (cm). Infiltration rate is measured using double ring infiltrometer (Bouwer 1986). The required volumes of water was added in the inner ring of 20 cm diameter and 15 cm height driven 3 cm inside the soil after specific time periods depending on the water intake rate. The fall of water (i.e soil intake) in the inner ring was determined through measuring the addition of water by the one litre measuring cylinder to the inner ring to keep the water level constant and this change in water with the measuring cylinder was expressed as cm/h. The mean weight diameter (MWD) of soil aggregates were determined using the procedure given by (Kemper and Roseneau 1986) MWD = $\sum$ Xi. Wi where, Wi, is the proportion of aggregates returned and the sieves in relation to the whole, Xi is the mean diameter of the class (mm). The line between macro- and micro- aggregates of soil is commonly drawn at 0.25 mm (Oades and Waters 1991). Soil samples collected from individual plots were analysed for organic carbon content by wet digestion method (Walkley and Black 1934), available nitrogen by alkaline $KMnO_4$ method (Subbiah and Asija 1956), available phosphorous by 0.5 M sodium bicarbonate extraction (Olsen *et al*. 1954) and available potassium by Flame photometry (Jackson 1973). Microbial biomass carbon (MBC) of soil was determined by the modified fumigation-extraction method of Vance *et al*. (1987). Root samples were taken in second year only once at flowering stage in soybean and grain filling stage in wheat by adopting standard procedure (Aggarwal and Sharma 2002) and studied the root morphological characteristics based on Regent's non-statistical method (Arsenault *et al*. 1995, Guay and Arsenault 1996).

RESULTS AND DISCUSSION

Soil physical properties

Bulk density had no significant variation at two different depths (0-15 and 15-30 cm) of soil layer among sequential tillage and crop establishment practices (Table 1) after harvest of *rabi* season crop in 2010-11. However, the maximum bulk density was registered by CT-Flat (S) – ZT-Flat (W) (1.70 and 1.75 g/cm^3) at 0-15 and 15-30 cm, soil layers respectively while lowest bulk density was recorded with CT-Bed (S) – ZT-Bed (W) treatment during both the years. The higher value of soil bulk density observed under ZT both in the surface and subsurface layers of flat and bed plots in the *rabi* season sequence may be due to non-

Table 1 Effect of sequential tillage, crop establishment techniques and residue management on bulk density, hydraulic conductivity and infiltration rate of soil

Treatment	Bulk density (g/cm^3)		Hydraulic conductivity (cm/h)		Infiltration rate (cm/h)
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	
Tillage and crop establishment					
CT-Flat (S)–ZT-Flat (W)	1.70	1.75	1.22	1.01	1.15
ZT-Flat (S)–CT-Flat (W)	1.67	1.71	1.11	0.90	1.10
CT-Bed (S)–ZT-Bed (W)	1.67	1.71	1.20	0.98	1.13
ZT-Bed (S)–CT-Bed (W)	1.66	1.69	1.05	0.85	1.07
SEm ±	0.008	0.012	0.038	0.034	0.015
CD (P=0.05)	NS	NS	NS	NS	0.052
Residue management					
No residue	1.70	1.75	1.06	0.86	1.09
Wheat residue	1.67	1.72	1.15	0.93	1.10
Soybean residue	1.67	1.71	1.14	0.96	1.10
Wheat + soybean residue	1.65	1.69	1.23	1.00	1.15
SEm ±	0.010	0.010	0.025	0.018	0.013
CD (P=0.05)	NS	NS	0.074	0.053	0.038

disturbance of the soil matrix for almost an year in the sequence, which may perhaps resulted in less total porosity compared to tilled plots (Bhattacharyya *et al*. 2008). Residue treatments were also non-significant for BD at two depths. The highest bulk density was recorded in the no residue treatments (1.70 and 1.75 g/cm^3) in 0-15 and 15-30 cm depth. The lowest bulk density was registered with wheat + soybean residue treatment at 0-15 and 15-30 cm depth of soil layers. This is in conformity with the findings of Obalum and Obi (2010).

Hydraulic conductivity had no significant variation at 0-15 and 15-30 cm depth of soil layers with sequential tillage and crop establishment treatments (Table 1) after harvest of *rabi* season crop in 2010-11. However, The maximum hydraulic conductivity was recorded with CT-Flat (S) – ZT-Flat (W) (1.22 and 1.01 cm/h). This is due to continuous channels formed by decaying roots of previous season crops serve as routes linking the soil surface to deeper layers and this corroborate the findings of Williams and Weil (2004), while the minimum was obtained with ZT-Bed (S) – CT-Bed (W) (1.05 and 0.85 cm/h) at 0-15 and 15-30 cm depth of soil layer. The maximum hydraulic conductivity of soil was recorded with wheat + soybean residue treatment (1.23 and 1.00 cm/h) at 0-15 and 15-30 cm depth of soil, while the lowest was recorded with control.

Infiltration rate was significantly influenced by the sequential tillage and crop establishment treatments (Table 1). The ZT-Flat (S)–CT-Flat (W) treatment recorded significantly maximum infiltration rate (1.15 cm/h) which was at par with CT-Bed (S)–ZT-Bed (W) (1.13 cm/h) and significantly higher than rest of the tillage and crop establishment treatments. Residue management treatments significantly influenced the infiltration rate of the soil. Nevertheless, no residue, wheat residue and soybean residue were at par with each other while heat + soybean were significantly higher than the rest of the treatments which was 5.9 % higher than no residue treatment.

Soil aggregation was analysed in main plots to determine the wet stability of aggregates, expressed in terms of mean weight diameter (MWD) and grand mean diameter (GMD) (Table 2). At all three depths (0-10, 10-20 and 20-30 cm) of soil the mean weight diameter (MWD) was found to be maximum with CT-Bed (S) – ZT-Bed (W) which was 35.2, 20.6 and 15.9% higher than the fresh bed ZT-Bed (S) – CT-Bed (W). The bed system of crop establishment was found to perform better MWD than the flat system of crop establishment. The CT-Flat (S) – ZT-Flat (W) and CT-Bed (S) – ZT-Bed (W) was found to 96.5 and 35.2 % at 0-10 cm; 15.6 and 20.7% at 10-20 cm and 11.3 and 15.9 % at 20-30 cm higher than their counterpart treatments. The top layer (0-10 cm) was recorded the maximum MWD irrespective of the sequential tillage and

Table 2 Effect of sequential tillage and crop establishment on MWD and GMD of soil

Treatment	Mean weight diameter (MWD) (mm)			Grand mean diameter (GMD)		
	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm
Tillage and crop establishment						
CT-Flat (S)–ZT-Flat (W)	0.786	0.319	0.267	0.444	0.394	0.371
ZT-Flat (S)–CT-Flat (W)	0.400	0.276	0.240	0.407	0.381	0.370
CT-Bed (S)–ZT-Bed (W)	0.707	0.393	0.284	0.471	0.409	0.385
ZT-Bed (S)–CT-Bed (W)	0.523	0.326	0.245	0.431	0.404	0.350

Table 3 Effect of sequential tillage and crop establishment on percentage of micro and macro aggregates of soil

Treatment	Percentage of micro aggregate(<0.25 mm)			Percentage of macro aggregate (>0.25 mm)		
	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm
Tillage and crop establishment						
CT-Flat (S)–ZT-Flat (W)	71.75	77.80	82.40	28.25	22.20	17.60
ZT-Flat (S)–CT-Flat (W)	75.55	79.80	81.30	24.45	20.20	18.70
CT-Bed (S)–ZT-Bed (W)	65.25	73.65	81.00	34.75	26.35	19.00
ZT-Bed (S)–CT-Bed (W)	74.75	75.25	86.80	25.25	24.75	13.20

crop establishment treatments. The MWD exhibited a decreasing trend from top to bottom of the soil in all the sequential tillage treatments. Apparently the GMD with CT-Bed (S) – ZT-Bed (W) was also exhibited the same trend as that of MWD throughout all the depths. The maximum percentage of micro aggregate was obtained with ZT-Flat (S) – CT-Flat (W) at the top 0-10 cm depth of soil layer while the minimum was obtained with CT-Bed (S) – ZT-Bed (W) system of tillage and crop establishment (Table 3). The pronounced effect of sequential tillage and crop establishment and residue management treatment is more or less similar percentage of micro aggregate till the deeper layers which indicated the direct impact of skipping/sequential tillage alternating with *kharif* and *rabi* seasons. As the depth of soil increased the percentage of micro aggregates were also increased but the reverse was true for macro aggregate. The maximum percentage of macro aggregate was found to record with CT-Bed (S) – ZT-Bed (W) treatment . Similar results were reported by Whalen *et al*. (2003).

Soil chemical properties

Available NPK of soil was non-significant with sequential tillage and crop establishment treatments (Table 4). In most of the cases the available NPK status of the soil was found to be more or less similar with the tillage treatments. The residue management practices significantly influenced the post harvest soil available NPK status. The wheat + soybean residue treatment recorded the maximum available NPK which was at par with soybean residue treatment and these two were significantly different from the control and wheat residue treatments. This is in agreement with results of Verhulst *et al*. (2009) in that they reported the soil was rich in those nutrients or adequate amounts of fertilizers were applied.

Soil organic carbon (SOC) was non-significant with sequential tillage and crop establishment treatments (Table 4). However, the maximum SOC was obtained with CT-Flat (S)–ZT-Flat (W) (0.40%) while the minimum was obtained with ZT-Flat (S)-CT-Flat(W) (0.38%). Evidently, in our study the SOM were not significantly influenced by the sequential tillage treatments due to the sequential nature of tillage during *kharif* and *rabi* seasons resulted in similar SOM. There was an improvement in the organic carbon content by the application of crop residue. Incremental increase in SOC was recorded with residue management treatments from control to wheat + soybean residue. The maximum was obtained with wheat + soybean residue (0.42%) which was statistically at par with wheat and soybean residue while differed significantly with no residue by 15.8%. Similar findings were also reported by Sarkar and Kar (2011).

Table 4 Effect of sequential tillage and crop establishment techniques, and residue management on chemical properties and MBC of soil

Treatment	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)	Organic carbon (%)	pH	EC (dS/m)	MBC (µg/g) of soil
Tillage and crop establishment							
CT-Flat (S)–ZT-Flat (W)	149.6	11.06	243.7	0.402	7.412	0.314	213.1
ZT-Flat (S)–CT-Flat (W)	148.9	10.66	238.7	0.384	7.460	0.313	195.1
CT-Bed (S)–ZT-Bed (W)	147.3	11.02	242.0	0.397	7.441	0.313	209.6
ZT-Bed (S)–CT-Bed (W)	148.8	11.04	238.9	0.390	7.497	0.320	189.3
SEm ±	1.67	0.470	1.17	0.022	0.035	0.008	3.430
CD (P=0.05)	NS	NS	NS	NS	NS	NS	11.87
Residue management							
No residue	145.3	9.96	236.2	0.362	7.527	0.314	183.3
Wheat residue	147.6	10.76	239.2	0.395	7.473	0.312	195.0
Soybean residue	150.0	11.38	242.5	0.397	7.433	0.316	207.4
Wheat + soybean residue	151.8	11.69	245.4	0.419	7.376	0.318	221.6
SEm ±	1.21	0.198	1.04	0.013	0.038	0.010	1.515
CD (P=0.05)	3.5	0.578	3.0	0.039	NS	NS	4.422

The pH of the soil was non-significant due to sequential tillage and crop establishment treatments (Table 4). Nevertheless, the maximum pH of the soil was recorded with ZT-Bed (S) – CT-Bed (W) (7.50), whereas the lowest pH was recorded with CT-Flat (S) – ZT-Flat (W) (7.41) treatment. The pH of the soil did not alter significantly by the different residue management practices however, the maximum pH was recorded in the no residue treatment and the lowest pH was recorded in the combination of wheat + soybean residue treatment. Combined application of wheat + soybean residue recorded 2.0% lesser pH than the no residue treatment. These findings were in conformity with Malhi *et al*. (2011). Electrical conductivity (EC) of the soil had not influenced significantly by the sequential and crop establishment treatments (Table 4). However, the maximum EC was recorded in ZT-Bed (S) – CT-Bed (W) (0.320 dS/m) and the lowest was recorded with ZT-Flat (S) – CT-Flat (W) and CT-Bed (S) – ZT-Bed (W) treatments. The EC of the soil was non-significant with residue management treatments. However, apparent increasing trend was obtained with the residue management treatments with varying sources and combination of crop residues. The wheat + soybean residue treatment recorded the maximum EC (0.318 dS/m) while the least with control (0.314 dS/m).

Biological properties

Microbial biomass carbon (MBC) had higher values in sequential tillage with ZT both flat and bed crop establishment in the *rabi* season [CT-Flat (S)–ZT-Flat (W) and CT-Bed (S)–ZT-Bed (W)] which was 9.2 and 11.0% with the counterpart treatments of flat and bed system of crop establishment treatments (Table 4). In sequential tillage flat system of crop establishment expressed the superiority over the bed system of crop establishment treatments irrespective of the ZT/CT in the *rabi* season. The maximum MBC was obtained with CT-Flat (S)–ZT-Flat (W) which was at par with CT-Bed (S)–ZT-Bed (W) while the other two treatments recorded the lower level of MBC. MBC had attained significantly higher levels with the varying sources and levels of residue management practices. All the residue management treatments were significantly differed among each other. The wheat + soybean residue recorded the maximum MBC (221.6 μg/g of soil) which was 6.9, 13.6 and 20.9% higher level than the soybean residue, wheat residue and no residue treatments, respectively.

Root parameters

Root parameters of soybean did not influence significantly by the sequential tillage and residue management practices (Table 5). Root length density (RLD) was not differed significantly with sequential tillage and crop establishment practices however the maximum RLD was obtained with CT-Flat (S) – ZT-Flat (W) while the minimum was with ZT-Bed (S) – CT-Bed (W). Numerically higher RLD was recorded with flat system than the bed system of crop establishment. Wheat + soybean residue treatment was found to record statistically higher RLD than the rest of the treatments while no residue, wheat residue and soybean residue treatments were found to be at par with each other. The root surface area density (RSD) of the soybean at 0-15 cm depth of soil layer did not influence significantly by the sequential tillage and crop establishment treatments. The maximum RSD was observed with CT-Flat (S) – ZT-Flat (W) (0.65 cm^2/cm^3) followed by ZT-Flat (S) – CT-Flat (W) (0.62 cm^2/cm^3), CT-Bed (S) – ZT-Bed (W) (0.63 cm^2/cm^3) and ZT-Bed (S) – CT-Bed (W) (0.61 cm^2/cm^3). The highest RSD was observed for wheat + soybean (0.79 cm^2/cm^3) which was significantly higher than the no residue, wheat residue and soybean residue while the lesser with no residue treatments. The root volume density (RVD) of soybean did not influence significantly by the sequential tillage and crop establishment treatments. The highest was with CT-Flat (S) – ZT-Flat (W) which was 4.0% higher than ZT-Flat (S) – CT-Flat

Table 5 Effect of sequential tillage and crop establishment techniques, and residue management on root parameters of soybean at 0-15 cm depth during 2010

Treatment	Root length density (cm/cm^3)	Root surface area density (cm^2/cm^3)	Root volume density ($\times 10^{-3}$ cm^3/cm^3)	Average root diameter (mm)
Tillage and crop establishment				
CT-Flat (S)–ZT-Flat (W)	2.36	0.65	15.96	0.99
ZT-Flat (S)–CT-Flat (W)	2.25	0.62	15.35	0.92
CT-Bed (S)–ZT-Bed (W)	2.30	0.63	15.04	0.87
ZT-Bed (S)–CT-Bed (W)	2.01	0.61	14.30	0.84
SEm ±	0.135	0.017	0.700	0.044
CD (P=0.05)	NS	NS	NS	NS
Residue management				
No residue	1.99	0.52	12.97	0.79
Wheat residue	2.12	0.57	13.94	0.88
Soybean residue	2.24	0.63	15.62	0.91
Wheat + soybean residue	2.57	0.79	18.11	1.04
SEm ±	0.077	0.014	0.290	0.015
CD (P=0.05)	0.225	0.041	0.846	0.045

Table 6 Effect of sequential tillage and crop establishment techniques, and residue management on root parameters of wheat at 0-15 cm depth during 2010-11

Treatment	Root length density (cm/cm^3)	Root surface area density (cm^2/cm^3)	Root volume density (× 10^{-3} cm^3/cm^3)	Average root diameter (mm)
Tillage and crop establishment				
CT-Flat (S)–ZT-Flat (W)	1.01	0.30	7.31	0.74
ZT-Flat (S)–CT-Flat (W)	0.95	0.27	6.96	0.69
CT-Bed (S)–ZT-Bed (W)	0.97	0.28	7.06	0.67
ZT-Bed (S)–CT-Bed (W)	0.91	0.27	6.68	0.67
SEm ±	0.014	0.014	0.331	0.015
CD (P=0.05)	0.047	NS	NS	0.051
Residue management				
No residue	0.89	0.24	6.62	0.58
Wheat residue	0.94	0.27	6.77	0.63
Soybean residue	0.99	0.30	7.16	0.71
Wheat + soybean residue	1.03	0.32	7.46	0.85
SEm ±	0.006	0.003	0.037	0.009
CD (P=0.05)	0.018	0.008	0.107	0.027

(W) likewise CT-Bed (S) – ZT-Bed (W) was 5.2% higher than the ZT-Bed (S) – CT-Bed (W). Wheat + soybean residue was found to record significantly higher RVD which was 15.9, 29.9 and 39.6% than soybean residue, wheat residue and no residue treatment respectively. The sequential tillage and crop establishment treatments did not influence the average root diameter of soybean at 0-15 cm layer of soil depth. However, the maximum with CT-Flat (S) – ZT-Flat (W) (0.99 mm) while the minimum was with ZT-Bed (S) – CT-Bed (W) (0.84mm) and it was better with flat system than the bed system of crop establishment treatments. Wheat + soybean residue recorded the maximum average root diameter while the minimum with no residue treatments. No residue and wheat residue treatment were found to be at par with each other.

Sequential tillage and crop establishment treatments did influence the RLD of wheat at 0-15 cm layer of depth (Table 6). The maximum RLD was recorded with CT-Flat (S) – ZT-Flat (W) while the minimum was obtained with ZT-Bed (S) – CT-Bed (W). The RLD of ZT-Flat (S) – CT-Flat (W) and CT-Bed (S) – ZT-Bed (W) were at par. The break of conventional tillage sequence by zero tillage during *rabi*/summer season in wheat was found to perform better than adoption of conventional tillage in the zero tillage sequence. The maximum RLD was recorded with wheat + soybean residue (1.03 cm/cm^3) which was significantly higher than the no residue, wheat residue and soybean residue by 15.73, 9.57 and 4.0% respectively. The RSD was not influenced significantly by the sequential tillage and crop establishment treatments. However, the maximum RSD was found to record with CT-Flat (S) – ZT-Flat (W) (0.30 cm^2/cm^3) which was followed by CT-Bed (S) – ZT-Bed (W) (0.28 cm^2/cm^3) while numerically the same RSD (0.27 cm^2/cm^3) was obtained with ZT-Flat (S) – CT-Flat (W) and ZT-Bed (S) – CT-Bed (W). The maximum RSD of wheat was obtained with wheat + soybean residue which was significantly higher than no residue, wheat residue and soybean residue by 33.3, 18.5 and 6.7% respectively. Sequential tillage and residue management treatments did not influence the RVD of the soybean however the maximum was recorded with CT-Flat (S) – ZT-Flat (W) while the minimum was with ZT-Bed (S) – CT-Bed (W). Irrespective of the crop establishment (flat/bed) zero tillage rotated with conventional tillage sequence in *rabi*/summer season found to perform better than skipping zero tillage rotation with conventional tillage. The residue management treatment was found to significantly influence the RVD of wheat at 0-15 cm depth of soil layer. The maximum RVD was obtained with wheat + soybean residue which was 4.2, 10.2 and 12.7% higher than soybean residue, wheat residue and no residue treatment respectively. Evidently the average root diameter of wheat was significantly influenced by the sequential tillage and crop establishment treatments. The CT-Flat (S) – ZT-Flat (W) was found to obtain maximum average root diameter (0.74 mm) which was followed by the ZT-Flat (S) – CT-Flat (W) (0.69 mm) while both CT-Bed (S) – ZT-Bed (W)and ZT-Bed (S) – CT-Bed (W) were at par (0.67 mm). Apparently the flat system of crop establishment was found to perform better than the bed system of crop establishment. Wheat + soybean residue application was found to obtain the maximum average root diameter while the minimum was with no residue treatment. The wheat + soybean residue treatment recorded 19.7, 34.9 and 46.6% higher average root diameter than the soybean residue, wheat residue and no residue treatment. Root growth varies considerably with environmental conditions (Stoffel *et al*. 1995).

Thus results of the present investigation clearly demonstrate that ZT either flat or bed in sequential tillage either in *kharif* for soybean or in *rabi* for wheat can be successfully adopted for better soil properties, plant root growth and sustainability of the production system in the soybean-wheat in sequence in the North Western Plain Zone (NWPZ) of India.

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