Soil & Tillage Research 106 (2009) 85–94

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China

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ARTICLE INFO

Article history:
Received 16 June 2009
Received in revised form 6 September 2009
Accepted 12 September 2009

Keywords:
Conservation tillage
Soil organic C and N
Labile soil organic C
Aggregate-size distribution
Winter wheat monoculture

ABSTRACT

The Loess Plateau in northwest China is one of the most eroded landscapes in the world, and it is urgent that alternative practices be evaluated to control soil erosion. Our objective was to determine how three different tillage practices for monoculture of winter wheat (*Triticum aestivum* L.) affected soil organic carbon (SOC) and N content after 11 years. Conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) were investigated. Carbon and N in various aggregate-size classes and various labile organic C fractions in the 0–15- and 15–30-cm soil layers were evaluated. The ST and NT treatments had 14.2 and 13.7% higher SOC stocks and 14.1 and 3.7% higher total N (N_t) stocks than CT in the upper 15 cm, respectively. Labile C fractions: particulate organic C (POC), permanganate oxidizable C ($KMnO_4$-C), hot-water extractable C (HWC), microbial biomass C (MBC) and dissolved organic C (DOC) were all significantly higher in NT and ST than in CT in the upper 15 cm. $KMnO_4$-C, POC and HWC were the most sensitive fractions to tillage changes. The portion of 0.25–2 mm aggregates, mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates from ST and NT treatments were larger than from CT at both 0–15- and 15–30-cm soil depths. The ST and NT treatments had significantly higher SOC and N_t in the 0.25–2 mm fraction at both depths and significantly higher N_t content in the upper 15 cm. Positive significant correlations were observed between SOC, labile organic C fractions, MWD, GMD, and macroaggregate (0.25–2 mm) C within the upper 15 cm. We conclude that both variants of conservation tillage (NT and ST) increase SOC stock in the rainfed farming areas of northern China and are therefore more sustainable practices than those currently being used.

1. Introduction

Soil organic matter (SOM) is an important indicator of soil fertility and productivity because of its crucial role in soil chemical, physical and biological properties (Gregorich et al., 1994). Therefore, maintenance of satisfactory level of SOM is necessary for sustainable agroecosystems. There are two ways to increase soil organic C (SOC): (1) increase of C input, or (2) decrease of SOC loss and decomposition. Carbon input can be increased and decomposition decreased by adopting residue management and using conservation tillage (no-tillage or reduced tillage). However, short- and medium-term SOC changes are difficult to detect because of high background C content and its temporal and spatial variability (Bosatta and Ågren, 1994). In contrast, labile C pools which turn over relatively rapidly can respond more quickly to land use change and soil management than SOC, and are thus suggested as early and sensitive indicators of SOC changes (Haynes, 2000; Ghani et al., 2003). Microbial biomass C (MBC), particulate organic C (POC), dissolved organic C (DOC), hot-water extractable C (HWC), permanganate oxidizable ($KMnO_4$-C) have been recognized as labile soil organic C pools, and important indicators of soil quality (Powlson et al., 1987; Cambardella and Elliott, 1992; Blair et al., 1995; Ghani et al., 2003). A suite of labile C fractions is typically required to assess SOM quality because of the multifunctional role of SOM (Haynes, 2005; Soon et al., 2007). Physical fractionation of soil for aggregate-size fractions (i.e. wet sieving) has been an effective technique for evaluating soil aggregation and degradation induced by management practices, studying the forms and cycling of SOC, and providing important information about C sequestration mechanisms (Six et al., 2002). Hence, for an improved understanding of the mechanisms leading to

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doi:10.1016/j.still.2009.09.009

C sequestration, more fundamental investigations of SOC pools and especially their labile fractions is necessary to quantify effects of tillage.

Many studies indicate that various tillage systems have a strong effect on labile SOC, soil aggregation, and SOC distributions in aggregates size fractions. Such effects varied depending on regional climate, soil type, residue management practice, and crop rotation (Paustian et al., 1997; Puget and Lal, 2005). Research on soil C sequestration for specific soil/climate/cropping system is therefore necessary. Furthermore, there has been very little number of studies investigating the effects of conservation tillage on C sequestration under rainfed agricultural systems on Loess Plateau of China.

Long-term experiments provide important information on management practice effects on soil productivity. Since 1997, the Australian Centre for International Agricultural Research (ACIAR) and the Chinese Ministry of Agriculture conducted a bilateral experimental project on conservation tillage in the Loess Plateau of Shanxi Province, northern China. This study is the first report of this conservation tillage project with regard to C sequestration. The specific objectives were to determine long-term (11 years) tillage [conventional tillage with residue removal (CT), no-tillage with residue cover (NT), and shallow tillage with residue cover (ST)] effects on (1) SOC and N storage; (2) labile soil organic C pools; (3) aggregate-size distribution and C and N sequestration in different aggregate-size fractions; and (4) relationships between SOC, soil aggregation, labile C pools, and aggregate associated C. Particular interest was pointed on whether conservation tillage with residue retention is a sustainable approach to sequester C for rainfed wheat monoculture in the dryland Loess Plateau of China.

2. Materials and methods

2.1. Description of sites and soil sampling

The research was based on a long-term conservation tillage experiment started in 1997 at Chenghuang, Linfen, in the Loess Plateau of Shanxi Province (Northern China, 38°6′N, 113°E, 456 m a.s.l.). It is located in a semi-arid, semi-humid, continental climate, with mean annual temperature of 10.7 °C and mean annual precipitation of 555 mm. Approximately 65% of annual precipitation occurs between June and September. The soil was developed from loess and is classified as a Chromic Cambisol according to the FAO/WRB. The basic soil properties are shown in Table 1. Winter wheat (*Triticum aestivum* L.) monoculture is common in this region and was grown every year under rainfed condition. The experiment had three treatments: conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT). Treatments were arranged in randomized block design with three replicates. Each plot was 4.5 m wide and 30 m long. The CT treatment consisted of moldboard ploughing to a depth of 15–20 cm after harvest during the first 10 days of June and tine tillage for seedbed preparation in late September. The second treatment ST – shallow tillage (5-cm depth) – was carried out in late September. no-tillage was used in the third, NT, treatment. Winter wheat was seeded between September 20th and 30th, and harvested between June 1st and 10th. A fallow period followed harvest until mid-September. At maturity winter wheat were harvested manually in the CT, most of the residue was removed, and only a small amount of standing stubble of about 8 cm in height remained. Both NT and ST treatments were harvested mechanically and standing stubble of about 15–20 cm in height was retained with all wheat residue left as a mulch cover (3.8 t ha^{-1}). All other management procedures were identical for the three tillage treatments: herbicide (2,4-D butylate) and insecticide (40% dimethoate) spraying in April and fertilizer applied at rates of 150 kg N ha^{-1} as $CO(NH_2)_2$, 140 kg P ha^{-1} as $(NH_4)_2HPO_4$ and 62 kg K ha^{-1} as KCl.

Soil samples were collected from two depths (0–15 and 15–30 cm) within the three tillage treatments in April 2008. Soils were sampled at three randomly chosen locations within each plot. The top 15 cm were taken by excavating a 30 cm × 30 cm pit with a spade. Samples were also collected for the 15–30-cm depth, just below where the surface samples were carefully taken. Soil samples within each replicate plot were bulked by depth to obtain a composite sample representing each plot. All together, there were 18 composite samples representing three tillage treatments, two depths, and three field replicates. Additional triplicate soil bulk density samples were taken at the same soil depth intervals by the core method (Blake and Hartge, 1986) by Bai et al. (2009). Field moist samples were sieved (8 mm) by gently breaking apart the soil along natural planes of weakness. Sieved soil samples were divided into three sub-samples. One portion was air-dried for aggregate separation; one portion was air-dried, ground with wooden blocks and passed through a 2 mm sieve for physical and chemical analysis; and the remaining portion was sieved again through a 2 mm sieve and frozen for biochemical analysis. Identifiable crop residues, root material and stones were removed during sieving, and fine plant residues were removed from sieved air-dried samples by electrostatic forces induced by a plastic cylinder being rubbed against wool (Kuzyakov et al., 2001).

2.2. Analyses of soil properties

2.2.1. Aggregate-size distribution

Aggregate-size distribution was measured with a modification according to a wet-sieving procedure described by Elliott (1986). Briefly, duplicate 80 g samples of air-dried soil (passing an 8 mm sieve) were spread uniformly on the uppermost of a set of nested sieves (2, 0.25, and 0.05 mm) and submerged in deionized water for 5 min to allow slaking. Thereafter, the nest of sieves was oscillated vertically in deionized water for 2 min with 25 oscillations per minute and amplitude of 3 cm. The materials

Table 1

Average surface (0–15- and 15–30-cm) soil characteristics where conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) were evaluated near Linfen China.

Depth (cm)	Tillage	pH_{CaCl_2} (1 : 2.5)	CEC (cmol kg^{-1})	BD (g cm^{-3})	Particle size distribution (mm), g kg^{-1}		
					Sand (2–0.05)	Silt (0.05–0.002)	Clay (<0.002)
0–15	CT	7.42 (0.03) ab	16.8 (1.4) a	1.47 a	443.9	322.4	233.7
	ST	7.38 (0.02) b	12.2 (0.2) b	1.25 b	481.7	338.6	179.7
	NT	7.43 (0.01) a	12.6 (0.0) b	1.33 b	455.0	356.1	188.9
15–30	CT	7.47 (0.01) a	15.9 (1.4) a	1.52 a	483.7	291.1	225.3
	ST	7.47 (0.03) a	13.3 (0.3) b	1.48 a	487.7	314.4	197.9
	NT	7.48 (0.03) a	12.7 (0.7) b	1.46 a	474.6	315.1	210.3

Values are means with the standard deviation in parenthesis ($n = 3$); values within a column followed by different lowercase letters are significantly different ($P < 0.05$).

retained on each sieve were gently back washed into preweighed aluminum containers. The <0.05 mm fraction was collected by centrifuging for 5 min at 4000 rpm and then washing the pellet into an aluminum container. This wet-sieving procedure resulted in the following fractions: >2 mm (large macroaggregates), 0.25–2 mm (small macroaggregates), 0.25–0.05 mm (microaggregates), and <0.05 mm (silt plus clay fraction). All fractions were oven dried at 60 °C for 48 h, weighed, and preserved for further processing. Each aggregates size fraction was expressed as a percentage of the total soil weight.

The sand content of each aggregate fraction (>0.05 mm) was determined by dispersing a sub-sample of the aggregate fraction in 5% sodium hexametaphosphate. Samples were shaken for 18 h, followed by sieving on the same size screen as the one from which the aggregates were collected (Six et al., 2002). Sand remaining on the sieve was dried and weighed.

2.2.2. Labile soil organic carbon fractions

Microbial biomass C (MBC) was analyzed by the fumigation-extraction method (Vance et al., 1987). Each replicate was divided into two equivalent portions, one was fumigated for 24 h with ethanol-free chloroform and the other was the unfumigated control. Both fumigated and unfumigated soils, were shaken for 30 min with 0.5 M K_2SO_4 (1:4 soil:extraction ratio) and centrifuged and filtered. Extracts were analyzed for DOC on a Multi 3100 N/C TOC analyzer (Analytik Jena, Germany). A K_C value of 0.45 and a K_N of 0.54 were used to calculate the C and N content of the microbial biomass (Joergensen, 1996; Joergensen and Mueller, 1996). The unfumigated samples were used to estimate background DOC values.

Hot-water extractable C (HWC) was determined by adapting the procedures of Ghani et al. (2003) and Zhang et al. (2006). Briefly, ten grams of sieved (<2 mm) fresh soil was mixed with 40 ml distilled water in 50 ml polypropylene centrifuge tubes. The tubes were shaken on a horizontal shaker at 30 rpm for 30 min. After shaking, the tubes were capped and left for 16 h in an 80 °C hot-water bath. The tubes were then shaken for 10 min on a horizontal shaker and subsequently centrifuged at 8000 rpm for 20 min. The supernatants were vacuum filtered through 0.45 μm cellulose acetate membrane filters. Extracts were analyzed for total organic C on a Multi 3100 N/C TOC analyzer.

A previously published protocol (Cambardella and Elliott, 1992; Martinez-Mena et al., 2008) was used to obtain particulate organic matter (POM). Twenty grams of air-dried soil (<2 mm) were dispersed in 100 ml of 5 g l^{-1} sodium hexametaphosphate by shaking for 18 h. After shaking, the dispersed materials were poured through 53 μm sieves, and retained materials were rinsed with deionized water until the water from the bottom of the sieve ran clear. The material left on the sieve was dried at 60 °C for 48 h and weighed and analyzed for carbon by combustion.

Permanganate oxidizable C ($KMnO_4$-C) was measured as described by Blair et al. (1995) and Vieira et al. (2007). Finely ground air-dried soil samples were reacted with 0.333 M $KMnO_4$ by shaking at 60 rpm for 1 h. The suspension was then centrifuged at 2000 rpm for 5 min. The supernatant was diluted and measured spectrophotometrically at 565 nm.

2.2.3. Analyses of general soil properties

Soil pH was measured using a 1:2.5 (w/v) soil to 0.01 M $CaCl_2$ ratio with a glass electrode. Soil texture was determined by the pipette method (Gee and Bauder, 1986). The soil of all plots had sandy loam texture. Soil pH values were nearly identical between the three tillage treatments at the 0–15 cm, and were similar at 15–30 cm (Table 1). Cation exchange capacity (CEC) was determined by the NH_4OAc method and was expressed as cmol kg^{-1} soil (Herrmann, 2005). The CEC was significantly higher under CT than under ST or NT at both soil depths (Table 1).

Soil samples for organic carbon measurements were pretreated with 0.5 M HCl to remove carbonates (Harris et al., 2001) and then ball-milled. Total C and N contents of bulk soil, aggregates, and POM were determined by dry combustion using an EA1108 CHN analyzer (Fisons Instruments, Germany).

2.2.4. Calculations and statistical analysis

Soil organic carbon (SOC) and total N (N_t) stocks were calculated by multiplying SOC (or N_t) content by bulk density and by depth.

Mean weight diameter (MWD, mm) of aggregates was calculated as follow:

$$\mathrm{MWD} = \sum_{i=1}^{n} (X_i \cdot W_i)$$

where X_i is the mean diameter of aggregate fraction i and W_i is the mass proportion of aggregate fraction I (Kemper and Rosenau, 1986).Geometric mean diameter (GMD, mm) was calculated as follow:

$$\mathrm{GMD} = \exp\left[\sum_{i=1}^{n} (W_i \cdot \ln(X_i))\right]$$

where W_i is the mass proportion of aggregate fraction i and X_i is the mean diameter of aggregate fraction i (Kemper and Chepil, 1965).

SOC (or N_t) contents (g kg^{-1}) of sand-free aggregates were calculated as follow (Six et al., 1998):

$$\text{Sand free SOC (or N}_t)_{\text{fraction}} = \frac{(\text{SOC or N}_t)_{\text{fraction}}}{(1 - (\text{sand portion}))_{\text{fraction}}}$$

Soil organic C (or N_t) contents of aggregates in g kg^{-1} soil were calculated by multiplying sand-free SOC (or N_t) contents in the aggregate-size fractions by the mass proportion of soil in each aggregate fraction.

Data were analyzed by ANOVA procedure using the SAS statistical package (SAS, 1998). Differences were considered significant at $P < 0.05$. Means of main effects were compared using the least significant difference (LSD) test after a significant ANOVA test. Pearson linear correlations between the parameters were performed with SPSS for windows, version 11.0.

3. Results

3.1. Bulk soil characteristics: organic carbon and total nitrogen content

At 0–15-cm soil depth, bulk density was significantly higher under CT than ST or NT, whereas no significant difference occurred between ST and NT (Table 1). At 15–30 cm, bulk density increased with soil depth and did not differ among the three tillage treatments.

The effect of tillage on SOC and N_t contents, stocks and C/N ratios is shown in Table 2. At 0–15 cm, soil organic C contents and stocks were significantly higher under ST (11.9 g kg^{-1}, 22.3 Mg ha^{-1}) and NT (11.1 g kg^{-1}, 22.2 Mg ha^{-1}) than CT (8.9 g kg^{-1}, 19.6 Mg ha^{-1}), while ST and NT were similar (Table 2). N_t content ranked in the order: ST > NT > CT at 0–15 cm. At 0–15 cm, ST had significantly higher N_t stocks than CT, while NT tended to have higher N_t stocks than ST. Tillage had no significant effect on SOC and N_t contents, stocks and C/N ratios at 15–30 cm. Both SOC and N_t stocks did not differ among the three tillage treatments at 0–30 cm. All the tillage treatments showed higher SOC and N_t contents and stocks in surface soil (0–15 cm) as compared to subsurface soil (15–30 cm) (Table 2). As expected,

Table 2
Soil organic C (SOC) and total N (N_t) content and stocks, C:N ratios for 0–15- and 15–30-cm depths under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) at Linfen, China.

Depth (cm)	Tillage	CT	ST	NT
0–15	SOC (g kg^{-1})	8.87 (0.76) b	11.91 (0.28) a	11.14 (0.32) a
	N_t (g kg^{-1})	0.87 (0.06) c	1.16 (0.07) a	1.00 (0.00) b
	C/N	10.25 (0.29) b	10.26 (0.41) b	11.21 (0.28) a
	SOC (Mg ha^{-1})	19.55 (1.68) b	22.33 (0.52) a	22.22 (0.65) a
	N_t (Mg ha^{-1})	1.91 (0.14) b	2.18 (0.13) a	1.98 (0.01) ab
15–30	SOC (g kg^{-1})	7.69 (1.39) a	7.68 (0.46) a	7.03 (0.25) a
	N_t (g kg^{-1})	0.78 (0.12) a	0.75 (0.09) a	0.69 (0.03) a
	C/N	9.89 (0.33) a	10.21 (0.64) a	10.13 (0.34) a
	SOC (Mg ha^{-1})	17.52 (3.16) a	17.04 (1.01) a	15.39 (0.56) a
	N_t (Mg ha^{-1})	1.77 (0.27) a	1.68 (0.21) a	1.52 (0.07) a
0–30	SOC (Mg ha^{-1})	37.07 (4.74) a	39.37 (0.94) a	37.61 (1.06) a
	N_t (Mg ha^{-1})	3.68 (0.38) a	3.86 (0.14) a	3.50 (0.09) a

Values are means with the standard deviation in parenthesis ($n = 3$); values within a row followed by different lowercase letters are significantly different ($P < 0.05$).

Table 3
Effects of tillage on labile soil carbon fractions and their proportions in soil organic C (SOC).

Treatment	CT	ST	NT
0–15 cm			
MBC (mg kg^{-1})	347.40 (18.76) b	446.02 (13.37) a	422.78 (31.73) a
MBC/SOC (%)	3.93 (0.22) a	3.74 (0.03) a	3.80 (0.37) a
DOC (g kg^{-1})	90.48 (3.78) c	118.36 (5.25) a	102.32 (5.12) b
DOC/SOC	1.02 (0.06) a	0.99 (0.03) ab	0.92 (90.04) b
HWC (mg kg^{-1})	375.24 (17.70) b	554.21 (51.30) a	514.19 (44.90) a
HWC/SOC (%)	4.25 (0.35) a	4.65 (0.40) a	4.61 (0.27) a
$KMnO_4$-C (g kg^{-1})	1.41 (0.21) c	2.65 (0.12) b	3.65 (0.19) a
$KMnO_4$-C/SOC (%)	16.01 (3.14) c	22.27 (1.51) b	32.85 (2.68) a
POC (g kg^{-1})	4.19 (0.57) b	7.09 (0.98) a	5.95 (0.22) a
POC/SOC (%)	47.81 (10.34) a	59.56 (8.23) a	53.42 (3.24) a
15–30 cm			
MBC (mg kg^{-1})	209.72 (29.03) a	228.75 (19.38) a	231.70 (14.90) a
MBC/SOC	2.75 (0.30) a	3.00 (0.42) a	3.31 (0.31) a
DOC (g kg^{-1})	66.77 (7.18) a	62.21 (4.28) a	64.56 (3.17) a
DOC/SOC (%)	0.90 (0.22) a	0.81 (0.02) a	0.92 (0.01) a
HWC (mg kg^{-1})	243.23 (37.25) a	232.95 (19.15) a	206.41 (29.95) a
HWC/SOC (%)	3.29 (1.01) a	3.05 (0.41) a	2.94 (0.46) a
$KMnO_4$-C (g kg^{-1})	0.54 (0.16) c	1.37 (0.20) a	1.04 (0.08) b
$KMnO_4$-C/SOC (%)	7.05 (2.02) b	17.75 (1.50) a	14.80 (0.66) a
POC (g kg^{-1})	2.60 (0.93) a	2.88 (0.54) a	3.07 (0.65) a
POC/SOC (%)	33.24 (6.20) a	37.39 (5.06) a	43.55 (7.87) a

Values are means with the standard deviation in parenthesis ($n = 3$); Values within a row followed by different lowercase letters are significantly different ($P < 0.05$). CT: conventional tillage with residue removal; ST: shallow tillage with residue cover; NT: no-tillage with residue cover; MBC: microbial biomass C; DOC: dissolved organic C; HWC: hot-water extractable C; POC: particulate organic C.

SOC and N_t were positively correlated with each other (Table 5, $R = 0.924$, $P < 0.01$ for 0–15 cm; $R = 0.931$, $P < 0.01$ for 15–30 cm, data not shown).

3.2. Labile soil organic carbon fractions

Tillage significantly affected labile soil organic C fractions at 0–15 cm, but seldom at 15–30 cm (Table 3). At 0–15 cm, soil MBC, DOC, HWC, and POC were all significantly lower under CT than under either ST or NT, which were not different from each other (Table 3). NT had significantly higher $KMnO_4$-C than ST, which had significantly higher $KMnO_4$-C than CT (Table 3). At 15–30 cm, there were no significantly differences in MBC, DOC, HWC, and POC among the three tillage treatments (Table 3). However, ST showed significantly higher $KMnO_4$-C than NT, which showed significantly higher $KMnO_4$-C than CT (Table 3).

In general, the portions of labile C fractions in SOC showed no significant differences among the treatments at both depths, except DOC/SOC and $KMnO_4$-C/SOC at 0–15 cm and $KMnO_4$-C/SOC at 15–30 cm (Table 3). The contents of all labile C fractions and their portions in SOC in all treatments tended to decrease with depth (Table 3). The mean portions of labile C fractions in SOC for all treatments and depths ranked in the order: POC > $KMnO_4$-C > HWC > MBC > DOC (Table 3).

3.3. Mean weight diameter, geometric mean diameter and aggregate-size distribution

The MWD and GMD of soil aggregates were significantly influenced by tillage (Fig. 1A and B). At 0–15 cm, MWDs and GMDs were significantly lower under CT than ST or NT, whereas the differences between ST and NT were not significant (Fig. 1A and B). At 15–30 cm, ST and NT had higher MWD and GMD than CT, but the differences were only significant between CT and NT (Fig. 1A and B). Both MWDs and GMDs decreased with increase in soil depth for all tillage treatments (Fig. 1A and B).

At both depths, the content of large macroaggregates (>2 mm) was very low (around 1% of the soil weight) (Fig. 2A and B). Small macroaggregates (2–0.25 mm) represented the greatest portions (52–70% of whole soil) in all treatments at both 0–15 and 15–30 cm. At 0–15 cm, CT contained significantly less small macroaggregates (2–0.25 mm) than ST or NT, which were not different

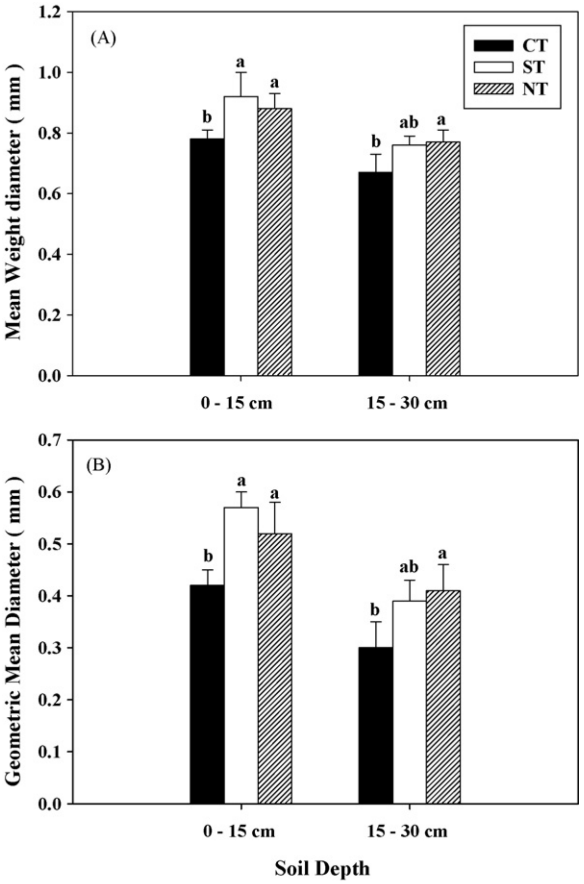

Fig. 1. Mean weight diameters (A) and geometric mean diameters (B) of soil from two depths among aggregate-size fractions under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) at Linfen, China. Error bars represent standard deviation. Values followed by different lowercase letters within depth are significantly different between tillage treatments ($P < 0.05$).

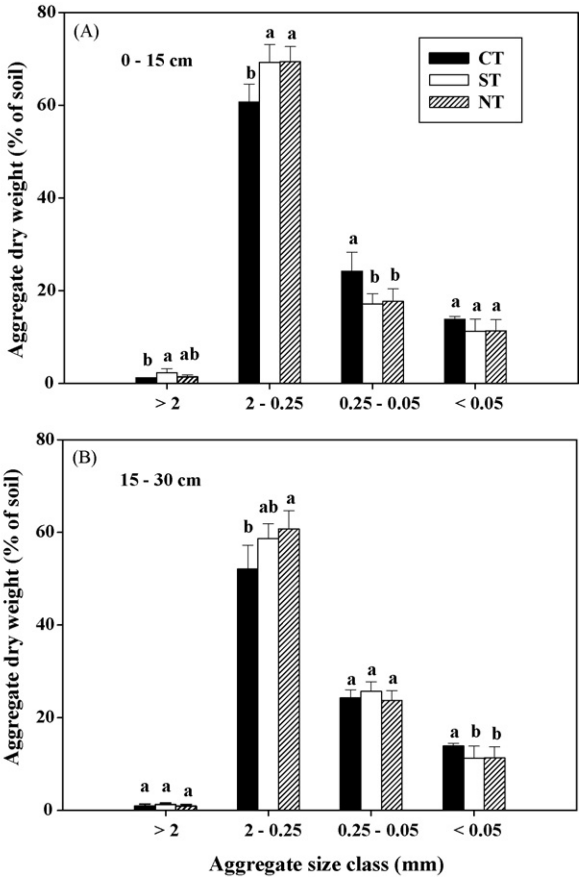

Fig. 2. Aggregate-size distribution as determined by wet sieving for (a) the 0–15-cm and (b) the 15–30-cm layers under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) at Linfen, China. Error bars represent standard deviation. Values followed by different lowercase letters within aggregate-size class within depth, are significantly different between tillage treatments at $P < 0.05$.

from each other (Fig. 2A). In contrast, CT had significantly higher amounts of microaggregates (0.25–0.05 mm) than ST or NT, which were similar (Fig. 2A). At 15–30 cm, ST and NT contained higher amounts of small macroaggregates than CT, the difference was only significant between CT and NT (Fig. 2B). However, the <0.05 mm fraction was dominated by CT (Fig. 2B).

3.4. Soil organic C and total N content in aggregate-size fractions

The amount of large macroaggregates was extremely low and made up of almost all rocks, therefore SOC and N_t content was not determined in large macroaggregates.

The influence of tillage on aggregate C and N_t content is shown in Fig. 3. At 0–15 cm, tillage effect was confined to the 2–0.25 mm size fraction, in which the conservation tillage treatments contained significantly higher SOC contents than CT, ST had significantly higher N_t contents than CT, and NT tended to have higher N_t contents than CT (Fig. 3A and C). No significant differences were detected in SOC and N_t contents in the 0.25–0.05 mm and <0.05 mm classes among all treatments (Fig. 3 A and C). The highest SOC and N_t contents were found in the 2–0.25 size fraction. Data from the 15- to 30-cm samples show generally diminished effect of tillage treatments (Fig. 3B and D). Soil organic C and N_t contents in the aggregate-size fractions generally decreased with increase in soil depth for all treatments (Fig. 3).

A very different distribution of SOC and N_t contents of aggregates in g kg^{-1} soil was obtained by mass weighting SOC and N_t contents in each aggregate-size fraction (Fig. 4). At 0–15 cm, there were no significant differences between ST and NT in SOC and N_t contents in the 2–0.25 mm fraction, but the two conservation tillage treatments lead to significantly higher SOC and N_t contents than CT (Fig. 4A and C). However, CT showed a clear dominance on N_t contents in the 0.25–0.05 mm and <0.05 mm fractions (Fig. 4C). At 15–30 cm, once again the two conservation tillage treatments resulted in significantly higher SOC contents in the 2–0.25 mm class (Fig. 4B). In contrast, CT contained significantly greater SOC and N_t contents in the <0.05 mm classes (Fig. 4B and D).

The aggregates of 2–0.25 mm size contained much more SOC and N_t than the two smaller size classes at both depths (Fig. 4). At 15–30 cm, generally lower SOC and N_t contents were detected among the aggregate fractions than those at the 0–15-cm depth (Fig. 4).

In general, the C/N ratio of each aggregate-size fraction was not impacted by tillage at both depths except that ST and NT showed higher C/N ratios of 0.25–0.05 mm class than CT at the 0–15-cm depth (Fig. 5). At both depths, the C/N ratios in both aggregate-size classes: 0.25–0.05 mm and <0.05 mm were similar, but were significantly lower than those of the 2–0.25 mm size class (Fig. 5).

4. Discussion

4.1. Effects of tillage on labile soil organic carbon fractions

The labile soil organic C pools were able to distinguish SOC changes due to tillage treatments: MBC, DOC, HWC, $KMnO_4$-C, and

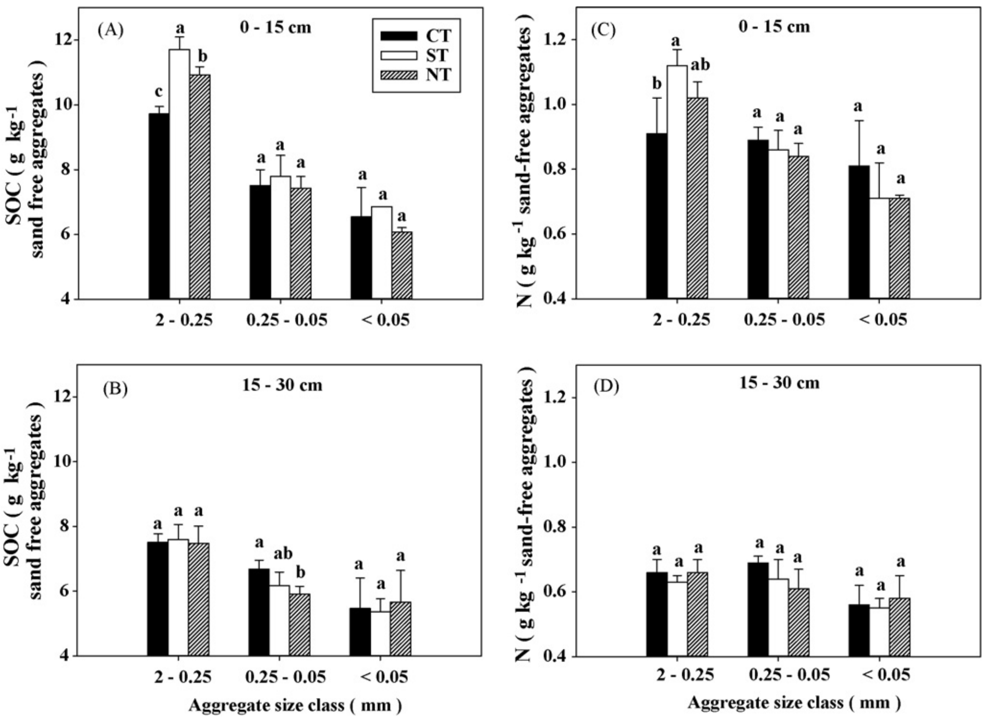

Fig. 3. Soil organic carbon (SOC) and nitrogen content (g kg^{-1}) of sand-free aggregates from two depths under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) at Linfen, China. Error bars represent standard deviation. Values followed by different lowercase letters within aggregate-size class within depth, are significantly different between tillage treatments at $P < 0.05$.

POC all were significantly higher in the conservation tillage treatments (ST and NT) than conventional tillage in the surface soil, but not in the subsurface layer (except KMnO$_4$-C) (Table 3). The results showed that conservation tillage effects occurred mainly in the top soil and also reflected the build-up of labile C pools under conservation tillage after 11 years. The first explanation for the differences of the labile C pools between CT and conservation tillage (NT and ST) is the result of tillage practices. Frequent tillage under CT breaks down aggregates and exposes protected organic matter to microbial decomposition and increases the loss of labile

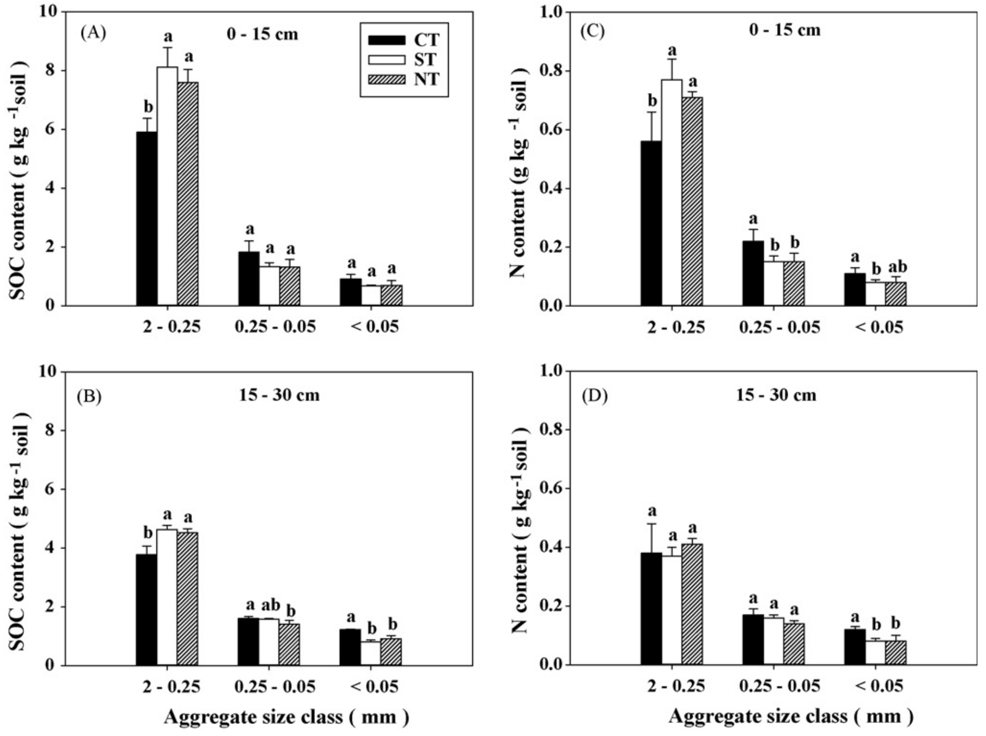

Fig. 4. Soil organic carbon (SOC) and nitrogen content of aggregates in g kg^{-1} soil from two depths under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) at Linfen, China. Error bars represent standard deviation. Values followed by different lowercase letters within aggregate-size class within depth, are significantly different between tillage treatments ($P < 0.05$).

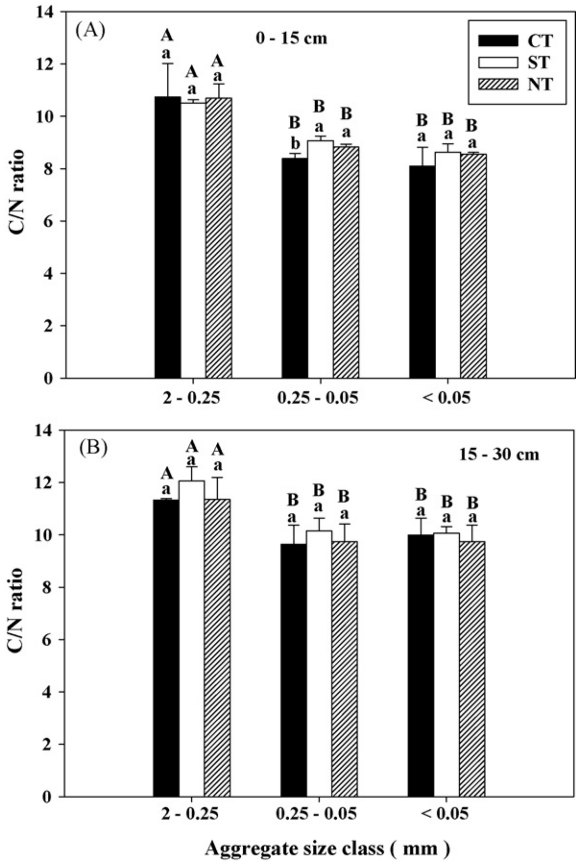

Fig. 5. Soil C/N ratio in different aggregate-size fractions of soil from two depths under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) at Linfen, China. Error bars represent standard deviation. Values followed by different lowercase letters within aggregate-size class within depth, are significantly different between tillage treatments ($P < 0.05$). Values followed by different uppercase letters indicate the means of the aggregate C/N are significant different between aggregate-size fractions at $P < 0.05$.

C (Elliott, 1986; Chen et al., 2007). A second explanation emerges from the different quantity of residues retained between CT and the conservation tillage: 3.8 t ha^{-1} residues in ST and NT vs. residue removal in CT. Plant residue might enter the labile C pools, provide substrate for soil microorganisms, and contribute to accumulation of labile C. An increase in labile C fractions leads to improvement of soil fertility under conservation tillage through increase of labile sources of nutrients. Therefore, conservation tillage is an important factor for increase of labile C compared to conventional tillage.

Labile soil organic C fractions: MBC, DOC, HWC, $KMnO_4$-C, and POC were significantly and positively correlated with SOC concentrations in the surface soil (0–15 cm) (Table 5). Such correlations suggested that SOC was a major determinant of the labile C fractions present. Likewise, depletion in labile C pools could also give an early indication of the decline of SOC. MBC, DOC, POC and HWC were significantly and positively correlated with each other at $P < 0.01$, $KMnO_4$-C was significantly and positively correlated with MBC and HWC at $P < 0.05$ (Table 5). These correlations indicated that they all provided an index of labile soil organic C, and also showed that they were closely interrelated. Dissolved organic C is the primary energy source for soil microorganisms (Stevenson, 1994). Hot-water extractable C consists of a labile pool of SOM, which includes microbial biomass, dissolved organic C, soluble soil carbohydrates, and amines (Sparling et al., 1998; Puget et al., 1999; Ghani et al., 2003). POC was obtained using a size based approach in this study, it is dominated by partially decomposed plant residues, and is thought to be an available C source for microorganisms (Janzen et al., 1992; Stevenson, 1994; Christensen, 2001). $KMnO_4$ oxidation simulates microbial decomposition and therefore $KMnO_4$-C partly reflects the in situ enzymatic decomposition of labile SOM (Loginow et al., 1987). Therefore, it is not surprising to find the positive correlations among the labile C pools as they have a close association with each other. Similar to our results, Dou et al. (2008) observed MBC, POM-C, DOC, hydrolysable C, and SOC were all positively correlated with each other. Rudrappa et al. (2006) reported that POC, $KMnO_4$-C, MBC, total C mineralization (C_{min}) and total organic C were significantly correlated with each other. Ghani et al. (2003) showed that HWC was positively correlated with MBC, water-soluble C, and total organic C.

Table 4
Percentage of increase of soil organic C (SOC) and each labile soil organic C as compared to conventional tillage with residue removal (CT) at 0–15 cm.

Tillage	SOC	MBC	DOC	HWC	$KMnO_4$-C	POC
ST	34.3	28.4	30.8	47.7	87.9	69.2
NT	25.6	21.7	13.1	37.0	158.9	42.0

ST: shallow tillage with residue cover; NT: no-tillage with residue cover; SOC: soil organic C; MBC: microbial biomass C; DOC: dissolved organic C; HWC: hot-water extractable C; POC: particulate organic C.

There were large differences in portions among the five labile C fractions. Soil microbial biomass C was 2.8–3.9%, DOC was 0.8–1.0%, HWC was 2.9–4.7%, POC was 33.2–59.6%, and $KMnO_4$-C was 7.1–32.9% of SOC in our study (Table 3). These results were generally in agreement with the literature (Blair et al., 1995; Mrabet et al., 2001; Ghani et al., 2003; Rudrappa et al., 2006; Soon et al., 2007).

Although the responses of the five labile C fractions to tillage effects were similar, their sensitivities to tillage effects were different. The magnitude of changes of labile C fractions between conservation tillage treatments and conventional tillage for 0–15-cm depth ranged in the order: $KMnO_4$-C (87.9–158.9%) > POC (42.0–69.2%) > HWC (37.0–47.7%) > DOC (13.1–30.8%) and MBC (21.7–8.4%) (Table 4). So we conclude that $KMnO_4$-C, POC and HWC were the most sensitive to tillage effects than total SOC which showed 25.6–34.2% enrichment. The lower sensitivity of MBC and DOC to tillage compared with $KMnO_4$-C, POC and HWC might be due to their smaller sizes and highly labile nature (Janzen et al., 1992).

4.2. *Effects of tillage on soil aggregation and aggregate C and N content*

The >2 mm soil fraction had the least percentage distribution at both depths (around 1% of the soil weight) (Fig. 2). The sandy loam nature of soils in the Loess Plateau might hinder the formation of large stable macroaggregates.

The aggregate-size distribution and stability are important indicators of soil physical quality (e.g. soil structure, aggregation and degradation) (Shrestha et al., 2007). Tillage reduced the proportion of 2–0.25 mm aggregates in comparison with the conservation tillage treatments and there was a corresponding increase in the proportion of microaggregates (0.25–0.05 mm and/or <0.05 mm fraction) (Fig. 2). Macroaggregates are less stable than microaggregates, and therefore more susceptible to the disruption forces of tillage (Elliott, 1986; Cambardella and Elliott, 1993). Many investigators have also found more macroaggregates in NT compared with CT soils (Beare et al., 1994; Six et al., 2000b; Mikha and Rice, 2004). Six et al. (2000a) observed that the rate of macroaggregate turnover (formation and degradation) was reduced under NT compared with CT.

Tillage significantly decreased MWD and GWD at both depths, although the differences were not always significant at the subsurface layer (Fig. 1). Reduction in aggregate stability with tillage has often been reported in the literature. Zotarelli et al. (2005) reported that the MWD of the aggregates was on average 0.5 mm greater under NT compared with CT in the 0–5-cm depth interval in Oxisols. Zibilske and Bradford (2007) showed that plow tillage had significantly lower MWDs than no-tillage and ridge tillage at both 0–5- and 10–15-cm depths in a Higalgo sandly clay loam soil.

The reduction in macroaggregates and MWD and GMD with CT could be mainly 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 macroaggregate susceptibility to disruption (Beare et al., 1994; Paustian et al., 1997; Mikha and Rice, 2004). Furthermore, NT and ST had greater residue cover than CT, which promoted aggregation. Fresh residues are C source for microbial activity and nucleation centers for aggregation, and the enhanced microbial activity induces the binding of residue and soil particles into macroaggregates (Jastrow, 1996; Six et al., 1999).

As expected, MWD and GMD were positively correlated with each other at both depths (Table 5, $P < 0.01$, data for 15–30 cm not shown). In the surface layer (0–15 cm), soil organic C and labile C fractions (except $KMnO_4$-C) were all significantly correlated to MWD and GMD (Table 5, $P < 0.01$), indicating the feedback mechanisms between aggregation and SOC and labile C fractions. On one hand, both SOC and labile C play important roles in aggregate stabilization. Labile C fractions were important cementing agents that form microaggregates into macroaggregates (Tisdall and Oades, 1982). The reduction in labile C associated with tillage was responsible for the disruption of soil aggregation, besides tillage disruption, as suggested by Bronick and Lal (2005). On the other hand, the destruction of macroaggregates could have adverse effects on labile C and limits the physical protection of labile C, which in turn result in the loss of SOC. Many investigators have found that the amount of labile organic C in the soil is positively correlated with aggregate stability (Tisdall and Oades, 1982; Cambardella and Elliott, 1993; Li et al., 2007)

The 2–0.25 mm fraction had much higher SOC and N_t contents than the 0.25–0.05 mm and <0.05 mm fractions in all treatments at both 0–15 and 15–30 cm (Fig. 4), highlighting the importance of macroaggregates for C and N sequestration (Dorodnikov et al., 2009). Previous studies have also reported that macroaggregates (>0.25 mm) were more C-rich than microaggregates (<0.25 mm) (Elliott, 1986; Cambardella and Elliott, 1993; Puget et al., 1995; Six et al., 2000b). Our results also indicated that the aggregate hierarchy theory suggested by Tisdall and Oades (1982) can also be applied to the sandy loam Cambisol in the Loess Plateau region.

Conservation tillage treatments contained significantly higher SOC and N_t contents in the 2–0.25 mm fraction compared with CT in the surface layer (Fig. 4), which corresponds with the suggestion that changes in macroaggregate C and N can serve as sensitive indicators of management effects (Six et al., 2002). The results also implied that the loss of C and N with tillage could be partly explained by the observed reduction of macroaggregate C and N. Similarly to our results, Six et al. (2000b) reported that NT increased the amount of C-rich macroaggrates and decreased the amount of C-depleted microaggregates.

In the surface layer (0–15 cm), SOC, MBC, DOC, HWC and POC were highly correlated with macroaggregate C, but not with microaggregate C or silt and clay sized C (Table 5, $P < 0.01$). These results suggested that the reduction of these labile C with tillage would be related to the reduction of macroaggregate C and the reduction of SOC was more closely associated with macroaggregate C and labile C than microggregate C.

The C/N ratios were significantly higher in macroaggregates (2–0.25 mm) than microaggregates and the silt and clay fractions at both depths (Fig. 5), which was in accordance with other studies (He et al., 2008). The C/N ratio reflects the degree of decomposition and humification of SOM. The high C/N ratio in the macroaggregates suggested SOC associated with that fraction is less decomposed material, such as roots and fungal hyphae (Tisdall and Oades, 1982; Six et al., 2000a), and reflected rapid changes in SOC induced by land use or management. The SOC in the microaggregates (<0.25 mm) is humified material and has a low C/N ratio (Christensen, 2001).

4.3. Effects of tillage on soil organic C and N content

SOC and N_t contents were influenced by different tillage treatments at 0–15 cm (Table 2). ST and NT had 14.2% and 13.7% greater SOC stocks, 14.1% and 3.7% greater N_t stocks than CT, respectively (Table 2). But conservation tillage treatments during 11 years failed to enhance SOC and N_t stocks in the subsurface layer (15–30 cm) (Table 2). The results showed that over the 11 years, conservation tillage (ST and NT) with all residues retained was effective in improved SOC and N_t in the upper soil layer, compared

Table 5
Pearson correlation between selected parameters at 0–15 cm.

	SOC	N	MBC	DOC	HWC	POC	$KMnO_4$-C	MWD	GMD	C in 2–0.25 mm	C in 0.25–0.05 mm	C in <0.05 mm
0–15 cm[a]												
SOC	1											
N	0.924^{**}	1										
MBC	0.900^{**}	0.867^{**}	1									
DOC	0.899^{**}	0.930^{**}	0.861^{**}	1								
HWC	0.925^{**}	0.812^{**}	0.810^{**}	0.896^{**}	1							
POC	0.816^{**}	0.774^{*}	0.825^{**}	0.902^{**}	0.913^{**}	1						
EOC	0.690^{**}	0.424	0.685^{*}	0.426	0.678^{*}	0.594	1					
MWD	0.884^{**}	0.829^{**}	0.806^{**}	0.952^{**}	0.956^{**}	0.913^{**}	0.551	1				
GMD	0.876^{**}	0.785^{*}	0.824^{**}	0.920^{**}	0.948^{**}	0.892^{**}	0.615	0.989^{**}	1			
C in 2–0.25 mm	0.945^{**}	0.934^{**}	0.940^{**}	0.972^{**}	0.922^{**}	0.922^{**}	0.599	0.941^{**}	0.924^{**}	1		
C in 0.25–0.05 mm	0.298	0.461	0.363	0.363	0.243	0.286	−.100	0.186	0.107	0.372	1	
C in <0.05 mm	0.263	0.442	0.162	0.313	0.064	−.015	−.393	0.080	0.012	0.198	0.574	1

GMD: geometric mean diameters; MWD: Mean weight diameters; MBC: microbial biomass C; DOC: dissolved organic C; HWC: hot-water extractable C; POC: particulate organic C.

[a] In general, there were no significant correlations between these selected parameters at 15–30 cm, data were not shown.

* Significant at the 0.05 level.

** Significant at the 0.01 level.

with the plough with residue removal (CT). The enhancements of SOC and N_t accumulation with adoption of conservation tillage could be attributed to increased soil aggregation, enhanced macroaggregate (2–0.25 mm) C and N and disproportional increase of labile C pools as a result of less disturbance and more residue retained.

The rates of SOC (or N_t) accumulation for the 0–15 cm layer were estimated by calculating the differences in SOC (or N_t) stocks between ST (or NT) and CT divided by 11 years (Puget and Lal, 2005). The rates of SOC and N accumulation (0–15 cm) for ST were 0.25 Mg C ha^{-1} $year^{-1}$ and 0.025 Mg N ha^{-1} $year^{-1}$, for NT were 0.24 Mg C ha^{-1} $year^{-1}$ and 0.006 Mg N ha^{-1} $year^{-1}$, respectively. Many studies showed that conservation tillage favored higher SOC and N stocks, especially near the surface soils (Kern and Johnson, 1993; Tan and Lal, 2005). Chen et al. (2009) reported that reduced tillage (RT) contained 7.3% more SOC and 7.9% more N stocks than plough tillage (PT) in the 0–20-cm depth, respectively, and estimated that RT accumulate an average 0.32 Mg C ha^{-1} $year^{-1}$ and 0.033 Mg N ha^{-1} $year^{-1}$ more than PT over an average period of 11 years, respectively, in Baden-Württemberg, southwest Germany. Alvarez (2005) gave a mean sequestration rate of 0.26 Mg C ha^{-1} $year^{-1}$ with conversion from conventional tillage to conservation tillage, ranging from a few years to 30 years, based on world wide data. The Intergovernmental Panel on Climate Change (IPCC) provided a multiplication factor of 1.1 for a change from conventional to NT, essentially corresponding to a 10% increase in SOC cited by West and Post (2002). Collectively, our results are in accordance with the results documented in literature.

The Loess Plateau covers 640,000 km^2 in northwest China, and has the unfortunate reputation of being one of the most eroded landscapes in the world. A unique combination of rainfall, topography, vegetation and soil character results in severe soil erosion (Zhang, 1991). Unsustainable agricultural practices such as moldboard plowing, complete residue removal for fodder or burning further accelerate soil erosion. Roughly 1.6 billion tons of sediment travel downstream to the Yellow River annually. Therefore, it is urgent to explore effective practices to control soil erosion. The results of this study clearly showed that adoption of conservation tillage with residue cover increased SOC and N_t storage, soil aggregation, and labile C pools, which in turn could improve soil infiltration, promote water retention, increase biological activity and nutrient storage, subsequently increase soil quality and productivity, and eventually reduce soil erosion. Therefore, conservation tillage in combination with residue mulching is an effective option for maintaining soil and environmental sustainability in Loess Plateau.

5. Conclusions

Soil organic matter quantity and quality as well as soil aggregation were significantly affected in the top soil (0–15 cm) after 11 years of the absence of conventional tillage. Soil organic C and N stocks, MBC, DOC, HWC, $KMnO_4$-C, POC, portions of macroaggrates (2–0.25 mm), GMD and MWD, macroaggregate-associated C and N were all significantly higher under ST and NT compared to CT. The labile organic C fractions and SOC were highly correlated with each other and MWD, GMD, and macroaggregate C. Labile C fractions were sensitive to SOC changes, with sensitivity decreasing in the order: $KMnO_4$-C > POC > HWC > DOC and MBC. C sequestration can be enhanced by increasing the proportion of C-rich macroaggregates in soils through the utilization of conservation tillage. Our study confirms that conservation tillage is a promising management option for enhancing soil C sequestration under rainfed wheat monoculture system in the Loess Plateau of northwest China.

Acknowledgements

This study was funded by National Natural Science Foundation of China (40801108), National Basic Research Program of China (973 Program) (2009CB118607), Scientific Research Startup Foundation of China Agricultural University. We are grateful to Prof. Dr. Rattan Lal and anonymous reviewers for the constructive comments on the manuscript.

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