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Research Article

Conservation Tillage Effects on Soil Physical Properties, Organic Carbon Concentration and Productivity of Soybean-Wheat Cropping System

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ABSTRACT

Excessive disturbance of the top soil through intensive tillage operations and removal of residues in conventional tillage systems result in breakdown of soil structure, accelerated oxidation, consequent loss of soil organic carbon (SOC) content and release of carbon dioxide to the atmosphere. In conservation tillage system, crop residues are retained and tillage operations are kept at minimum, which stimulates sequestration of SOC and improvement in soil health. This study was conducted to evaluate the long-term impact of conservation tillage on SOC concentration, physical health and productivity of soybean-wheat system after nine crop cycles. Treatments consisted of four tillage systems *viz.*, conventional tillage (CT), mouldboard tillage (MB), reduced tillage (RT) and no tillage (NT) as the main plot, and three nitrogen (N) levels *viz.,* 50% ($N_{50\%}$), 100% ($N_{100\%}$) and 150% ($N_{150\%}$) of the recommended rate as sub-plot. Results showed that the SOC content up to 15 cm soil depth were significantly higher in NT, RT and MB where wheat residues were left after harvest, than that in CT system. The SOC in MB were significantly higher than CT in 15-30 cm soil layer. Soil water retention at 4 cm and at air entry potential (50 cm suction) was significantly higher in NT, MB and RT treatments than in CT. Soil physical properties *viz.*, infiltration rate, bulk density, mean weight diameter and water stable aggregation also improved under NT and RT. The SOC and aggregate stability were higher in $N_{150\%}$ as compared to $N_{50\%}$. Soil water retention did not vary among the N levels. However, yields of both the crops were similar under the tillage systems.

Key words: Soil organic carbon, Conservation tillage, Soil physical properties, Nitrogen

Introduction

Tillage systems influence physical, chemical, and biological properties of soils and have a major impact on soil productivity and sustainability. However, impact of a particular tillage system on soil properties depends on the site (i.e., soil, climate) and the number of years since the tillage system has been implemented (Rhoton, 2000). Conventional tillage (CT) disturbs soil structure and may adversely affect long-term soil productivity due to erosion and loss of organic matter in soils. Conventional tillage affects soil temperature (Dwyer *et al.,* 1996), soil mechanical impedance (Cox *et al.,* 1990), continuity of macropores (Shipitalo *et al.,* 2000), soil water availability (Cox *et al.,* 1990; Fuentes *et al.,* 2012), and the depth and distribution of roots

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(Dwyer *et al.,* 1996). Sustainable soil management can be practiced through conservation tillage, high crop residue return and crop rotation (Hobbs *et al.,* 2008). Studies conducted under a wide range of climatic conditions, soil types, and crop rotation systems showed that soils under no-tillage and reduced tillage have significantly higher SOC contents compared with conventionally tilled soils (Alvarez, 2005). No-tillage (NT) has been shown to improve soil properties, thereby enhancing water transmission, water retention, and crop yield in many parts of the world (He *et al.,* 2009).

Soil organic matter (SOM) is an important determinant of soil fertility. Its dynamics are influenced by agricultural management practices such as tillage, mulching, removal of crop residues and application of organic and mineral fertilizers. Removal of crop residues from the fields hastens decline in SOC especially when coupled with conventional tillage (Mann *et al.,* 2002). In central and northern India, crop residues are either removed for use as fodder or burnt *in situ.* No-tillage practices have been reported to maintain and sometimes enhance soil aggregation (Mahboubi and Lal, 1998, Celik *et al.,* 2012) and increase infiltration in presence of surface mulches (Diaz-Zorita *et al.,* 2004). Crop residues as mulch (as in no tillage system) improves soil aggregation better than when the residue is incorporated in soil through conventional tillage (CT). Similarly, soil bulk density is modified under conservation tillage (Lal *et al.,* 1994). McGarry *et al.,* (2000) have found the no tillage (NT) as an effective practice for clay soils to minimize sub-soil compaction and to induce natural structure formation through shrink-swell cycles.

Harvesting of wheat crop by combined harvester is generally practiced in central India. This leaves a considerable quantity of residues on the field, which makes difficulty in mechanically seeding of succeeding soybean crop. Farmers thus resort to burning wheat residues in the field itself. The burning cause air pollution and a considerable quantity of recyclable nutrients is lost through burning. Keeping this in view, a study was undertaken to examine if these residues could be managed *in situ* either by incorporating these by mouldboard ploughing during summer, or retaining them on surface by adopting NT or reduced tillage practices for subsequent soybean crop in the rainy season. There are contradictory reports of the effect of NT and CT on yield of soybean, which are variable among years (Singer *et al*., 2008), higher with NT (Temperly and Borges, 2006) or marginal difference between CT and NT (Koga and Tsuji, 2009). Further, the influence of tillage systems on crop production, soil physical properties and C sequestration is not well documented for soybean-wheat rotation in heavy clay soils of central India. We hypothesize that conservation tillage system along with crop residue retention sustains crop yield, facilitates SOC increment and improves soil physical properties. There could also be some positive interaction between tillage and N management on crop yield. To test the hypothesis, a field experiment was conducted with the objectives to evaluate the effect of tillage, crop residues and N fertilization rates on: i) physical properties of soil *viz*., aggregate stability, water retention, infiltration characteristics, and bulk density, ii) the distribution of SOC content and (iii) productivity of soybean-wheat cropping system, in a Vertisol of central India.

Materials and Methods

Information generated through a long-term field experiment on soybean-wheat cropping system on a Vertisol at the research farm of the Indian Institute of Soil Science, Bhopal, India (23°18' N, 77°24' E, 485 m above mean sea level) was used for this study. The field experiment was initiated in the rainy season of 2000 and soil samples were collected after harvest of wheat at the end of 9th year cropping. 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}), medium in available P (5.6 mg kg^{-1}) and high in available K (230 mg kg^{-1}). The pH, CEC, bulk density of the surface soil (0-15cm) were 7.8, 46 cmol(+) kg^{-1} soil and 1.3 Mg m^{-3}, respectively, while water holding capacity at saturation, field capacity (-33 kPa) and permanent wilting point

(-1500 kPa) were 62.8, 38.9 and 24.6% (v/v), respectively. The climate of the experimental site was hot sub-humid with a mean annual rainfall of 1130 mm and potential evapotranspiration of 1400 mm. About 80% of the rainfall occurs during the rainy season i.e. June to September. Average maximum monthly temperature (40^0 C) was reached in May while the minimum (9^0 C) was in January.

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

1. Conventional tillage (CT): Removal of wheat residue; one summer ploughing by tractor-drawn cultivator, two ploughing with same cultivator before sowing of soybean by tractor drawn seed drill; two passes of tillage by cultivator before sowing of wheat by seed drill.
2. Mould board tillage (MB): Wheat residue retention; summer ploughing by MB plough, two passes of cultivator before sowing of soybean by seed drill; one pass of rotavator tillage and sowing of wheat by seed drill.
3. 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.
4. 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 sub-plot treatments consisted of three fertilizer-N rates *viz*., $N_{50\%,}$ $N_{100\%}$ and $N_{150\%}$ representing 50, 100 and 150% of the recommended dose of N, respectively, for soybean (30 kg ha^{-1}) and wheat (100 kg ha^{-1}). The recommended doses of N (in the form of urea) were decided on the basis of initial soil test. The size of the individual sub-plots was 15 × 8 m. The P (single super-phosphate) and K (muriate of potash) were applied at uniform rates to both the crops in all the treatments. Soybean was fertilized with 26 and 25 kg ha^{-1} P and K, respectively while wheat was fertilized with 26 and 33 kg P ha^{-1} and K, respectively. For wheat, half of the N and full P and K were applied as basal dose, and the remaining dose of N was applied at crown root initiation stage. Soybean was sown during last week of June or 1st week of July depending upon the onset of monsoon, at a row spacing of 30 cm, and was harvested in 3rd week of October. Wheat was sown in 3rd week of November with a row spacing of 22.5 cm and harvested in 1st week of April. 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. Standing wheat residues of 30 cm height were left at harvest to simulate harvesting by combined harvester in NT and RT plots while in CT plots, wheat was harvested from base level as practiced by farmers. Yields were recorded at harvest on net plot basis.

The bulk density at 0-7.5 and 7.5-15 cm layers was determined in quadruplicate from each replication by a core sampler. The water stable aggregates of the surface (0–15 cm) soil was estimated by wet sieving method (Yoder, 1936) and the mean weight diameter (MWD) of the water stable aggregates was calculated following van Bavel (1949). The percent weight of water stable aggregates retained on sieves >0.25 mm diameter was expressed as per cent water stable macro-aggregates (% WSMA). The SOC was determined by Walkley and Black wet digestion method (Nelson and Sommers, 1996). Undisturbed core samples of 5 cm height and 5 cm diameter were collected from the 0-15 cm soil depth at 7.5 cm intervals from all replications and soil water retention at 4 and 50 cm suction was estimated using sand box method (Klute and Dirksen, 1986). The cumulative and steady state infiltration rates in all the plots were determined by double ring infiltrometer (falling head) having an inner ring diameter of 30 cm (Bouwer, 1986). The infiltration measurements were carried out after the harvest of the wheat crop. Infiltration data was fitted to the Phillip's model (1957), which is described by the following equation.

$$I=St^{0.5}+At$$

$$\frac{I}{t^{0.5}} = S + At^{0.5}$$

where, I is the cumulative infiltration (cm), S is soil water sorptivity, A is parameter close to saturated hydraulic conductivity, and t is the time (min). The infiltration rate, I (cm) was divided by a corresponding value of $t^{0.5}$ (min) in the entire infiltration run. The values obtained were then regressed against $t^{0.5}$ to obtain S as the intercept and A as the slope of the regression line.

Crop yields, soil physical characteristics and SOC content data were analyzed using analysis of variance (ANOVA) technique following the split-plot design. The significance of the treatment effect was determined using F-test, and to compare the significant differences between the two treatments, Duncan's multiple range tests at $p < 0.05$ was used for ranking of the treatments at the same probability level.

Results and Discussion

Soil organic carbon (SOC) content

The SOC content was the highest in NT (8.6 g kg^{-1}) and the lowest in CT (6.5 g kg^{-1}) in 0-5 cm soil layer (Table 1). It was higher in RT and MB than in CT in the same soil layer. However, in 5-15 cm soil layer, SOC concentration was the highest in MB, which was significantly more than that in RT and CT (Table 1). In 15-30 cm soil layer, SOC concentration was also the highest in MB and was significantly more than that in CT but was on par with that in NT and RT. The increase in SOC in the surface soil is attributed to a combination of crop residue retention, reduced litter 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 NT and RT treatments, which resulted in higher SOC in these treatments (Al-Kaisi *et al.,* 2005). Our observations are consistent with those of Mrabet *et al.* (2001), who recorded an increase in SOC by 14% at 0-20 cm soil over a period of 11 years under NT in comparison to CT in a semi-arid area of Morocco. Conservation tillage, particularly NT 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 (McCarty *et al.,* 1998). In our study, the increase in SOC was largest near the surface but this increase was much less below 15 cm depth in the NT system. Significant increase in SOC content under NT compared to CT were widely reported (Mando *et al.,* 2005; Li *et al.*, 2007; Abid and Lal, 2008). Organic matter in the soil is frequently occluded within macro-aggregates where it is protected from decomposition. Tillage operation exposes this protected organic matter and enhances its decomposition (Chung *et al.*, 2009). This is responsible for lower SOC under CT than NT. Higher SOC content in 5-15 and 15-30 cm layers in MB was due to incorporation of crop residues up to 22 cm soil depth by the inversion type mould board tillage operation. Among the N-treatments, SOC was significantly higher in $N_{150\%}$ as compared to $N_{50\%}$ at all the three soil layers. SOC content at $N_{100\%}$ was statistically similar to $N_{150\%}$ and $N_{50\%}$ at 0-5 and 15-30 cm soil depth. The increase in SOC content with increase in N rate was attributed to the addition of higher organic matter owing to better crop growth and consequent addition of more root biomass in soil (Christensen, 1988).

Table 1. Effect of tillage treatment and nitrogen levels on soil organic carbon (SOC) concentration of 0-5, 5-15 and 15-30 cm layers

Treatment	SOC content (g kg^{-1})		
	0-5 cm	5-15 cm	15-30 cm
	Tillage		
NT	8.6a	6.6ab	5.2ab
RT	7.9b	6.3b	5.1ab
MB	7.4b	7.0a	5.3a
CT	6.5c	5.2c	4.8b
	N levels		
$N_{50\%}$	7.3b	5.9b	4.8b
$N_{100\%}$	7.7ab	6.2b	5.2ab
$N_{150\%}$	7.9a	6.7a	5.3a

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

Soil physical properties

Soil aggregation represented by MWD and %WSMA was significantly ($P < 0.05$) affected

Table 2. Effect of tillage and nitrogen levels on mean weight diameter (MWD) of soil aggregates and % water stable macro aggregate (WSMA) in 0-15cm soil layer

Treatment	MWD (mm)	% WSMA
	Tillage	
NT	1.05a	63.5a
RT	0.92b	58.3ab
MB	0.83b	52.6bc
CT	0.71c	50.2c
	N levels	
$N_{50\%}$	0.84b	54.8b
$N_{100\%}$	0.88ab	57.6ab
$N_{150\%}$	0.91a	59.7a

Note: Different letters within a column indicate significant difference between values at P<0.05.

by tillage systems and N levels (Table 2). The MWD of the top 15 cm soil under NT (1.05 mm) was significantly higher than that under RT and MB systems and the MWD was the least under CT (0.71 mm). Similarly, %WSMA was the maximum under NT (63.5%) and was the minimum under CT (50.2%). The difference between CT and MB with respect to %WSMA was not significant. Soil aggregation followed the trend similar to SOC content, which implied that SOC content was the major contributor to soil aggregate formation in Vertisols. This finding is in agreement with Hati *et al.* (2004) and Bandyopadhyay *et al.* (2010), who reported significant positive correlation for SOC content with %WMSA and MWD 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 highest MWD and WSA in $N_{150\%}$ might be due to better crop growth with concomitant higher root biomass generation and residue addition, which led to improvement on organic carbon content facilitating higher WSA and MWD of aggregates (Campbell *et al.,* 2001). It has been reported that fertilizer application enhanced crop production and C inputs and there was a positive effect of N additions on the soil C balance (Glendining and Powlson, 1995).

Tillage treatments had significant effect on bulk density of the soil (Table 3). Significantly lower bulk density was observed under 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 (Hussain *et al.,* 1998). Absence of crop

Table 3. Effect of tillage treatment and nitrogen levels on bulk density and water retention in 0-7.5 and 7.5-15 cm layers

Treatment	Bulk density (Mg m^{-3})		Soil water retention (%)			
			4 cm suction		50 cm suction	
	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
			Tillage			
NT	1.24a	1.26bc	50.80a	49.70a	46.08a	45.72a
RT	1.17b	1.22cd	50.02a	49.52a	45.29a	44.83a
MB	1.16b	1.19d	51.72a	50.47a	45.58a	45.12a
CT	1.28a	1.32a	46.85b	45.85b	40.94b	40.76b
			N levels			
N50%	1.25a	1.29a	48.26a	47.16a	43.36a	43.05a
N100%	1.21ab	1.25b	50.25a	49.35a	44.59a	44.23a
N150%	1.18b	1.22b	51.05a	50.16a	45.46a	45.06a

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

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.* (1996), who observed slight or no difference in bulk density values between conventional 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. Soil water retention both at 4 cm and at air entry potential i.e. 50 cm suction was significantly higher in MB, NT and RT treatments than in CT where residues were not retained (Table 3).

The steady state infiltration rates in plots under NT and MB treatments were significantly higher than that in RT and CT treatments (Table 4). Cumulative infiltration in NT was also significantly higher than the other three tillage treatments and it was lowest in CT treatment. Benjamin (1993) and Baumhart and Lescano (1996) also reported that soils under no-tillage treatment have greater infiltration rates and water storage capacities than tilled soils. The greater final infiltration rate in the plots under NT was probably owing to residue retention of the surface, less disturbance to the continuity of water conducting pores (Acharya and Sood, 1992), and increased large (>2 mm) aggregate stability (He *et al.,* 2009). Higher infiltration rate in MB might be due to incorporation of crop residues into soil, which kept the soil at deeper layers relatively more porous and aggregates were more stable compared to CT. In CT soils, the reduction in aggregate stability with nine years of conventional ploughing significantly reduced both macroporosity and pore continuity, thereby decreasing water infiltration. In addition, reduction of large water-stable aggregates under CT leaves more small soil particles free to move with water, clog soil pores, and reduce infiltration (He *et al.,* 2009). Among the N levels, $N_{100\%}$ recorded significantly higher steady state and cumulative infiltration than $N_{50\%}$. However, the infiltration rates in $N_{150\%}$ was not significantly different than that in $N_{50\%}$. Sorptivity values (using Philips equation) was the highest in NT followed by RT, MB and CT treatments. Nitrogen level showed no significant effect on the sorptivity of the soil.

Table 4. Effect of tillage treatment and nitrogen levels on soil infiltration characteristics

Treatment	Infiltration rate (cm hr $^{-1}$)	Cumulative Infiltration (cm)	Sorptivity (cm.hr$^{-1/2}$)
	Tillage		
NT	9.23a	499.31a	50.19a
RT	4.67b	265.67b	29.62bc
MB	7.20a	226.48b	17.48cd
CT	1.37c	65.69c	8.13d
	N levels		
$N_{50\%}$	4.06b	199.62b	28.73a
$N_{100\%}$	7.18a	347.83a	32.89a
$N_{150\%}$	5.62ab	245.42b	17.45a

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

Crop yield and residue addition

Tillage treatments did not show any influence on yields of soybean and wheat although N levels had significant effects (Table 5). Seed yields of soybean at $N_{150\%}$ and $N_{100\%}$ were significantly higher than that at $N_{50\%}$. Grain yields of wheat also followed a similar trend. However, there was no significant difference between $N_{100\%}$ and $N_{150\%}$. The interaction effect of tillage and N was also not significant. No effect of tillage on soybean yields were reported earlier (Alvarez and Steinbach, 2009; Rodrigues *et al.,* 2009). Celik *et al.* (2011) could also not find difference between conservation and conventional tillage systems on yields of soybean, maize and wheat crops on a Vertisol in the semi-arid Mediterranean region. Melero *et al.* (2011) while studying the effects of long-term tillage systems in Vertisols of Mediterranean region, found similar yields of wheat under wheat-wheat and wheat-sunflower rotation in NT and CT. Similar results were also found by Merrill *et al.* (1996) for spring wheat grown under CT, minimum tillage and NT during three seasons in a Pachic Haploboroll soil, and by Acharya and Sharma (1994) in a Typic Hapludalf soil of India.

Table 5. Effect of tillage treatment and nitrogen levels on yield, leaf litter fall and residue addition from soybean and wheat (pooled over the years)

Treatment	Soybean		Wheat	
	Seed yield (Mg ha^{-1})	Leaf litter fall (Mg ha^{-1})	Grain yield (Mg ha^{-1})	Residue addition (Mg ha^{-1})
		Tillage		
NT	1109a	1.145a	2754a	2.114a
RT	1120a	1.205a	2734a	2.003a
MB	1116a	1.157a	2766a	2.049a
CT	1146a	1.195a	2778a	0.724b
		N levels		
$N_{50\%}$	1017b	0.910c	2429b	1.524c
$N_{100\%}$	1143a	1.248b	2849a	1.724b
$N_{150\%}$	1216a	1.369a	2997a	1.919a

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

As expected, the amount of leaf litter fall from soybean was not significantly different among the tillage treatments but was higher at higher N levels (Table 5). On the other hand, amount of wheat residue added to the system were similar in NT, MB and RT and more than CT. However, fate of residues in different tillage systems varied as the biomass were partially or fully incorporated in the soil in RT and MB tillage systems, respectively while they remain on the surface in NT. Addition of wheat residue was also significantly higher in $N_{150\%}$ level compared to $N_{50\%}$ owing to higher biomass yield of the crops at higher N level.

Conclusions

Conservation tillage practices *viz.* no tillage and reduced tillage for soybean-wheat cropping system could sustain yields similar to that under conventional tillage practice. At the same time, the SOC content and soil physical properties improved under no tillage and reduced tillage systems due to retention of residues and minimum disturbance of the soil. Higher dose of N increased the SOC content and improved soil physical properties through their positive influence on biomass productivity. No tillage with residue retention and recommended dose of fertilizer N can be a viable alternative to conventional tillage for sustainable production of soybean-wheat system in Vertisols of central India.

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