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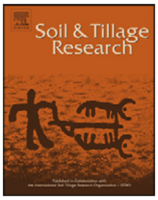

Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio

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ABSTRACT

Knowledge about the changes in carbon (C) concentration and mechanical and hydrological properties under different tillage and mulch treatments is necessary to assess the feasibility of adoption of conservation practices for sustaining productivity and protecting the environment. It is widely recognized that no-till (NT) farming conserves soil and water, saves energy, improves the environment and enhances soil quality. However, the magnitude and direction of tillage and mulch-induced changes are soil and site specific. Therefore, a field study was conducted on a long-term on-going experiment to evaluate the effects of three tillage {NT, ridge till (RT) and plow till (PT)} and three mulch rates (0, 8 and 16 Mg $\text{ha}^{-1}\ \text{yr}^{-1}$) on soil physical properties and total C concentrations in macro (250–2000 μm) and micro (<250 μm) aggregates. The experiment was initiated in 1989 on a Crosby Silt Loam (Stagnic Luvisol) in Central Ohio. The data show positive effects of mulch rate on soil physical attributes and total C concentration under NT. Significant ($P < 0.05$) variations in bulk density (ρ_b) and penetration resistance (PR) along with their interactions were observed among tillage and mulch treatments. The water infiltration capacity (i_c) ranged from 1.2 cm h^{-1} (PT) to 4.6 cm h^{-1} (NT). With increase in mulch rate from 0 to 16 Mg ha^{-1}, saturated hydraulic conductivity (K_s) for 0–10 cm depth increased from 1.78 to 3.37, 1.57 to 2.95 and 1.37 to 2.28 ($\times 10^{-2}$ cm h^{-1}) under NT, RT and PT, respectively. Analyses of variance indicate significant interaction between tillage, mulch and soil depth for the $K_{s.}$ Similarly, the mean weight diameter (MWD, mm) increased from 0.36 to 1.21, 0.29 to 0.84, 0.25 to 0.62 under NT, RT and PT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. Total C (%) increased from 1.26 to 1.50, 1.20 to 1.47 and 0.95 to 1.10 under NT, RT and PT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. Macro-aggregates (250–2000 μm) contained 30% more total C and N concentrations than microaggregates (<250 μm). Under NT, the soil showed a higher structural stability than PT with significantly lower compaction values. Further, with NT the soil showed a higher capacity to retain C than PT. Thus, long term use of NT along with mulch application enhances soil quality with respect to soil mechanical, hydrological properties along with carbon concentration in the soil.

1. Introduction

Soil tillage and residue mulch strongly influence soil properties, environment quality and crop productivity (Keshavarzpour and Rashidi, 2008; Ogban et al., 2008). However, excessive and unnecessary tillage without residue retention can degrade soil physical quality, decrease soil organic carbon (SOC) concentration, and reduce crop yield (Ahmad et al., 1996). Thus, there is a strong interest and emphasis on adoption of conservation tillage (CT) and no-till (NT) systems along with application of crop residue mulch for reducing soil erosion risks, improving soil quality by enhancing soil organic matter (SOM) concentration and soil fertility, infiltration rate and soil water storage capacity, bio diversity, stability of ecosystem and energy use efficiency (Lal, 1995; Ogban et al., 2001; Iqbal et al., 2005). Physical disturbance and pulverization caused by plow till (PT) produce a fine and loose soil structure compared to NT methods which leave soil intact (Rashidi and Keshavarzpour, 2007; Rashidi and Keshavarzpour, 2008; Rashidi et al., 2008). Thus, different tillage systems can change number, shape, continuity and size distribution of the pore network, which controls the ability of soil to store and transmit water and regulate aeration. Adoption of CT and NT can also improve soil porosity and available water capacity (AWC), which enhance edaphic environment and use efficiency of inputs (Khan et al., 2001; Khurshid et al., 2006). The pore network in NT soil is usually more continuous because of biopores created by earthworms and root channels, and by vertical cracks (Cannel, 1985). Further, PT reduces the proportion of macro-aggregates (0.25–2 mm) and increases that of microaggregates (0.05–0.25 mm

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and/or $<$0.05 mm fraction) vis-à-vis the CT treatments. In general, there are more macroaggregates in NT compared with PT soils (Cambardella and Elliott, 1993a; Beare et al., 1994a,b; Six et al., 2000b; Mikha and Rice, 2004). The rate of macroaggregate turnover (formation and degradation) is also reduced under NT compared with PT (Six et al., 1998, 2000a), and aggregate stability is decreased with PT. Zotarelli et al. (2005) reported that the MWD of the aggregates was on average 0.5 mm greater under NT compared with that under PT. Zibilske and Bradford (2007) also reported that soil under PT had significantly lower MWD than those under NT and RT in 0–5 and 10–15 cm depths. The reduction in macroaggregates and MWD with PT may be due to mechanical disruption of macroaggregates from frequent tillage operations and reduced aggregate stability. Tillage increases the effect of drying–rewetting and freezing–thawing, which increase susceptibility of macroaggregate to physical disruption (Beare et al., 1994b; Paustian et al., 1997; Mikha and Rice, 2004). In contrast, mulch improves edaphological environment (Anikwe et al., 2004; Aniekwe et al., 2007), moderates soil temperature (Sarkar and Singh, 2007; Sarkar et al., 2007), increases soil porosity and water infiltration rate during intense rains (Gajri et al., 1994; Glab and Kulig, 2008), and reduces runoff and soil erosion (Bhatt and Khera, 2006). Fresh residues (mulches) are C source for microbial activity and form nucleation centers for aggregation, and the attendant enhanced microbial activity accentuates formation of macroaggregates (Jastrow, 1996; Six et al., 1999). Dorodnikov et al. (2009) highlighted the importance of macroaggregates in C and N sequestration. In general, macroaggregates ($>$0.25 mm) are more enriched in C than microaggregates ($<$0.25 mm) (Elliott, 1986; Cambardella and Elliott, 1993a,b; Puget et al., 1995; Six et al., 2000b). Adoption of NT increases the amount of C-rich macroaggregates and decreases that of C-depleted microaggregates (Six et al., 2000b). The high C/N ratio in the macroaggregates suggests that SOC associated with that fraction comprises of less decomposed material, and primarily consists of roots and fungal hyphae (Six et al., 2000a, 2002), and indicates rapid changes in SOC induced by land use or management. In comparison, the SOC encapsulated within the microaggregates ($<$0.25 mm) is a humified material with a low C/N ratio (Christensen, 2001). Therefore, a long-term use of CT favors higher SOC and N concentration, especially in the surface layers (Kern and Johnson, 1993; Duiker and Lal, 2000; Tan and Lal, 2005). Chen et al. (2009) reported that soil managed by CT contained 7.3% more SOC and 7.9% more N concentration than that under PT in the 0–20 cm depth. Therefore, a long term use of NT can play a key role in enhancing the soil C budget. Globally soils contain 3.5% of the C reserves of the earth, compared with 1.7% in the atmosphere and 1.0% in biota (Lal et al., 1995). Therefore, depending on management, world soils can be an important sink for atmospheric CO_2. Crop residues returned to the soil can increase or maintain SOC concentration (Havlin et al., 1990; Paustian et al., 1997), and enhance soil aggregation (Christensen, 1986; Skidmore et al., 1986; Lal, 1997; Unger, 1997a). Further, SOC in microaggregates is usually more resistant to decomposition and has a longer turnover time compared with SOC in macroaggregates or labile fractions (Beare et al., 1994b; Carter, 1996). In contrast to NT or CT, use of PT reduces SOC concentration in the surface soil (Angers et al., 1997; Paustian et al., 1997; Unger, 1997b), although the reverse may be true in the subsoil (Dick, 1983; Blanco-Canqui and Lal, 2009). Lal (1975) demonstrated that residue mulch improves infiltration characteristics, stability of aggregates, plant available water capacity (AWC) and crop yield on coarse-textured soils in West Africa. Hulugalle et al. (1987) observed that water infiltration rate increases only when CT and mulch are combined. Both aggregate-size distribution and stability are important indicators of soil physical quality (e.g., soil structure, infiltration, aggregation, and AWC) (Shrestha et al., 2007). Reddy et al. (2007) quantified carbon dioxide (CO_2) emissions from soil for different tillage methods, and reported 37% higher CO_2 efflux from PT than NT soils. Although the positive effect of CT and crop residues on soil physical quality and SOC pool are well established, only a limited number of studies have evaluated the interactive effects of residue application rates on overall soil physical quality and total SOC and N concentrations under a range of tillage systems. Thus, the objectives of this study were to determine: (1) the effects of RT, PT and NT on SOC and N pools and (2) changes in soil mechanical and hydrologic properties under different mulch rates and tillage methods. The hypotheses tested were: (1) a continuous use of NT enhances SOC and N concentrations in soil as compared to PT; (2) adoption of PT and RT degrades soil physical quality compared with NT; and (3) long-term use of NT and residue mulch increase proportion of soil macroaggregates.

2. Materials and methods

The experiment was located on the Waterman Farm of the Ohio State University (40°00′ N latitude and 83°01′ W longitude). The average annual temperature is 11 °C, and precipitation is 1016 mm (Jagadamma et al., 2009). The soil is a Crosby silt loam (Stagnic Luvisol in the FAO classification and a fine, mixed, active, mesic, Aeric Epiaqualf in the USDA classification). The experiment was initiated in the summer of 1989 as a split plot design with three replicates. The experiment involved three tillage systems {ridge tillage (RT), plow tillage (PT) and no-till (NT)} and three rates of application of wheat straw mulch (i.e., 0, 8 and 16 Mg ha^{-1}). Tillage treatment was the main plot and mulch rate was the sub-plot (2 m × 2 m). Soil tillage was performed each spring after which crop residue was applied manually. It was observed that residue mulch was rapidly compacted after a rainstorm (very frequent around the time of residue application) and, therefore, no special measures were taken to keep it on the plots. Plowing and ridging were done with a multiple and single moldboard plow operations, respectively, to a depth of ≈20 cm, after which the soil was not tilled any more during the year. No crop was planted and no fertilizer applied. Herbicides (usually glyphosate i.e. N-phosphonomethyl glycine) were used to control weeds when necessary. Soil sampling and other in situ measurements were made during June to November 2010.

2.1. Soil bulk density and penetration resistance

Soil bulk density (ρ_b) was determined for 0–10 and 10–20 cm depths using the core method (Blake and Hartge, 1986). The stainless steel cores were 60 mm high and 54 mm in diameter (137 cm^3 inner volumes). After obtaining the samples for the specific depth, cores were wrapped in polythene sheets, and placed in a thermo-box. Soil moisture content was measured gravimetrically for the same depth. Soil penetration resistance (PR) was measured by a hand-held digital cone-tipped (12.8-mm diameter) penetrometer (Field Scout, SC 900 Soil Compaction Meter; Spectrum Technologies, Inc., Plainfield, IL, USA) at four random locations for 10, 20, and 30 cm depths, and were averaged for each depth and plot.

2.2. Mean weight diameter, water stable aggregates and total carbon and total nitrogen

Relative proportion of water stable aggregates (WSA) (%) was determined on 50 g air dry aggregates of 5–8 mm diameters obtained from the bulk samples (0–15 and 15–30 cm) taken in July 2010 using the wet sieving method (Nimmo and Perkins, 2002). The aggregates were placed on top of a nest of sieves of 4.75, 2, 1, 0.5 and 0.25 mm size, wetted by capillarity for 15 min and oscillated through a vertical distance of about 3 cm at 30 oscillations per minute in a water column for 30 min. The fractions retained in each sieve were washed into different beakers. The soil fraction of <0.25 mm (microaggregates) was obtained by filtering the sediment in the collection tank after the sieving. The collected fractions were oven dried at 40 °C and weighed to compute the mean weight diameter (MWD), and percent WSA calculated by the methods of Kemper and Rosenau (1986). The aggregates retained on each sieve size fractions were then mixed together to get proportionate sample of macroaggregates for total C (TC) and total N (TN) analyses. Subsamples from each aggregate fraction were grouped and mixed together to represent two aggregate-size fractions (Tisdal and Oades, 1982): macroaggregates (>0.25 mm), and microaggregates (<0.25 mm), ground using a mortar and pestle, sieved through 0.125 mm sieve and stored at room temperature and then shaken overnight (16 h) in glass vials on end to end floor shaker pending total C and total N analyses using CN analyzer for surface (0–15 cm) soil only.

2.3. Water infiltration capacity

Field measurements of infiltration characteristics were made by using a double ring infiltrometer (Reynolds et al., 2002). Two cylinders, 25 cm high and of 60 cm and 30 cm diameters for outer and inner rings, respectively, were inserted to a depth of 10 cm with 15 cm remaining above ground. While maintaining a constant head in the inner ring, the experiment was continued for 270 min with measurements made at 1, 3, 5, 10, 20, 30, 60, 120, 180, 240 and 270 min. The water infiltration data were fitted to several models including the Green and Ampt (1911), Kostiakov (1932), Horton (1933) and Philip (1957). In general, the Kostiakov (1932) and Philip (1957) models are the most commonly used because of their simplicity. The Philip (1957) model is in the form of a power series but an adequate description is given by the first two parameters (Eq. (1)):

$$i = \frac{1}{2}St^{-1/2} + A \tag{1}$$

where i is infiltration rate, S is sorptivity ($LT^{-1/2}$), t is time and A is transmissivity (LT^{-1}). The latter is a gravity factor related to hydraulic conductivity, and S is the measure of ponded water infiltrability of the soil matrix or the rate at which water will be drawn into a soil in the absence of gravity. It comprises the combined effects of adsorption at surfaces of soil particles and capillarity in soil pores. The gravity factor is due to the impact of pores on the flow of water through soil under the influence of gravity. The S is influenced by the initial and final moisture contents. As the moisture content approaches saturation, S approaches zero and the infiltration rate becomes equal to the field saturated hydraulic conductivity (K_s). This implies that the steady state infiltration rate reached after a long time should be largely independent of the antecedent moisture content. The parameter A is a measure of mean K_s of the entire soil profile at steady state. The values of 'S' and 'A' are obtained from the graph(s) drawn between i and $T^{-0.5}$ as the slope and intercept, respectively (Eq. (1)).

The Kostiakov (1932) model expresses cumulative infiltration (I) as a function of time (t) thus,

$$I = Kt^a \tag{2}$$

where 'K' and 'a' are the fitting parameters, and depend on soil properties, especially the initial water content of the soil. The model is ideal for expressing horizontal flows (where the effect of gravity is essentially zero) but is grossly deficient for vertical flows. One weakness of this model is that it does not predict a final and constant infiltration rate. However, the model was used in this study for its simplicity.

2.4. Saturated hydraulic conductivity

Undisturbed core samples from 0 to 10 and 10 to 20 cm soil depths were used also for the determination of K_s. Soil cores were saturated by capillarity for 24 h with de-aired tap water for the determination of K_s using a constant-head method (Reynolds et al., 2002).

2.5. Oxygen diffusion rate

The oxygen diffusion rate (ODR) in soil was measured for 0–5 cm depth by the method of Lemon and Erickson (1952) using the platinum micro-electrode. Ten platinum and a reference electrodes were inserted into the soil and electric current was applied in the circuit. The electric current flowing between the electrodes was proportional to the rate of oxygen reduction which in turn is related to the rate of oxygen diffusion to the electrodes. The ODR was calculated from the measured electric current by Eq. (3).

$$\mathrm{ODR} = \frac{Mi}{nFA} \tag{3}$$

where M is the molar weight of oxygen, n is number of electrons involved in reduction of one molecule of oxygen, F is the Faraday constant, i is current in amperes and A is the exposed surface of the electrode. The ODR value of 20×10^{-8} g cm^{-2} s^{-1} or more suggests sufficient oxygen supply for root growth.

2.6. Statistical analysis

The differences between the means of ρ_b, PR, i_c, K_s, MWD, WSA, ODR and SOC were assessed by t-test and analysis of variance (ANOVA). Linear regression was used to evaluate the relationships between soil aggregation and SOC concentration. The mean and interaction effects of treatment were separated using the F-protected least significant differences (LSD) test, at the probability level $P \leq 0.05$. All collected data were subjected to Analysis of Variance (ANOVA) following statistical software CPCS 1 (Cheema and Singh, 1990). The significance of interaction between tillage, soil depth and mulch application rate on soil physical characteristics and SOC was also tested statistically.

3. Results and discussion

3.1. Soil bulk density and penetration resistance

The ANOVA test indicated that tillage methods and mulch rate had a significant effect on ρ_b (Mg m^{-3}), which decreased from 1.46 to 1.31, 1.45 to 1.36 and 1.50 to 1.47 under NT, RT and PT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. In comparison with unmulched control, the ρ_b decreased significantly for 8 and 16 Mg ha^{-1} of mulch rate. Soil depth had a significant influence ($P < 0.05$) on ρ_b, and the maximum range in ρ_b of 1.31 to 1.50 Mg m^{-3} was observed for 0–10, and 1.38–1.63 Mg m^{-3} for 10–20 cm depth (Table 1). The lowest ρ_b values were measured for the surface layer (0–10 cm). In-comparison with PT, average decrease in ρ_b was 6.1% and 5.4% for 0–10 cm depth and 7.6% and 5.7% for 10–20 cm depth for NT and RT tillage, respectively. Reduction in ρ_b in NT system has also been reported by other researchers (Hill and Cruse, 1985; Croretto, 1998; Dao, 1996; Shaver et al., 2002; Shirani et al., 2002; McVay et al., 2006). Plowing operations for PT systems along with the lower SOM concentrations of the PT soils, however, result in subsoil compaction. Lower ρ_b in NT soils may also be associated with greater soil biological activities, especially earthworms (Lal, 1976). The data from this study show that tillage systems had significant influence on soil ρ_b. Similar results have been reported by Lal (2000), who observed

Table 1
Mulch and tillage effects on soil bulk density (Mg m^{-3}).

Tillage	Mulch rate (Mg ha^{-1})					
	0		8		16	
	Soil depth (cm)					
	0–10	10–20	0–10	10–20	0–10	10–20
NT	1.46	1.52	1.40	1.45	1.31	1.38
RT	1.45	1.54	1.40	1.48	1.36	1.41
PT	1.50	1.63	1.46	1.57	1.47	1.52
LSD (<0.05)	Tillage = 0.01 Mulch = 0.02 Depth = 0.02 Tillage × mulch × depth = NS					

that annual application of 16 Mg ha^{-1} of rice (*Oryza sativa* L.) straw for 3 yr decreased ρ_b from 1.20 to 0.98 Mg m^{-3} on a sandy loam. Similarly, Blanco-Canqui et al. (2006) reported that corn stover mulching at 5 and 10 Mg ha^{-1} for a period of 1 yr reduced ρ_b from 1.42 Mg m^{-3} (control) to 1.26 and 1.22 Mg m^{-3}, respectively, in NT systems in a silt loam. The interactive effect of tillage, mulch and depth on ρ_b was not significant in the present study. In accord with ρ_b, PR was also significantly affected by tillage and mulch rate treatments (Table 2). Increase in mulch rate from 0 to 16 Mg ha^{-1} decreased PR (MPa) of 10–20 cm depth from 1.79 to 1.46, 2.08 to 1.68 and 2.35 to 2.06 under NT, RT and PT, respectively. The maximum PR (2.84 MPa) was observed under PT at 20–30 cm depth and the least (0.79 MPa) under NT at 0–10 cm depth (Table 2). Irrespective of mulch treatment, PR (MPa) increases from 0.88 (NT) to 0.97 (PT) at 0–10 cm depth, 1.66 (NT) to 2.19 (PT) at 10–20 cm depth and 2.26 (NT) to 2.65 (PT) at 20–30 soil depth. The ANOVA for PR (Table 2) showed that tillage and soil depth interactions were significant though the interaction between tillage, mulch and soil depth was not. The PR was significantly greater in the PT (mean of 1.94 MPa when averaged over all depths) compared to the RT (1.74 MPa) and NT treatments (1.60 MPa). Irrespective of soil depth, PR in NT plots averaged 1.68, 1.61, and 1.51 MPa for 0, 8, and 16 Mg ha^{-1} mulch rates, respectively. Similarly, PR in RT and PT averaged 1.94, 1.74, 1.58 and 2.08, 1.95, 1.78 MPa at the 0, 8, and 16 Mg ha^{-1} mulch rates, respectively. Crop residue mulch reportedly improves soil quality in terms of SOC concentration, biological activity and PR. Soil PR in NT for the 0–10 cm depth was significantly different and smaller compared with those for 10–20 and 20–30 cm depths. In RT and NT, there were significant differences in soil PR among the three depths sampled (Table 2). However, soil PR at the 10–20 cm depth in PT was more than those for NT and RT systems. The data indicates the possibility of a plow pan at 10–20 cm depth. Similar observations were also reported by Materechera and Banda (1997) and Unger (1995).

3.2. Infiltration capacity and saturated hydraulic conductivity

Effects of tillage and mulch treatments on soil hydrological properties (i_c and K_s) are presented in Tables 3 and 4. In general, relatively higher i_c and K_s were measured in NT than PT treatments (Figs. 1 and 2). The i_c (cm h^{-1}) increased from 3.1 to 4.6, 2.3 to 3.5 and 1.2 to 2.1 under NT, RT and PT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. Similar observations were also reported by Lal (1997). The parameter A ranged from 1.85 to 2.53 cm h^{-1}, putting the soil conductivity class between medium to moderately high, whereas *S* ranged from 22.7 to 50.3 cm h$^{-1/2}$ among three tillage practices. The coefficients of '*k*' and '*a*' of Kostiakov (1932) equation ranged from 2.45 to 5.04 and 0.06 to 0.11, respectively, among three tillage practices. Similarly, to infiltration rate, K_s were also significantly affected by tillage methods and mulch rates. The K_s ($\times 10^{-2}$ cm h^{-1}) increased from 1.78 to 3.37, 1.57 to 2.95 and 1.37 to 2.28 under NT, RT and PT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. The ANOVA showed significant differences in K_s among three tillage

Table 2
Mulch and tillage effects on soil penetration resistance (MPa).

Tillage	Mulch rate (Mg ha^{-1})								
	0			8			16		
	Soil depth (cm)								
	0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30
NT	1.01	1.79	2.24	0.84	1.73	2.27	0.79	1.46	2.28
RT	1.03	2.08	2.61	0.91	1.95	2.36	0.84	1.68	2.23
PT	1.04	2.35	2.84	1.02	2.15	2.68	0.85	2.06	2.43
LSD (<0.05)	Tillage = 0.02 Mulch = 0.06 Depth = 0.05 Tillage × depth = 0.08 Tillage × mulch × depth = NS								

Table 3
Mulch and tillage effects on initial and steady state infiltration rate.

Tillage practices	Infiltration characteristics					
	Initial infiltration rate (cm h^{-1})			Steady infiltration rate (cm h^{-1})		
	Mulch rate (Mg ha^{-1})					
	0	8	16	0	8	16
NT	24	30	48	3.1	4.0	4.6
RT	18	24	30	2.3	2.9	3.5
PT	12	24	24	1.2	1.8	2.1
LSD (<0.05)	Tillage = 10.1 Mulch = 8.5 Tillage × mulch = NS			Tillage = 0.5 Mulch = 0.4 Tillage × mulch = NS		

Table 4
Mulch and tillage effects on saturated hydraulic conductivity of soil ($\times 10^{-2}$ cm h^{-1}).

Tillage	Mulch rate (Mg ha^{-1})					
	0		8		16	
	Soil depth (cm)					
	0–10	10–20	0–10	10–20	0–10	10–20
NT	1.78	1.44	2.47	1.81	3.37	3.24
RT	1.57	1.31	2.39	2.36	2.95	2.14
PT	1.37	1.23	1.84	1.75	2.28	1.66
LSD (<0.05)	Tillage = 0.13 Mulch = 0.14 Depth = 0.11 Tillage × mulch = 0.24 Tillage × mulch × depth = 0.33					

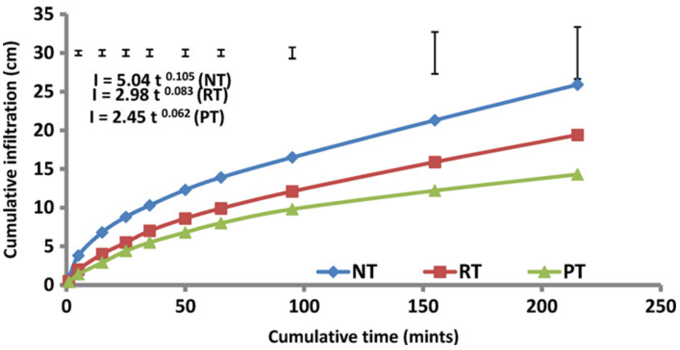

Fig. 1. Cumulative infiltration under different tillage practices. Coefficients '*k*' and '*a*' of infiltration equation proposed by Kostiakov (1932). Bars show LSD values ($P < 0.05$).

treatments. Irrespective of soil depth and mulch treatment, soil K_s ($\times 10^{-2}$ cm h^{-1}) was significantly influenced by tillage and ranged from 1.68 for PT to 2.35 for NT. The K_s ($\times 10^{-2}$ cm h^{-1}) decreased from 2.54 to 2.16, 2.30 to 1.94 and 1.83 to 1.55 under NT, RT and PT, respectively, with increase in soil depth from 0–10 cm to 10–20 cm depth. Significant interaction between tillage, mulch and soil depth was observed for K_s. Gangwar et al. (2006) reported that the crop residues left on the soil surface limit evaporation, soil sealing and crusting and thereby increase soil infiltration. Barzegar et al. (2002) observed that infiltration rate and water retention increased linearly with increase in wheat straw application rate from 0 to 15 Mg ha^{-1}. Similar observations were also reported by Lal (1986). Ogban et al. (2008) also reported that equilibrium infiltration rate and cumulative infiltration were significantly higher under mulched NT than mulched PT plots. The K_s results are in accord with those of Zachman et al. (1987) and Shirani et al. (2002) who reported that NT with residue mulch had higher infiltration rate than that without it. The differences in K_s suggest more porosity, less tortuous paths, and better pore continuity in NT compared to PT practice. Thus, soil K_s decreased with increased intensity of soil manipulation by tillage practices. Soil macropores and aggregations under NT formed by decayed roots can be preserved under NT whereas conventional tillage breaks up the continuity of these macropores (Mikha and Rice, 2004). Macropores generally occupy a small fraction of the soil volume but their contribution to water flow in soil is high. The higher K_s in NT system may have been caused by better pore continuity, aggregation, and less tortuosity. Soil macropores and aggregations under NT formed by decayed roots can be preserved under NT whereas PT breaks up the continuity of these macropores (Shipitalo et al., 2000). Macropores generally occupy a small fraction of the soil volume but their contribution to water flow in soil is high.

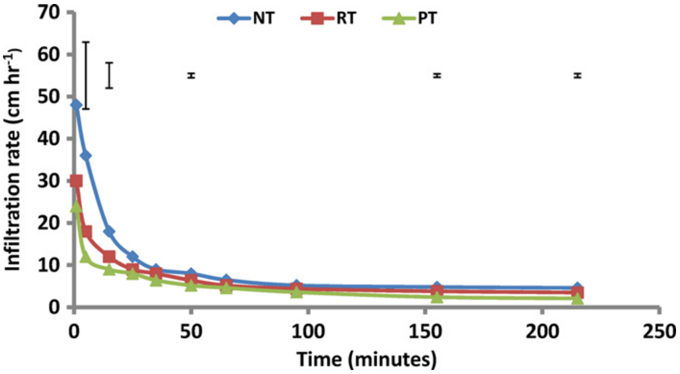

Fig. 2. Infiltration rate as affected by different tillage practices at mulch rate of 16 Mg ha^{-1}. Bars show LSD values ($P < 0.05$).

3.3. Mean weight diameter and water stable aggregates

The data on MWD and WSA for 0–10 cm and 10–20 cm depths are presented in Table 5. Across all tillage, mulch and depth, WSA (%) ranged from 21.7 to 77.4 and MWD (mm) from 0.19 to 1.21. The MWD (mm) increased from 0.36 to 1.21, 0.29 to 0.84 and 0.25 to 0.62 for 0–10 cm compared with 0.23 to 0.65, 0.21 to 0.53 and 0.19 to 0.47 for 10–20 cm depth under NT, RT and PT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. Similarly, WSA (%) increased from 52.7 to 77.4, 43.7 to 66.6, and 39.5 to 59.5 for 0–10 cm compared with 31.7 to 54.3, 26.8 to 46.1, 21.7 to 38.5 for 10–20 cm depth under NT, RT and PT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. Under NT practice different sizes of WSA were formed under the influence of natural conditions due to the absence of artificial disturbance, which implies that the degree of soil aggregation under NT was more than that under PT practices. Mechanical tillage disrupts aggregation, accentuates mineralization of SOM, and the decrease activity and species diversity of organism in the cultivated layer. Such tillage-induced changes lead to the reduction of the binding-force between soil particles and reduce WSA. On the other hand, application of residue mulch increases the quantity of WSA (Unger et al., 1998). Irrespective of mulch application rate, MWD (mm) was 0.74, 0.57

Table 5
Mulch and tillage effects on mean weight diameter (mm) and water stable aggregates (%).

Tillage	Mulch rate (Mg ha^{-1})					
	0		8		16	
	Soil depth (cm)					
	0–10	10–20	0–10	10–20	0–10	10–20
MWD (mm)						
NT	0.36	0.23	0.64	0.51	1.21	0.65
RT	0.29	0.21	0.57	0.45	0.84	0.53
PT	0.25	0.19	0.44	0.37	0.62	0.47
LSD (<0.05)	Tillage = 0.07 Mulch = 0.02 Depth = 0.01 Tillage × mulch = 0.04 Tillage × mulch × depth = 0.05					
WSA (%)						
NT	52.1	31.7	68.7	43.9	77.4	54.3
RT	43.7	26.8	58.6	36.5	66.6	46.1
PT	39.5	21.7	50.9	30.6	59.5	38.5
LSD (<0.05)	Tillage = 5.6 Mulch = 3.1 Depth = 0.62 Tillage × mulch = 1.07 Tillage × mulch × depth = NS					

and 0.43 for 0–10 cm soil depth and 0.46, 0.40 and 0.34 for 20–30 cm depth in NT, RT and PT, respectively. Similarly WSA (%) was 66.1, 56.3 and 50.0 for 0–10 cm depth and 43.3, 36.5 and 30.3 for 10–20 cm depth in NT, RT and PT, respectively. Significant interaction was observed in tillage, mulch rate and soil depth for MWD. However, such interactions were lacking in WSA except between tillage and mulch treatments (Table 5). West et al. (1992) indicated that the WSA in the soil under NT practice was 67% higher than that under PT tillage. Beare et al. (1994a,b) reported that microaggregates (<2.5 mm) in soil under PT were unstable and also lesser than that under NT (21% vs. 65%). Unger (1995) also observed that the diameter of WSA under NT was about 0.5 mm more than that under PT. Across mulch and soil depth, the MWD was 0.60, 0.48 and 0.39 mm in NT, RT and PT, respectively. A similar trend was observed in WSA with the maximum value of 54.7% in NT, 46.4% in RT and 40.1% in PT. Thus, in comparison with PT, MWD increased by 20% and 35% in RT and NT, respectively. In a study conducted on a high clay Orthic Humic Gleysol in Canada, Angers et al. (1993) observed a decrease in MWD of WSA after four years of PT compared with NT. Beare et al. (1994b) reported that PT reduced the size of WSA compared with NT on a well-drained sandy clay loam in Athens, Georgia. In comparison with PT and similar to the trends in MWD, WSA also increased by 14% and 27% in RT and NT, respectively. Across tillage treatments, MWD (mm) increased from 0.30 to 0.55 to 0.89 for 0–10 cm depth and 0.21 to 0.44 to 0.55 for 10–20 cm depth with increase in mulch rate from 0 to 8 to 16 Mg ha^{-1}. The WSA (%) increased significantly with increase in mulch rate irrespective of tillage treatment. The WSA (%) was 45.1, 59.4 and 67.8 for 0–10 cm depth and 26.7, 37.0 and 46.3 for 10–20 cm depth at 0, 8 and 16 Mg ha^{-1} much rate, respectively.

3.4. Oxygen diffusion rate

The ODR was not significantly affected by tillage treatments (Fig. 3). However, significant increase in ODR was observed with increase in rate of mulch application. The general trend presented in Fig. 3 indicate that ODR ($\times 10^{-8}$ g cm^{-2} s^{-1}) increased from 30.6 to 45.0, 28.9 to 39.7 and 27.8 to 43.7 under NT, RT and PT treatments, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1}. Similar observations were also reported by Lal (1986). Erickson and Van Doren (1960) observed that root elongation is seriously limited as the ODR falls below 58 g cm^{-2} s^{-1}. Dowdell et al. (1979) reported that the average O_2 concentration in direct-drilled and plowed soils was 10.2 and 7.2%, respectively. This trend was attributed to systems of large pores and channels that developed in the direct-drilled plots but were destroyed by plowing. Aeration porosity (f_a) being inversely related to ρ_b, a higher ρ_b under PT decreases ODR. However, in present study no significant difference in ODR was observed with respect to tillage treatments, and ODR ($\times 10^{-8}$ g cm^{-2} s^{-1}) values were 38.7, 34.4 and 36.7 in NT, RT and PT, respectively. Irrespective of tillage treatment, ODR was 29.1, 37.7 and 42.8 at 0, 8 and 16 Mg ha^{-1} mulch rate, respectively.

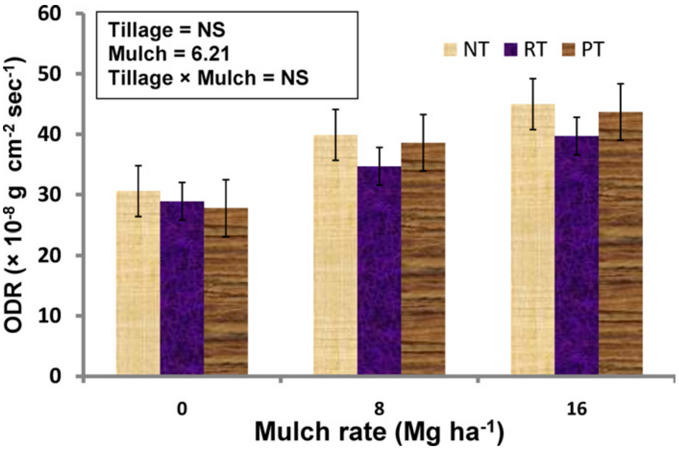

Fig. 3. Mulch and tillage effects on oxygen diffusion rate (ODR) ($\times 10^{-8}$ g cm^{-2} s^{-1}). Bars showed standards errors.

3.5. Total carbon and total nitrogen concentrations

Significant variations in total C (TC) and total N (TN) concentrations and C:N ratio were observed among tillage and mulch treatments. On average, 30% more TC and TN concentrations were observed under NT than PT. Further, macroaggregates (>250 μm) contained about 35% more TC and TN concentrations than microaggregates (<250 μm). The TC (%) concentration increased from 1.26 to 1.50, 1.20 to 1.47 and 0.95 to 1.10 under NT, RT and CT, respectively, with increase in mulch rate from 0 to 16 Mg ha^{-1} (Table 6). Irrespective of aggregate classes and mulch rate, the maximum TC concentration (%) was observed in NT (1.18) followed by that in RT (1.12) and the least in PT (0.96). Similar to TC, the TN concentration (%) was also the maximum in NT (0.13), followed by that in RT (0.12) and the least in PT (0.10). However, averaging across tillage treatments, TC (%) increased from 1.14 to 1.36 for macroaggregates and 0.79 to 1.10 for microaggregates with increase in mulch rate from 0 to 16 Mg ha^{-1}. The C:N ratios were significantly higher in macroaggregates (0.25–2 mm) than microaggregates. In general, macroaggregates contained more C and N concentrations than microaggregates (Dorodnikov et al., 2009). The enhancements of C and N concentrations in NT may be attributed to increase in soil aggregation, especially macroaggregates (0.25–2 mm) and relatively higher increase in labile C pools as a result of less disturbance and more residue retention (Havlin et al., 1990). Dell et al. (2008) reported that the NT fields had approximately 50% more C and N concentrations in particulate and mineral-associated pools in the upper 5 cm compared to PT, but C and N accumulations below 5 cm were similar. Duiker and Lal (2000) observed 10% C conversion efficiency per year under NT as compared to 8% under PT.

Table 6
Impact of tillage and mulch application rates on total C (TC) and N (TN) in surface soils (0–15 cm).

Tillage	Mulch rate (Mg ha^{-1})					
	0		8		16	
	Aggregate class					
	Macro	Micro	Macro	Micro	Macro	Micro
TC (%)						
NT	1.26	0.84	1.29	1.00	1.50	1.24
RT	1.20	0.77	1.28	0.95	1.47	1.07
PT	0.95	0.76	1.04	0.94	1.10	0.99
LSD (<0.05)	Tillage = 0.09					
	Mulch = 0.02					
	Aggregate class = 0.07					
	Tillage × aggregate class = 0.11					
	Tillage × mulch × aggregate class = NS					
TN (%)						
NT	0.14	0.11	0.13	0.10	0.15	0.11
RT	0.13	0.11	0.12	0.11	0.14	0.11
PT	0.11	0.09	0.11	0.09	0.12	0.10
LSD (<0.05)	Tillage = NS					
	Mulch = NS					
	Aggregate class = 0.08					
	Tillage × aggregate class = NS					
	Tillage × mulch × aggregate class = NS					

4. Conclusions

Long-term NT and mulch application (22 yr) strongly impacts soil physical characteristics, hydrological properties and C concentration in Central Ohio. Higher total C and N concentrations in NT than PT support the first hypothesis. Long term addition of crop residue and more decomposition of organic matter under NT favor increase in both C and N concentration in the soil. Higher bulk density and penetration resistance and lower infiltration capacity and saturated hydraulic conductivity under PT than NT along with mulch application also support the second hypothesis and indicate the positive effect of NT and residue mulch in enhancing structural properties. The soil compaction results suggest that the PT was not able to create a stable structure and that its positive effects on the physical soil properties was annulled by the compression action due to wheel transit of the agricultural machines, reconsolidation under the weight of the soil mass, soil deformation from wetting and drying, the impacts of rain drop and the disintegration of soil aggregates. Conversely, the lower soil compaction values recorded with NT show that via the reduction of the soil disturbance level, this tillage practice could be able to improve the physical soil properties and structural stability, minimizing the negative consequences of the wheel trafficking. Higher proportion of macroaggregates observed under NT than PT supports the third hypothesis. Furthermore, the results of this study support the following conclusions:

- No-till significantly affected soil mechanical (bulk density, penetration resistance) and hydrological (infiltration rate and saturated hydraulic conductivity) properties in combination with residue application.
- Soil carbon concentration is enhanced through formation of macroaggregates under long term conservation tillage along with application of crop residue mulch.

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