

Effects of Tillage, Residue and Fertilizer Nitrogen on Crop Yields, and Soil Physical Properties Under Soybean–Wheat Rotation in Vertisols of Central India

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Abstract Soybean–wheat cropping system is predominant in vertisols of central India. Long-term field experiment was conducted to assess the effect of four tillage systems [conventional tillage (CT), mouldboard tillage (MB), reduced tillage (RT) and no tillage (NT)] and three rates of fertilizer N (50, 100 and 150 % of recommended fertilizer) on crop yields, root growth, soil organic carbon (SOC) content and physical properties in soybean–wheat cropping system. Productivity of soybean and wheat was similar in different tillage systems. Response of fertilizer N was not influenced by tillage systems, and crop response to fertilizer N was generally observed up to 100 % of the recommended N fertilizer. Root length density of soybean in the top 15 cm depth was higher in NT and RT than in MB and CT. An improvement in selected soil physical properties like soil water storage, bulk density, aggregate stability and saturated hydraulic conductivity (Ks) was recorded in NT and RT than in CT. SOC content at 0–15 cm depth was significantly higher in NT, RT and MB where wheat residues were retained after harvest than that in CT system. The SOC, aggregate stability and Ks were significantly higher in N₁₅₀ % compared to N₅₀ %. It is concluded that no tillage and reduced tillage systems with residue retention and recommended rate of N would be a suitable practice for sustainable production of soybean–wheat cropping system in vertisols of central India.

Keywords Soybean–wheat cropping system · Tillage · Nitrogen · Root density · Soil physical properties · Organic carbon

Introduction

The productivity of soybean–wheat cropping system in vertisols of central Indian is adversely affected by uncertain rainfall, soil-related constraints like low water

infiltration, accelerated runoff and soil erosion and indiscriminate tillage practices [42]. Vertisols in India occupy a total area of 70.3 m ha, constituting 22 % of the total geographical area of the country of which 34.3 and 30.2 % area comes under the states of Maharashtra and Madhya Pradesh, respectively, in central India. As these soils become very hard when dry and extremely sticky when wet, they can only be cultivated and tilled within a limited soil moisture range. Suitable tillage practices for this region are required to be adopted to overcome the soil-related constraints, as well as to improve the soil physical health for a sustainable plant production.

Studies conducted in different places showed that reduced and no tillage (NT) systems conserve soil moisture, reduce soil erosion [39] and save time and energy without losses in crop yield when compared to conventional tillage (CT) practices [7]. No-tillage has been reported to maintain and sometimes enhance soil aggregation [5, 26] and increase infiltration in the presence of

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surface mulches [9]. Using crop residues as mulch, increases aggregation more than when the residue is incorporated; residue left on the surface modifies soil moisture and temperature regimes, and increases the soil organic matter content in comparison to incorporation [22]. But the effect of tillage on soil physical properties is often soil and site specific and depend on antecedent soil characteristics, predominant clay minerals and cropping system [10]. Conservation tillage practices have been reported to increase the organic matter content of the surface layer and consequently modify the bulk density of the soil [24]. McCarty et al. [28] have found that for clay soils no tillage is a suitable management option which minimises sub-soil compaction and also induces natural structure formation through shrink-swell cycles.

Harvesting of wheat crop by combined harvester is practiced in central India. This operation leaves a considerable quantity of residues on the field. Although these residues have other competitive demand like feed for cattle, material for roof cover of thatched hut, but use of these residues, loosely distributed in the field, becomes uneconomical due to shortage of labour during the harvest season. The residues cause inconvenience in mechanical seeding of succeeding soybean. The farmers, therefore, resort to burning to clear the field. The residue burning is blamed for polluting the air, loss of recyclable plant nutrients and organic carbon from the system. These residues can be managed either by incorporating into the soil by mould-board ploughing in the summer season or adoption of no or reduced tillage practices for growing subsequent soybean crop in the rainy season. Very little effort has so far been made for in situ management of wheat residues left in the field by the combined harvesters in central India. This long-term field experiment was conducted to evaluate the effectiveness of different tillage systems in managing the residues in field and also to study the effect of different tillage systems on yield sustainability and soil physical health. The comparison of different tillage systems has received considerable attention in other countries [23]. Contradictory reports are available about the effect of NT and CT on yield of soybean [32, 36]. It is reported to be variable among years [32, 36], or higher with NT [38] or marginal difference between CT and NT [21, 35]. Further, the influence of tillage systems on crop production, soil physical properties, carbon sequestration in heavy clay soils of central India is not well documented. In this backdrop, it was hypothesized that reduced or no tillage system along with crop residue management could enhance root proliferation, sustain crop yield improve soil physical properties, and facilitate organic carbon increment, and there could be positive interaction between tillage and nitrogen management on crop yield. Addition of wheat residue either on the surface or incorporated into the soil influences the nitrogen

availability of the soil through its effect on immobilization in the short term and subsequent mineralization. Thus to evaluate the optimum dose of nitrogen requirement under conservation tillage system, different doses of nitrogen levels were tested with the hypothesis that in the long-run the nitrogen requirement to the crop may come down as residue will release nitrogen in the rhizosphere through decomposition and subsequent mineralization. Hence, the objective of this study was: (i) to evaluate the effects of different tillage systems and fertilizer-N rates on root growth and yields of soybean–wheat cropping system, (ii) to study the soil physical properties viz. cone penetration resistance, bulk density, aggregate stability, and (iii) to assess soil organic carbon due to crop residue management along with different tillage systems and fertilizer-N rates in central Indian vertisols.

Materials and Methods

A field experiment on soybean–wheat cropping system on a Vertisol was initiated in the rainy season of 2000 at the research farm of Indian Institute of Soil Science, Bhopal, India (23°18'N, 77°24'E, 485 m above mean sea level). Soil of the experimental site was deep heavy clay (isohyperthermic Typic Haplustert). The top soil (0–15 cm) was low in available N (120 mg kg⁻¹), alkaline permanganate method [37], medium in available P (5.6 mg kg⁻¹) [33] and high in available K (230 mg kg⁻¹) [13]. The pH (1:2), CEC, bulk density of the surface soil (0–15 cm) were 7.8, 46 cmol(+) kg⁻¹ soil and 1.30 Mg m⁻³, respectively, while water holding capacity at saturation, field capacity (-33 kPa) and permanent wilting point (-1,500 kPa) were 62.8, 38.9 and 24.6 % (v/v), respectively. The climate of the experimental site was hot sub-humid type with a mean annual rainfall of 1,130 mm and potential evapo-transpiration of 1,400 mm. About 80 % of the rainfall occurs during the rainy season, i.e. June to September. Average maximum monthly temperature (40 °C) was reached in May, while the minimum (9 °C) was in January. Average weekly distribution of rainfall during the study period given in Fig. 1.

The experiment was laid out in a split-plot design with three replications. Four tillage treatments assigned to main plots were:

- (i) Conventional tillage (CT): wheat residue removed, one summer ploughing by tractor-drawn cultivator and two ploughing with same cultivator before sowing of soybean by tractor-drawn seed drill; before sowing of wheat by seed drill, two passes of tillage by cultivator.
- (ii) Mould board tillage (MB): wheat residue retention, summer ploughing by MB plough, two passes of

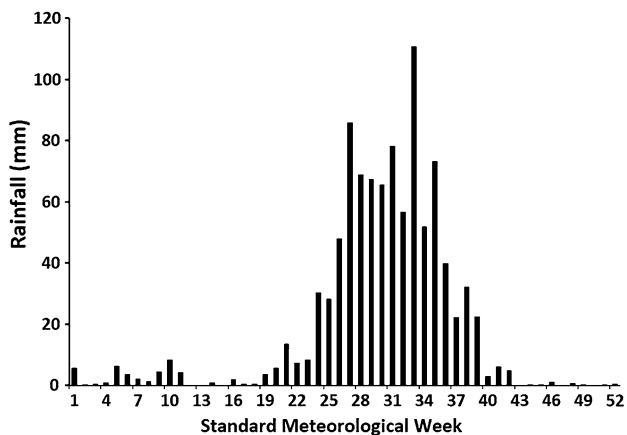


Fig. 1 Average weekly distribution of rainfall during the study period (2000–2007)

cultivator before sowing of soybean by seed drill; one pass of rotavator tillage and sowing of wheat by seed drill.

- (iii) Reduced tillage (RT): wheat residue retention, one pass of cultivator and sowing of soybean by no-till seed drill; direct seeding of wheat by no-till seed drill.
- (iv) No tillage (NT): wheat residue retention, direct seeding of soybean by no-till seed drill; direct seeding of wheat by no-till seed drill.

The average tillage depth was 12 cm with the cultivator, 25 cm with mould board plough and 10 cm with rotavator tillage before wheat. The sub-plot treatments consisted of three fertilizer-*N* rates viz., N_{50} %, N_{100} % and N_{150} % where 50, 100 and 150 %, respectively, of the recommended rate of *N* for soybean and wheat which was decided on the basis of recommended dose of fertilizer for the region. The rate of *N* was 30 and 100 kg ha⁻¹ for soybean and wheat, respectively. The sub-plot size was 15 m × 8 m. The soybean crop was fertilized uniformly with 26 kg P ha⁻¹, 25 kg K ha⁻¹ and the wheat crop with 26 kg P ha⁻¹ and 33 kg K ha⁻¹ in all the treatments. The fertilizer sources for *N*, *P* and *K* were urea, single superphosphate and muriate of potash. In the rainy season, soybean was sown during the last week of June or first week of July depending upon the onset of monsoon at a row spacing of 30 cm. Soybean was harvested in the third week of October. In the winter season, wheat was sown in the third week of November each year. Soybean residues, generated mainly from the leaf fall and dried stem left after harvest, retained on the soil surface and were decayed into the soil with time as they were easily decomposable. The necessary plant protection and other management practices were followed during crop growth. Before sowing of soybean, glyphosate was applied to control weeds. One hand

weeding was done 1 month after crop sowing to keep the field weed free. Soybean was grown as a rainfed crop, while wheat was irrigated at critical growth stages with the harvested rainwater stored in the water harvesting pond. Wheat was sown after application of a pre-sowing irrigation of 6 cm depth. Two to three post-sowing irrigations, depending up on the availability of water in the water harvesting pond, were applied to wheat crop at crown-root initiation, flowering and soft dough stages. Standing wheat residues of 30 cm height were left at harvest to simulate harvesting by combined harvester in all the treatments except in the conventional tillage to soybean main plot treatment where wheat was harvested from base level as practiced by farmers.

Root samples of soybean were collected from crop rows at four depth increments viz. 0–7.5, 7.5–15, 15–22.5 and 22.5–30 cm using a core sampler with cores of 8.5 cm diameter and 6 cm length. Each core sample collected was soaked overnight with 10 % sodium hexameta-phosphate dispersing agent. Roots were separated from soil and other residues using a hydropneumatic elutriation system. Root samples were then stained with methyl blue. Subsequently, roots collected from each core were spread on a tray, scanned using the ‘Delta-T’ root scanner and analyzed for root length using the ‘Delta-T-SCAN’ image analysis software (Delta-T Devices Ltd., 128 Low Road, Burwell, Cambridge). Root length density was determined by dividing total root length obtained from each root-samplingcore with the volume of the core.

Soil samples were collected for determination of physical properties and SOC after harvest of wheat at the end of seventh year cropping, in April 2007. The bulk density of 0–7.5 cm and 7.5–15 cm soil layer was determined in quadruplicate from each replication by a core sampler. The soil penetration resistance (PR) was measured twice during the early vegetative stage and pod-filling stage of soybean in 2006 using a hand-held recording penetrometer (Eijkkamp Agrisearch Equipment, The Netherlands). Readings from three random positions per plot were averaged for each depth and the mean cone resistances were expressed in MPa. Penetrometer readings in the rainy season were recorded when the moisture content in the field was near the field capacity (39 % v/v) for ease of comparison among the treatments. The water stable aggregates of the surface (0–15 cm) soil were estimated by wet sieving method [43], and the mean weight diameter (MWD) of the water stable aggregates was calculated by following van Bavel [41]. The percent weight of water stable aggregates retained on sieves greater than 0.25 mm diameter was expressed as per cent water stable macro-aggregates (%WSMA). The organic carbon was determined by wet digestion method [31]. Undisturbed core samples of 5 cm height and 5 cm diameter were collected

from the 0 to 15 cm soil layer at 7.5 cm intervals from all replications for estimation of saturated hydraulic conductivity by falling head method using a closed system permeameter [20]. Soil water content up to 90 cm depth at 15 cm increment was determined thermo-gravimetrically at regular time interval during the soybean growing season in 2006. Then profile water storage was obtained by summation of water stored at individual layers.

Crop yields and soil physical characteristics data were analyzed using analysis of variance (ANOVA) technique following the split-plot design. The *F*-ratio indicated that interaction between tillage and nitrogen rates on soil physical properties and crop yield was not significant; hence only main effects of tillage and nitrogen rate are discussed. The significance of the treatment effect was determined using *F*-test, and to compare the significant differences between the two treatments, least significant differences (LSD) were estimated at $P < 0.05$, and Duncan's multiple range tests were used for ranking of the treatments at the same probability level.

Results and Discussion

Crop yields and Residue Addition

As soybean was grown as a rainfed crop, the yearly variation in the onset of monsoon and distribution of rainfall like the frequency of occurrence of dry spell during the rainy season has major influence on the yield variability of the crop between the years [25]. The soybean yield has not shown any specific trend-like increase or decrease in the productivity with time as the year wise variation due to rainfall distribution might have masked the effect. The interaction effects of tillage and fertilizer N treatments were not significant on yield of both soybean and wheat, hence yield of crops due to the main effects is presented (Tables 1, 2). Seed yield of soybean did not vary significantly among the tillage treatments, whereas fertilizer N rate effect on seed yield was significant. Seed yield of soybean at N_{150} % and N_{100} % was significantly higher than that at N_{50} %. Except in the years 2000 and 2005, soybean

Table 1 Effect of tillage systems and fertilizer-N rates on seed yield of soybean (kg ha^{-1}) over the years

Treatment	Year						
	2000	2001	2002	2003	2004	2005	2006
<i>Tillage system</i>							
NT	1432a	1062a	1068a	1438a	659a	1251a	1103a
RT	1479a	1066a	1071a	1430a	663a	1306a	1133a
MB	1528a	1062a	1093a	1381a	678a	1256a	1188a
CT	1488a	1101a	1141a	1471a	609a	1386a	1210a
<i>N levels</i>							
N_{50} %	1379c	976b	985b	1151b	601b	1193c	1003b
N_{100} %	1473b	1089a	1117a	1514a	687a	1301b	1209a
N_{150} %	1593a	1153a	1177a	1624a	744a	1405a	1265a

Different letters within a column indicate significant difference between values at $P < 0.05$

Table 2 Effect of tillage systems and fertilizer-N rates on grain yield of wheat (kg ha^{-1}) over the years

Treatment	Year ^a					
	2000–2001	2001–2002	2003–2004	2004–2005	2005–2006	2006–2007
<i>Tillage systems</i>						
NT	2389a	2962a	3560a	2238a	1866a	2389a
RT	2368a	2936a	3579a	2149a	1919a	2368a
MB	2377a	2947a	3599a	2245a	1864a	2377a
CT	2433a	3017a	3481a	2311a	1960a	2433a
<i>N levels</i>						
N_{50} %	2002b	2482b	3169c	1972b	1714b	2923b
N_{100} %	2523a	3129a	3675b	2309a	1945a	3345a
N_{150} %	2650a	3286a	3820a	2426a	2050a	3494a

Different letters within a column indicate significant difference between values at $P < 0.05$

^a Yields in 2002–2003 were very low due to shortage of irrigation water, hence not reported

yield at N_{100} % and N_{150} % was not differed significantly. Our finding is in agreement with several previous researchers [4, 18, 21, 35] who did not find any significant difference in the yield of soybean due to tillage treatments. In our study, the inconsistent effects of tillage on soil water contents of various soil layers were presumably the reason why yield variation due to tillage treatments was not observed. Some of the previous studies [1] done elsewhere indicated that changes in soil water content in response to different tillages were not of the magnitude to influence the crop yield. The soybean crop in NT exhibited faster reproductive growth compensating the relatively slow early season plant development, thereby minimizing the growth differences between the two tillage systems, NT and CT.

There were no significant differences in wheat yield among tillage systems (Table 2). However like soybean, the effect of nitrogen levels on grain yield of wheat was significant. The grain yield increased significantly from N_{50} % to N_{100} % in all the years. Except in 2003–2004, the yield variation among N_{150} % and N_{100} % was not significant. The average yield of wheat varied between the years owing to the variations in the availability of harvested rainwater for irrigation of the crop during the winter season. This is also a major problem for farmer who grows wheat in this region face. In 2002–2003, due to non-availability of harvested rainwater for post-sowing irrigation, as rainfall was very low during the rainy season of 2002 wheat yield was very low, hence not reported. Our results showed that though tillage systems influenced the organic carbon content and physical properties of the soil but it has not influenced the crop yield significantly. Higher organic carbon content and better soil physical environment might have provided better aeration and increased moisture availability to wheat in no and reduced tillage treatments and have compensated the negative effect of relatively poor crop establishment in the initial stages in these tillage treatments on grain yield. Kapusta et al. [19] while studying the effects of tillage systems for 20 years, found equal yield of maize in no-tillage, reduced tillage, and conventional tillage despite the lower plant population in no-till. The amount of residue left on the surface was similar in NT, RT and MB system and the amount was substantially more than CT system where wheat was harvested manually from the base leaving very less amount of above ground stubble. In seven years, a total of about 13,000 kg ha⁻¹ wheat residues were left in NT, RT and MB treatments compared to only 4,550 kg ha⁻¹ in CT.

Soybean Root Growth

Tillage treatments significantly influenced the root length density (RLD) of soybean. At 0–7.5 and 7.5–15 cm depths, RLD were higher in NT and RT than that in MB and CT

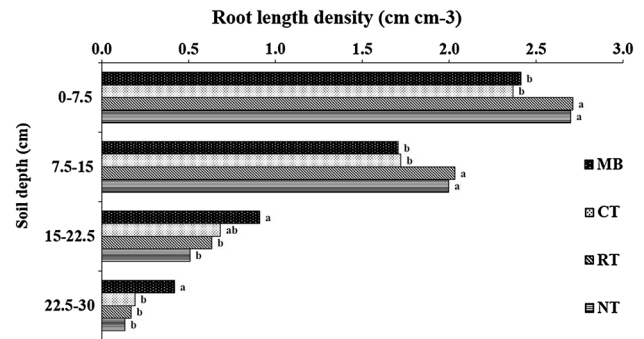


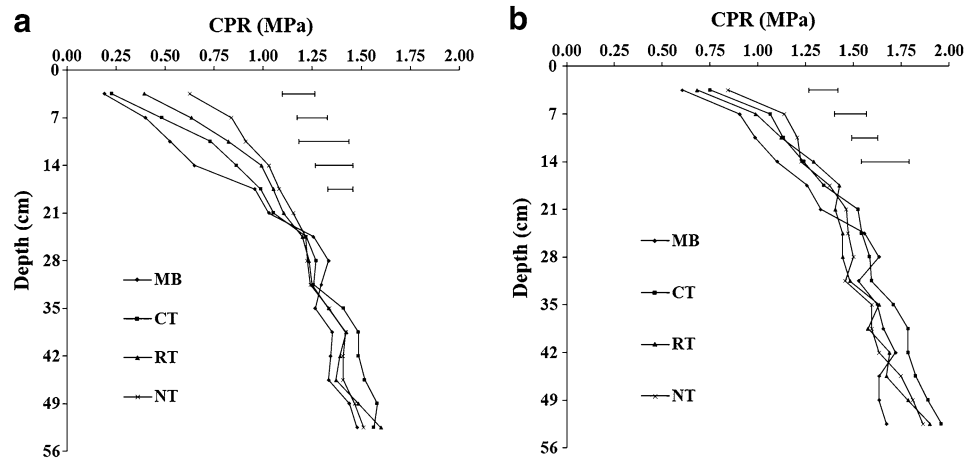
Fig. 2 Root length density (RLD) of soybean sampled at pod development stage as influenced by tillage treatment; MB, CT, RT and NT are mould board, conventional, reduced and no tillage, respectively

treatments, while at 15–22.5 and 22.5–30 cm depths, RLD was maximum in MB (Fig. 2). However, the average RLD considering all the four soil layers did not vary among four tillage treatments. About 76–88 % of the total root length was distributed at the top 15 cm soil depth. In another study, we have found that about 85–87 % of soybean root length was confined to the top 15 cm soil depth under conventional tillage in the same soil [3]. The tillage treatments showed a distinct difference in percent distribution of roots with depth. On average, 88 and 85 % of the total root length were found to be confined at the 0–15 cm soil depth in NT and RT, respectively; while in MB, 76 % of the total root length was found in the top 15 cm soil. More root growth at deeper layer in MB was due to lower penetration resistance and bulk density at 15–30 cm layer in MB tillage which might have facilitated roots to proliferate at deeper layers. Our study also showed a significant negative correlation between root length density of soybean and soil penetration resistance [3, 15]. Qin et al. [34] examined the variation in root density distributions of maize in ploughed and no-till soils, and reported that RLDs were greater in no-till soils at upper 10 cm, but in the ploughed soil, it was greater in deeper soils. Similar to our findings, Ijima et al. [17] also observed that at pod-filling stage of soybean root length density in the surface layer was higher in no tillage than in conventional tillage, while the root growth in the sub-soil (15–30 cm) was higher in conventional tillage than in no tillage.

Soil Physical Properties

Soil penetration resistance (PR) up to 17.5 cm was significantly less in MB than in NT during early vegetative growth stage of soybean (Fig. 3a); in CT and RT, it was significantly less than that in NT at 3.5 and 7 cm depths. Tillage effect on PR was not significant below 17.5 cm depth. PR increased with depth in all treatments due to

Fig. 3 Effect of tillage systems on soil penetration resistance during the **a** early vegetative stage, and **b** pod-filling stage of soybean; horizontal lines represent LSD ($P < 0.05$) between the treatments for a depth; MB, CT, RT and NT are mould board, conventional, reduced and no tillage, respectively



higher intrinsic bulk density of the soil at deeper layers [40]. Loosening of the soil due to ploughing in MB, CT and RT has reduced the mechanical resistance of the soil compared to NT. The average PR values recorded during pod-filling stage of soybean were higher than those recorded during the early vegetative stage (Fig. 3b). At pod-filling stage, PR up to a depth of 10 cm was the least in MB followed by CT and RT, and it was the highest in NT; the differences among the tillage treatments were less pronounced compared to observations at early vegetative stage. This might be due to consolidation of the initially loose ploughed top soil in the MB, RT and CT plots with time on receipt to rainfall. But the penetration resistance in every tillage treatments remained well below the threshold value for root growth of soybean which is 2.5–3.0 MPa [29]. Similar to our findings, Mahboubi et al. [27] also reported higher penetration resistance in no-till system in the upper 15-cm soil layer compared with chisel plough

Table 3 Effect of tillage systems and nitrogen levels on bulk density and saturated hydraulic conductivity of the surface 15 cm soil; MB, CT, RT and NT are mould board, conventional, reduced and no tillage, respectively

Treatment	Bulk density (Mg m^{-3})		Saturated hydraulic conductivity ($\times 10^{-6} \text{ m s}^{-1}$)	
	0–7.5 cm	7.5–15 cm	0–7.5 cm	7.5–15 cm
<i>Tillage system</i>				
NT	1.24a	1.26b	7.32a	3.95a
RT	1.17b	1.22bc	5.28a	1.78b
MB	1.16b	1.19c	6.44a	3.86a
CT	1.28a	1.32a	2.13b	1.56b
<i>N levels</i>				
$N_{50} \%$	1.25a	1.29a	3.84b	2.02b
$N_{100} \%$	1.21ab	1.25b	5.08ab	2.91ab
$N_{150} \%$	1.18b	1.22b	6.95a	3.44a

Different letters within a column indicate significant difference between values at $P < 0.05$

and mould board plough systems after 28 years of tillage treatment on a silt loam soil in Ohio. Tillage treatments had significant effect on bulk density of the soil (Table 3). Significantly lower bulk density was observed in MB (1.16 Mg m^{-3}) and RT (1.17 Mg m^{-3}) compared to NT (1.24 Mg m^{-3}) and CT (1.28 Mg m^{-3}) at 0–7.5 cm soil depths. But at 7.5–15 cm depth, it was the highest in CT followed by NT and RT and was the lowest in MB. The loosening of soil by tillage and the mixing of crop residues into the soil caused the bulk densities to be lowered in MB and RT [16]. Absence of crop residues in CT resulted in consolidation of initially ploughed surface soil which resulted in higher bulk density compared with MB and RT. Our results closely accord with the finding of Azooz et al. [2], who observed slight or no difference in bulk density values between conventional tillage and zero tillage. However, among the N treatments, bulk density decreased with increasing N rates. It was the lowest at $N_{150} \%$ at both soil depths. This might be due to higher organic matter content and better aggregation at higher N rate. Saturated hydraulic conductivity (K_s) in CT was significantly lower than NT, RT and MB at 0–7.5 cm soil (Table 3). Similarly at 7.5–15 cm soil depth, K_s was the lowest in CT, but it was on par with RT. Thus our study showed an improvement in the hydraulic conductivity of the top 15 cm soil under conservation tillage systems. Probably, better soil aggregation, lower bulk density, presence of more conducting pores [6] and surface cover to prevent the slaking and sealing of the soil surface by rain drop impact, are the factors responsible for improved hydraulic conductivity under conservation tillage systems. Among the N treatments, K_s increased with the increasing N level. It was the lowest at $N_{50} \%$ at both the soil depths. Higher organic carbon content, better aggregation and lower bulk density might have attributed to higher hydraulic conductivity in $N_{150} \%$ compared with $N_{50} \%$ treatment.

Soil aggregation represented by mean weight diameter (MWD) and percent water stable macro-aggregates

(%WSMA) was significantly ($P < 0.05$) affected by tillage systems and nitrogen levels (Table 4). The MWD of the top 15 cm soil under NT (0.94 mm) was significantly higher than that under RT and MB. The MWD was the least under CT. Similarly, %WSMA was the maximum under NT and was the minimum under CT. The difference between CT and MB with respect to %WSMA was not significant. Soil aggregation followed the trend similar to soil organic carbon concentration, which implied that soil organic carbon was the major contributor to soil aggregate formation in vertisols. This finding is in agreement with Hati et al. [14] and Bandyopadhyay et al. [3], who reported significant positive correlation between the MWD and soil organic carbon concentration and %WSMA and soil organic carbon concentration, respectively, in the same soil. Removal of residues from the surface and exposing the surface soil through tillage for accelerated

decomposition might be responsible for reduced aggregate stability in CT. With increase in N rates, the MWD increased, but the difference is only significant between N_{50} % and N_{150} %. The improvement in aggregate stability with increase in nitrogen level was attributed to higher organic matter content owing to better crop growth with concomitant higher root biomass generation and higher return of leftover surface plant residues [8].

The soil water storage in the 0–90 cm depth during the soybean season was above the 50 % threshold of available water throughout the season (Fig. 4). During the early crop growth period up to 30 DAS, soil water storage was more in MB and CT than NT. This might be due to higher infiltration of rainwater in MB and CT as the soil was relatively loose owing to ploughing during summer before the onset of rainfall. But in the later phase (78 DAS onwards), NT retained more water in the profile than other three tillage treatments. This might be attributed to reduction of initially high infiltration rate in MB and CT treatments with time due to detachment of soil particles by the impact of raindrops. Besides this, better aggregation could have favoured stability of pore space and higher water retention [10] together with less evaporation due to the presence of plant residues might have helped in maintaining greater soil water content under NT [11]. Nitrogen treatments have not shown any distinct difference on soil water storage.

Table 4 Effect of tillage systems and nitrogen levels on mean weight diameter (MWD) of soil aggregates and % water stable macro-aggregates (WSMA) of the top 15 cm soil; MB, CT, RT and NT are mould board, conventional, reduced and no tillage, respectively

Treatment	MWD (mm)	%WSMA
<i>Tillage system</i>		
NT	0.94a	60.47a
RT	0.88b	56.15b
MB	0.84b	53.70bc
CT	0.76c	51.36c
<i>N levels</i>		
N_{50} %	0.83b	53.28b
N_{100} %	0.85ab	56.78a
N_{150} %	0.87a	56.21a

Different letters within a column indicate significant difference between values at $P < 0.05$

Soil Organic Carbon (SOC)

The SOC concentration was the highest in NT followed by RT, MB and CT at 0–5 cm depth, whereas at 5–15 cm depth, MB showed the highest SOC value, which was significantly higher than the RT and NT (Table 5). The increase in SOC in the surface soil is attributed to a

Fig. 4 Temporal variation of soil water storage at 0–90 cm depth during soybean growing season as affected by tillage treatments; UL is upper limit of available water (AW), LL is lower limit of available water, vertical lines represent LSD ($P < 0.05$) between the treatments in each date of sampling, NS is not significant; MB, CT, RT and NT are mould board, conventional, reduced and no tillage, respectively

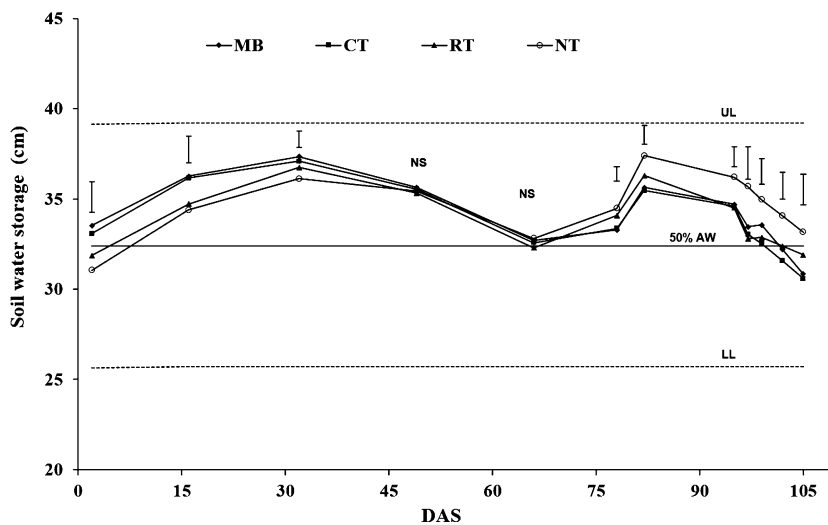


Table 5 Effect of tillage systems and nitrogen levels on soil organic carbon (SOC) content, stratification ratio (0–5 cm)/(15–30 cm) and SOC pool of the top 30 cm soil; MB, CT, RT and NT are mould board, conventional, reduced and no tillage, respectively

Treatment	SOC content (g kg ⁻¹)			Stratification ratio	SOC pool (0–30 cm) (Mg ha ⁻¹) equivalent depth basis	SOC pool (0–30 cm) (Mg ha ⁻¹) equivalent mass basis
	0–5 cm	5–15 cm	15–30 cm			
<i>Tillage system</i>						
NT	10.4a	6.3b	5.0a	2.11a	24.80	24.96
RT	9.1b	6.6b	5.1a	1.77b	24.23	24.85
MB	8.3c	7.4a	5.4a	1.54b	25.54	26.08
CT	7.8d	5.9c	5.1a	1.53b	24.15	23.26
<i>N levels</i>						
N ₅₀ %	8.6b	6.2b	4.9b	1.79a	23.82	23.69
N ₁₀₀ %	8.9ab	6.6ab	5.3a	1.70a	24.96	25.31
N ₁₅₀ %	9.2a	6.9a	5.3a	1.72a	25.26	25.36

Different letters within a column indicate significant difference between values at $P < 0.05$

combination of crop residue decomposition and less soil disturbance under NT. Besides this, the organic matter below the surface, including the previous crop's roots, was left undisturbed and thus was not subjected to accelerated decay in conservation tillage (NT and RT). Our observations are consistent with those of Mrabet et al. [30], who recorded an increase in SOC by 14 % at 0–20 cm soil over a period of 11 years under zero tillage compared to conventional tillage in a long-term tillage experiment conducted in a semiarid area of Morocco. Conservation tillage, particularly no tillage leads to a concentration of SOC in the top layer of the soil (0–5 cm) and alters its distribution within the soil profile because plant residues tend to accumulate on the soil surface [28]. In our study, the increase in organic matter in the NT system was largest near the surface, but below 15 cm soil depth this increase was much less. This attribute is referred to as stratification of soil organic carbon in the profile [16]. Higher stratification ratio was registered under NT (2.11) and RT (1.77) compared to MB (1.54) and CT (1.53). This indicates better soil quality and soil ecosystem functioning under no tillage and reduced tillage compared to conventional tillage and MB tillage as surface organic matter is essential to control erosion, increase infiltration and conservation of nutrients [12]. Higher soil organic carbon stock in the 0–30 cm profile was recorded under MB because of relatively higher SOC concentration at lower depth owing to better inversion of crop residues; whereas SOC pool in NT system was greater than that of CT. Among the N treatments, SOC was significantly higher in N₁₅₀ % compared to N₅₀ %. SOC concentration at N₁₀₀ % was in between the N₁₅₀ % and N₅₀ %. The increase in SOC concentration with the increase in N rate was attributed to the addition of more organic matter owing to better crop growth and consequent addition of more biomass in soil [8].

Conclusions

Conservation tillage practices viz. no tillage and reduced tillage for soybean–wheat cropping system could sustain yield similar to that under conventional tillage practice, while it saved energy and time by reducing the frequency of tillage operations. Due to the retention of crop residues and minimum disturbance of the surface soil, the organic carbon content and physical properties like, aggregation and saturated hydraulic conductivity of the soil under no and reduced tillage were improved compared to the conventional tillage system. The no tillage system accumulated higher amount of organic carbon near the surface soil layer. Our findings suggests that no tillage to soybean and wheat with balanced dose of fertilizer can be a viable alternative to conventional tillage for sustainable production with concomitant improvement in physical properties and carbon sequestration in vertisols of central India. However, detailed study in future is required to critically assess the mechanisms of soil aggregate formation, carbon sequestration, changes in the relative distribution of different carbon pools, nutrient and water dynamics on crop performance and sustainability of the conservation tillage production system through long-term tillage experiment.

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