Effects of no-tillage systems on soil physical properties and carbon sequestration under long-term wheat–maize double cropping system

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Carbon sequestration
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Manure
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A B S T R A C T

A thorough assessment of changes in soil quality associated with soil management practices is vital for the selection and establishment of sustainable agricultural management. The winter wheat (Triticum aestivum L.)–maize (Zea mays L.) double cropping system was used to study the integrated effects of a 9-year-old tillage coupled with fertilization on soil carbon sequestration and other physical properties in the Yellow River Delta (YRD). Three tillage systems were selected: no-tillage with straw cover plus recommended urea nitrogen rate (NTS), no-tillage with straw removed and manure applied plus recommended urea nitrogen rate (NTM), and conventional tillage with straw removed plus conventional urea nitrogen application rate (CT). There were three replicates of each treatment organized in a randomized block design. NTS and NTM treatments were found to result in a slightly decrease in the soil bulk density (BD), and significantly increased the proportion of water stable aggregates (WSA) (>2 mm), as well as the water infiltration capacity. The proportion of water stable macroaggregates (>0.25 mm), the mean weight diameter (MWD) and the geometric mean diameter (GMD) of aggregates in the 0–20 cm layer were unchanged by NTS and NTM. The total soil organic carbon (SOC) stock at a depth of 0–60 cm was not significantly different among the treatments. Both aggregate-associated SOC concentration significantly different among the treatments. Both aggregate-associated SOC concentration significantly increased the proportion of water stable macroaggregates (>0.25 mm) and its associated OC pool accounted for the highest percentages in the whole soil profile under the CT treatment. The NT system was found to have a positive effect on the investigated soil physical properties and increase soil carbon content in the soil surface layer. The CT system in conjunction with the wheat–maize double cropping system, however, improved soil aggregation in the soil profile (0–60 cm) and also maintained a higher fraction of SOC in the subsoil compared with the NT systems.

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1. Introduction

Soil organic matter (SOM) and various physical properties are important indicators of soil quality and play an important role in the soil functionality of production (Shukla et al., 2006; Benbi and Chand, 2007). Cavaleri et al. (2009) reported that dynamic properties such as soil aeration, aggregation, bulk density and water transmission have a greater impact on soil physical quality in the surface layers. Soil organic carbon (SOC) is the measured major determining factor of soil physical properties. SOC sequestration is related to the agricultural contribution of soil to CO2 emissions and subsequent effect on global climate change (Buyanovsky and Wagner, 1998; Lal, 2004).

Soil aggregates are closely correlated with both soil physical properties and SOC sequestration. SOM is known to compress mineral particles into aggregates to improve soil structure and stability (Tisdall and Oades, 1982; Tejada et al., 2006). Soils with good structural generally display a high water-holding capacity, moderate saturated hydraulic conductivity, and sufficient aeration for plant establishment and growth (Jastrow and Miller, 1991; Karami et al., 2012). In addition, stable aggregates may better protect SOM from decomposition (Six et al., 1999; Haile et al., 2008; Abiven et al., 2009; Carter, 2004). Soil aggregate fractionation has been widely used to evaluate the SOC stability and the impacts of soil management on SOC dynamics (Six et al., 2002; Koe et al., 2012).

Soil physical properties and soil gaseous emissions are influenced by agricultural practices such as tillage, cropping systems, and fertilization (Yang et al., 2008; Obalum and Obi, 2010). Intense tillage can increase surface soil compaction, reduce aggregate stability, disrupt surface vented pores, decrease retention and transmission of water and solutes, and exacerbate losses due to runoff and erosion. Intense tillage may also deplete SOM as a result of the increased rate of organic carbon mineralization following tillage as well as contribute to erosion loss and reduced cycling of organic matter through crop removal (Gregorich et al., 2001; Yu et al., 2006). Soils under no tillage (NT) management systems tend to become more porous with time due to the creation of a more stable soil structure, an increase in the SOM pool and an increase in the number of biopores directly connected to the soil surface. Higher
infiltration rate measured in NT compared with conventional tillage (CT) may be attributed to macropore flow and reduced surface sealing under the mulch (Goddard et al., 2008). However, previous studies have also shown adverse conclusions about physical properties and SOC sequestration under NT (Wright et al., 2005; Pastorelli et al., 2013). Such findings necessitate an improved understanding of the impacts of NT systems on soil C sequestration and SOC stability.

Long-term unbalanced inorganic fertilizer application alone has been shown to negatively impact crop yields and also reduce the benefits of fertilization. While balanced fertilization of chemical fertilizers may be capable of sustaining current crop yields, such practice is likely to induce soil acidification and degradation of soil structure in a long term (Huang et al., 2010). Residue management and artificial addition of organic material sources, including the production and incorporation of green manure crops, application of livestock manure, and crop residue incorporation into the topsoil, are among the more promising methods for improving soil structural and aggregation properties (Bhattacharyya et al., 2009; Wagner et al., 2007). Long-term application of organic matters has been found to increase SOC and soil microbial activity, and in turn produce positive effects on mean weight diameter (MWD) and geometric mean diameter (GMD), while simultaneously decrease bulk density (BD) and increase infiltration rates (Fließbach et al., 2007; Karimi et al., 2012). The use of organic fertilizers and compost has also found to enhance the SOC sequestration to a greater extent compared with application of equivalent amount of inorganic fertilizers (Gregorich et al., 2001). Pathak et al. (2011) reported that the application of N, P and K in combination with farmyard manure (MWD) and geometric mean diameter (GMD), while simultaneously reduced urea rate under NT (Robertson et al., 2000; Pastorelli et al., 2013).

The Yellow River Delta (YRD) is an important agronomic and animal husbandry area in the North China Plain. According to the soil survey data (1979–1983) and the FAO–Unesco system, the soil is classified as a calcareous fluvisol (referred locally to as Chao soil). The Chao soil originates from the alluvial parent material of the YRD and was named for its historically salty characteristics. The salinity problems in this region have been alleviated through the development of an extensive irrigation–drainage system. At present, these practices are representative of the middle to high yield agricultural productivity of a winter wheat–summer maize double crop under a conventional tillage system. Over the past few decades, the adoption of NT practices has increased due to reduced costs and the lower amount of fieldwork required relative to conventional tillage. Approximately 23% of the total YRD area is currently under NT system (Dai et al., 2009). Several studies have evaluated the effect of tillage and fertilizer management regimes on crop yields and the environment (Huang et al., 2015). Generally, the practice of organic matter (crop straw or manure) inputs with a reduced urea rate under NT has been found to have no significant impact on crop yields compared with CT, while the treatment of crop straw rather than manure application with a reduced urea rate under NT significantly decreased N₂O emissions and NO₃⁻N leaching loss in YRD. However, the feasibility of NT in YRD depends if the quality of a soil being converted from CT to NT with organic material inputs is improving, remaining stable or declining in the YRD (Lal, 1998; Shukla et al., 2006). There is limited information available regarding the combined effects of NT with organic fertilizer plus mineral fertilizer application on soil quality in this region.

The objective of this study was to investigate the influence of three different tillage systems (NT with straw cover plus recommended urea nitrogen rate (NTS), NT with straw removed and manure applied plus recommended urea nitrogen rate (NTM), and conventional tillage with straw removed plus conventional N rate (CT)) on soil physical properties. The hypotheses tested were as follows: compared to CT, (1) NTS and NTM will decrease soil density and increase soil water infiltration than CT; and (2) the practice of organic matter inputs together with a reduced urea rate under no-till will significantly increase SOC under the winter wheat/maize double cropping system in the YRD.

2. Materials and methods

2.1. Location of the experimental site

Experiments beginning in 2003 were designed to investigate the long-term effects of different farming practices on soil properties and crop yields in Beiqiu, the YRD, China. Long-term average annual rainfall in this area is approximately 600 mm with a rainy season from July to September and a mean annual temperature of 13.5 °C. The annual reference evapotranspiration is 879.3 mm and the aridity index is approximately 0.68. The surface soil texture is silty loam (sand, 12%; silt, 66%; clay, 22%) according to the USDA classification system. Additional soil features are listed in Table 1.

2.2. Treatments used

The experiment was organized in a randomized complete block design with the three treatments (NTS, NTM, and CT). There were three replicates for each treatment. The plot size was 300 m² (7.5 m width × 40 m length). Two crops, winter wheat (Jimei 22) and summer maize (Dehai 7), were grown annually. Winter wheat was seeded (NHII 28BF–9 planter with width of 1570 mm) between 15 and 25 October, and harvested (4LZ–5120 combine harvester with width of 2500 mm) during the first 10 d of June. Summer maize was then seeded (2BYSF–3 maize seeder with width of 1420 mm) between 15 and 25 October. After harvesting (4YZP–2 maize harvester with width of 1660 mm), the standing stubble of each crop was cut to the same height (15 to 20 cm for wheat and 10 cm for maize), and all other residues were removed for NTM and CT.

For the CT treatment, a moldboard plow was used with a tillage depth of ca. 25 cm followed by disk harrowing to fully incorporate standing stubble into the soil after the maize harvest. As is historically

Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH (H₂O, 1:2.5)</td>
<td>8.3 (0.1)</td>
</tr>
<tr>
<td>EC1, 5 (dS m⁻¹)</td>
<td>0.12 (0.0)</td>
</tr>
<tr>
<td>CaCO₃ (%)</td>
<td>6.8 (1.1)</td>
</tr>
<tr>
<td>Total N (g kg⁻¹)</td>
<td>0.76 (0.05)</td>
</tr>
<tr>
<td>Olsen P (mg kg⁻¹)</td>
<td>16.8 (3.4)</td>
</tr>
<tr>
<td>CEC (cmol kg⁻¹)</td>
<td>12.0 (2.5)</td>
</tr>
<tr>
<td>Water retention (kg cm⁻¹)</td>
<td>33 kPa</td>
</tr>
<tr>
<td></td>
<td>1500 kPa</td>
</tr>
</tbody>
</table>

Numbers in parentheses are standard errors.
common in the YRD, there was no tillage before maize seeding under CT.

After harvesting crops under NTS treatment, crop residues were shredded into pieces (approximately 5 cm in length) by hand and plots were covered by residue at fixed rates of 5.92 Mg ha\(^{-1}\) for wheat straw (N content of 7.60 g/kg, C:N ca. 60:1) during maize planting and 4.93 Mg ha\(^{-1}\) for maize straw (N content of 9.12 g/kg, C:N ca. 42:1) during wheat planting.

During the NTM treatment, dry cattle (Bos taurus) manure at a rate of 1.73 Mg ha\(^{-1}\) was applied by hand and left on the surface before winter wheat and maize seeding. Manure N, P\(_2\)O\(_5\), K\(_2\)O and C contents were 26.0, 10.5, 16.7 and 450 g/kg, respectively.

An equivalent total N application rate of 225 kg N ha\(^{-1}\) for each crop was used among each of the three treatments. The N application rate for each crop as mineral fertilizer under the NTS, NTM, and CT systems was 180 kg N ha\(^{-1}\), with an additional 45 kg N ha\(^{-1}\) applied as mineral fertilizer under CT, as dry manure under NTM and as crop straw under NTS. The chemical nitrogen fertilizer rate of 225 kg N ha\(^{-1}\) for each crop is a conventional fertilization rate in the north China plain, while 180 kg N ha\(^{-1}\) is the current recommended application (Huang et al., 2011; Liu et al., 2003).

Under CT treatment, urea for winter wheat was used with 45 kg N ha\(^{-1}\) as the base fertilizer and the remaining fraction was used as supplementary fertilizer in equal proportions in late March (wheat green turn stage) and mid-April (wheat stem elongation stage) in the following year. For summer maize, urea (225 kg N ha\(^{-1}\)) was applied during the early growth period. Base fertilizer for winter wheat was incorporated with a moldboard plowing operation into the top 25 cm of soil.

Under both the NTS and NTM systems, urea (180 kg N ha\(^{-1}\)) for winter wheat was surface applied in equal quantities in late March and mid-April, and in a single dose during the early growth period for maize. Maize straw (45 kg N ha\(^{-1}\)) for winter wheat and wheat straw (45 kg N ha\(^{-1}\)) for summer maize were surface applied before planting under NTS. Manure (45 kg N ha\(^{-1}\)) for winter wheat and summer maize was applied to the soil surface before planting under NTM.

All other management procedures were identical for the three treatments. Herbicide (2,4-dichlorophenoxyacetic acid butylate) and insecticide (40% dimethoate, O,O-dimethyl S-(2-[(methylamino)-2-oxyethyl] dithiophosphatate) were applied after sowing of wheat in October and maize in June, respectively.

2.3. Soil sampling and analysis

Soil sampling was conducted in October 2012 after the maize harvest. Five representatives’ field-moist soil samples were collected from each of the replicate treatment areas at depths of 0–5, 5–10, 10–20, 20–40 and 40–60 cm with a bucket auger. Aliquots were pooled together to create a composite sample for each depth and replicate. Once in the laboratory, field-moist soil was passed through a 4.75-mm sieve and then air-dried and stored at room temperature. Additional triplicate undisturbed soil cores (5.0 cm diameter and 8.0 cm length) collected using a stainless steel core sampler were used for the determination of BD for the same five depths mentioned above following the method of Blake and Hargte (1986).

A wet sieving procedure was used for determination of the aggregate-size distribution and stability (Elliott and Cambardella, 1991). Approximately 100 g of air-dried (4.75 mm sieved) soil samples was capillary-wetted to field capacity to minimize slaking following immersion. Wetted soil was immersed in water on a nest of sieves (2 mm, 250 μm, and 53 μm) and shaken 3 cm vertically for 50 times over a 2-min period. Soil fractions retained on each sieve along with a subsample taken from the soil suspension collected in the oscillation cylinder that passed through a 53 μm sieve (‘silt + clay’ sized fraction) were transferred into a pre-weighted container and dried at 65 °C. The amount of material that passed through the 53-μm sieve was determined from the difference between whole soil and the sum of the three aggregate-size fractions (>2 mm, 250 μm–2 mm, and 53–250 μm). Using this method, different aggregate-size fractions including coarse macroaggregates (>2 mm), mesoaggregates (250 μm–2 mm), microaggregates (53–250 μm), and a ‘silt + clay’ fraction (<53 μm) were collected. Subsamples from each aggregate size fraction were then ground to pass a 0.5-mm sieve and analyzed for SOC. Whole soil samples that were not used for aggregate size fractionation were also analyzed.

SOC was determined using a modified Mekius method (Nelson and Sommers, 1982). Briefly, 0.5 g of soil was digested with 5 mL of 1.0 N K\(_2\)Cr\(_2\)O\(_7\) and 10 mL of H\(_2\)SO\(_4\) at 150 °C for 30 min, followed by titration of the digests with standardized FeSO\(_4\). Since sand-associated C was assumed to be minimal (Elliott and Cambardella, 1991), adjustments were made for sand contents in different aggregate size fractions.

After collecting sand for all aggregate fractions by dispersal in sodium hexametaphosphate, the water stable aggregates (WSA), MWD and GMD of the WSA were estimated following the methods of Oguike and Mbagwu (2009) and Karami et al. (2012). Aggregates were then divided into water-stable macroaggregate (WSM\(_{AC}\), >0.25 mm) and microaggregate (WSM\(_{MC}\), <0.25 mm) categories and their mass ratio was designated as aggregate ratio (AR).

The OC pool was calculated from OC concentration (g kg\(^{-1}\)) for each soil depth to Mg ha\(^{-1}\) using the following equation:

\[
C-\text{Pool} \ (\text{Mg ha}^{-1}) = A \times D \times Bd \times OC \times 10^{-3}
\]

where A is the area (ha: \(10^4\) m\(^2\)); D is the depth (m); Bd is the bulk density (Mg m\(^{-3}\)); and OC is the aggregate-associated organic carbon concentration (g kg\(^{-1}\)) (Lal et al., 1998).

The cumulative values of organic C present in soil aggregate size fractions of >2.0 mm, 0.25–2.0 mm, 0.053–0.25 mm and <0.053 mm were defined as coarse macroaggregated C (C\(_{M\ AC}\)), mesoaggregated C (C\(_{M\ AC}\)), coarse microaggregated C (C\(_{M\ AC}\)) and ‘silt + clay’-associated OC, respectively. The sum of organic C in the >0.25 mm aggregate size fractions was referred to as macroaggregated organic C (Mac\(_{AC}\)), while organic C in the <0.25 mm size fractions was dubbed microaggregated organic C (Mic\(_{AC}\)).

2.4. Water infiltration

The infiltration rate in the experimental plots was measured in October 2012 after the harvest of maize crop using the double rings method, with a 50 cm outer diameter and 30 cm inner diameter. Measurements were conducted over 180 min. The data were fit to the Philip’s (1957) model for soil water sorptivity (S) and transmissivity (A) using the following numerical analysis:

\[
I = St^{1/2} + At, \quad i = 0.5St^{-(1/2)} + A
\]

where I is the cumulative infiltration (mm), i is the infiltration rate (mm), t is the time (min), S is the soil water sorptivity (mm min\(^{-0.5}\)), A is the transmissivity (mm) equal to I/T\(^{1/2}\), and T is the cumulative time.

2.5. Statistical analysis

The independent variables in the study included Bd, aggregate size fraction, AR, MWD, GMD, SOC concentration, SOC stock, S, A, I, and \(i\). Differences among treatments were evaluated using single-factor analysis of variances (ANOVA). Multiple comparisons of means were conducted with a Fisher’s protected least significant difference (LSD) test (P < 0.05).
The initial infiltration rate (i_d) steady-state infiltration rate (I) and cumulative infiltration (I) increased significantly in the NTS- and NTM-treated plots. Cumulative infiltration was observed to increase by up to 69.4% and 62.5% under NTS and NTM treatments, respectively, compared with CT treatment (48 mm in 3 h), with equilibrium rates 84.9% and 69.8% higher compared with CT (11.5 mm h^{-1}). NT produced no significant effect on soil sorptivity. The transmissivity (A) in NTS- and NTM-treated plots was determined to be 237% and 173% higher than that of the CT plots.

3.2. SOC stock

At depths of 0 to 60 cm in the soil, the total SOC concentrations ranged from 3.0 to 12.9 g kg⁻¹ (Table 3). The SOC concentrations under NTS in the 0–10 cm soil layer and under NTM in the 0–5 cm layer were significantly greater compared with those under CT. However, a higher concentration of SOC in the 0–10 cm soil layer compared with the CT system and compared with NTM in the 5–10 cm soil layer. Higher SOC content was also found in the 0–5 cm soil layer of NTM plots compared with the CT system. In contrast, the 20–60 cm layer of the CT plots and the 20–40 cm layer of NTM plots were found to contain significantly higher SOC compared with NTS plots. No difference in the total SOC content up to a depth of 60 cm was observed among the different treatments.

3.3. Aggregate size distribution

The distribution of soil aggregate fraction size classes in the soil profile was stratified, which was significantly different among the treatments (Table 5). The percentages of WSMaca (>0.25 mm) and AR for all treatments were higher in the 0–10 cm surface layer compared with those in the deeper soil. Except in the 0–5 cm soil layer, the CT system was found to significantly increase the percentage of soil aggregate >0.25 mm and AR in the deeper soil layers compared with the NT system. While the percentage of aggregates >2.0 mm in the 0–20 cm soil layer in plots treated with NTS and NTM was greater compared with CT, the amounts of small macroaggregates (0.25–2 mm) in CT-treated plots were significantly greater compared with NTS and NTM at all soil depths. The percentages of coarse macroaggregates in the 10–60 cm soil layers and silt + clay fractions in the 0–10 and 40–60 cm soil layers in both NTS and NTM treatments were significantly higher compared to the CT treatment.

3.4. Aggregate associated carbon concentration

On average, the aggregate-associated OC concentration in the soil (Table 6) tended to decrease with increasing soil depth (P < 0.05) with the exception of coarse microaggregated C in NTM-treated soil (P = 0.32). The distribution of SOC within aggregates was as follows: mesoaggregates (0.25–2.0 mm) > coarse microaggregates (0.053–0.25 mm) > silt + clay (<0.053 mm) > coarse macroaggregates (>2.0 mm). Each fraction accounted for 55.2, 22.7, 16.7 and 5.4% of the total aggregated OC, respectively.
Table 5
Structural indices and distribution of particle size at soil depths under different treatments after 9 years of winter wheat–maize double cropping.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>WSA [%]</th>
<th>AR</th>
<th>MWD</th>
<th>GMD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;2</td>
<td>0.25–2</td>
<td>0.25–0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>0.05–0.05 m</td>
<td>CT</td>
<td>3.6 b 1</td>
<td>62.8a</td>
<td>18.1</td>
</tr>
<tr>
<td>NTS</td>
<td>11.5a</td>
<td>50.6b</td>
<td>16.8</td>
<td>21.2a</td>
</tr>
<tr>
<td>NTM</td>
<td>10.9a</td>
<td>50.9b</td>
<td>19.0</td>
<td>19.2a</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>2.8</td>
<td>4.8</td>
<td>NS</td>
<td>2.1</td>
</tr>
<tr>
<td>0.05–0.10 m</td>
<td>CT</td>
<td>5.3b</td>
<td>60.3a</td>
<td>18.2</td>
</tr>
<tr>
<td>NTS</td>
<td>8.0a</td>
<td>49.7b</td>
<td>20.9</td>
<td>21.4a</td>
</tr>
<tr>
<td>NTM</td>
<td>8.0a</td>
<td>51.1b</td>
<td>21.8</td>
<td>19.1a</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>0.05–0.10 m</td>
<td>1.2</td>
<td>8.5</td>
<td>NS</td>
</tr>
<tr>
<td>0.10–0.20 m</td>
<td>CT</td>
<td>1.8b</td>
<td>48.4a</td>
<td>30.3c</td>
</tr>
<tr>
<td>NTS</td>
<td>6.1a</td>
<td>39.1b</td>
<td>34.6a</td>
<td>19.9b</td>
</tr>
<tr>
<td>NTM</td>
<td>5.4a</td>
<td>33.7c</td>
<td>32.5b</td>
<td>28.4a</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>0.10–0.20 m</td>
<td>1.2</td>
<td>2.4</td>
<td>1.8</td>
</tr>
<tr>
<td>0.20–0.40 m</td>
<td>CT</td>
<td>0.7</td>
<td>55.4a</td>
<td>23.3b</td>
</tr>
<tr>
<td>NTS</td>
<td>1.4</td>
<td>41.6c</td>
<td>29.2a</td>
<td>27.9a</td>
</tr>
<tr>
<td>NTM</td>
<td>1.7</td>
<td>47.4b</td>
<td>28.3a</td>
<td>22.2b</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>0.20–0.40 m</td>
<td>NS</td>
<td>2.7</td>
<td>4.1</td>
</tr>
<tr>
<td>0.40–0.60 m</td>
<td>CT</td>
<td>0.8</td>
<td>58.9a</td>
<td>19.4c</td>
</tr>
<tr>
<td>NTS</td>
<td>1.0</td>
<td>43.0b</td>
<td>28.8b</td>
<td>27.2b</td>
</tr>
<tr>
<td>NTM</td>
<td>0.8</td>
<td>30.2c</td>
<td>32.5b</td>
<td>28.4a</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>0.40–0.60 m</td>
<td>NS</td>
<td>9.7</td>
<td>4.2</td>
</tr>
</tbody>
</table>

CT: conventional tillage; NTS: no-tillage with residue cover; NTM: no-tillage with residue removed and manure applied; WSA = water stable aggregates; AR: the ratio of the water stable macroaggregate (0.25 mm) and microaggregate (0.05–0.25 mm); MWD: mean weight diameter; GMD: geometric mean diameter.

1 Within a column of an aggregated OC, numbers followed by different lowercase letters are significantly different between treatments at each depth at P ≤ 0.05 by LSD test.

2 Within each tillage system, different letters indicate significant difference between depths at P ≤ 0.05.

Table 6
Aggregate associated organic carbon concentration (AOC) in soil profile under different treatments after 9 years of winter wheat–maize double cropping.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Aggregate associated organic carbon (AOC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coarse macroaggregate (&gt;2 mm)</td>
</tr>
<tr>
<td></td>
<td>g C kg⁻¹ soil</td>
</tr>
<tr>
<td>0.05–0.05 m</td>
<td>CT</td>
</tr>
<tr>
<td>NTS</td>
<td>1.74aB</td>
</tr>
<tr>
<td>NTM</td>
<td>1.31aB</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>0.57</td>
</tr>
<tr>
<td>0.05–0.10 m</td>
<td>CT</td>
</tr>
<tr>
<td>NTS</td>
<td>0.84aC</td>
</tr>
<tr>
<td>NTM</td>
<td>0.69aBC</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>0.29</td>
</tr>
<tr>
<td>0.10–0.20 m</td>
<td>CT</td>
</tr>
<tr>
<td>NTS</td>
<td>0.47aC</td>
</tr>
<tr>
<td>NTM</td>
<td>0.43abC</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>0.16</td>
</tr>
<tr>
<td>0.20–0.40 m</td>
<td>CT</td>
</tr>
<tr>
<td>NTS</td>
<td>0.11aC</td>
</tr>
<tr>
<td>NTM</td>
<td>0.18aD</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>NS</td>
</tr>
<tr>
<td>0.40–0.60 m</td>
<td>CT</td>
</tr>
<tr>
<td>NTS</td>
<td>0.05aC</td>
</tr>
<tr>
<td>NTM</td>
<td>0.04aC</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>NS</td>
</tr>
</tbody>
</table>

CT: conventional tillage; NTS: no-tillage with residue cover; NTM: no-tillage with residue removed and manure applied.

1 Within a column of an aggregated OC, numbers followed by different lowercase letters are significantly different between treatments at each depth at P ≤ 0.05 and within a row of a treatment, numbers followed by different uppercase letters are significantly different between different size classes at each depth at P ≤ 0.05 by LSD test.
CT and NTS treatments in 10.

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higher than those measured under CT. CT treatment was also found to concentrations with coarse macroaggregates in the 0

at 0

concentrations within the mesoaggregate fraction under NTS treatment greater under NTS and NTM treatments compared with CT. The OC'

and

occurred during sowing and harvesting under CT, NTS and NTM systems compared with CT in the surface layer of soil. In contrast, a decline in BD in the 0–10 cm layer under NT treatment with higher crop-residue levels was also observed by Blanco-Canqui and Lai (2007) and Ghuman and Sur (2001).

In contrast to the decreasing trend observed with BD, soil infiltration parameters (A, i, i, and I) were observed to increase at surface soil under NTS and NTM compared with CT. This finding is consistent with results from previous studies (Franzluebbers, 2002; Shukla et al., 2003; Alvarez and Steinbach, 2009). Since organic materials have relatively low bulk density and higher porosity, the addition of organic matter to soil through application of crop residues (NTS) or manure (NTM) generally results in a decline in BD (Celik et al., 2004). As a result of soil biological activity under NTS and NTM systems, increased aggregation and permanent pore development resulted in an increase in the amount of macro-aggregates and the total and effective porosity. This in turn led to greater infiltration and crop water availability (McVay, 2006). The lower infiltration rates observed under CT may be also associated with the additional compaction in the sub-soil during seedbed preparation. However, the greater i, observed under NTS and NTM compared with CT may also be attributed to the production and preservation of channels by earthworms and plant roots (Strudley et al., 2006).

The surface application of crop residues and manure likely isolated the residue and raw material from the soil profile under NTS and NTM treatments, which impacted the percentage of macroaggregates (>0.25 mm) and SOC concentration in surface soil layer compared with CT. Prior studies have also reported a higher SOC concentration near the surface layer in NT compared with CT soils (Hernanz et al., 2009; Sombrero and de Benito, 2010). The higher input of crop residues and raw material in the NT system is known to play a key role in aggregation of the soil (Barreto et al., 2009; Alvaro-Fuentes et al., 2009). Live roots or organic material and decomposing roots have been reported to release compounds rich in carbon which can serve as energy sources for soil microbiota (Six et al., 2006). These organisms in turn are capable of releasing considerable quantities of polysaccharides, which also contribute to soil aggregation. Consequently, SOC which accumulated in the top soil layer was occluded by soil macroaggregates (Six et al., 1999; Hernanz et al., 2002). Conversely, the low concentrations of carbon at the surface under CT treatments can likely be attributed to dilution of organic matter during tillage and also to rapid mineralization resulting from high oxidation rates and greater microbial activity (Dolan et al., 2006; Balesdent et al., 2000). The greater accumulation of SOC in the bottom layer under CT treatment may result from the transfer of crop residues into the subsoil and from crop root growth and distribution in deeper soil layer (Stemmer et al., 1999). Prior field observations have indicated that crop roots under CT systems were relatively denser and larger compared with roots under NT systems in the bottom layers in the North China Plain (Zhang and Miao, 2006; Qi et al., 2012).

Although the percentages of aggregates >2.0 mm were greater under NTS and NTM treatments compared with CT in 0–20 cm soil layer, the percentages of 0.25–2 mm under CT in all soil layers were significantly greater compared with NTS and NTM (48.4–62.8% vs. 39.1–50.6% and 30.2–51.1%) at all the soil depths. Higher concentrations of C in the coarse macroaggregates, mesoaggregates and ‘silt + clay’ fractions at soil surface were observed under NT systems compared with CT. However, at the 40–60 cm depth, greater mesoaggregated C concentrations in CT compared with NTS and NTM were measured. These results are in agreement with those from a study by Plaza-Bonilla et al. (2010). When mixing crop residues at depth (full inversion tillage case), residue C is moved in close proximity to mineral soil particles (Angers and

Within each aggregate size class, the aggregate-associated OC concentrations with coarse macroaggregates in the 0–20 cm soil layers and ‘silt + clay’ aggregates in the 0–10 cm soil layers were found to be greater under NTS and NTM treatments compared with CT. The OC concentrations within the mesoaggregate fraction under NTS treatment at 0–10 cm and under NTM treatment at 0–5 cm layer were significantly higher than those measured under CT. CT treatment was also found to result in higher mesoaggregate-associated OC concentrations in the 10–60 cm soil layers compared with NTM, and the difference between CT and NTS treatments in 10–60 cm was not significant. There was also no significant difference in microaggregated organic carbon concentrations between treatments throughout the soil profile (Table 6).

The physical fractions of the four different aggregated C pools were distributed in MacAOC and MicAOC by 60 and 40%, respectively (Fig. 1). Soil under CT contained a higher amount of MacAOC (66%) compared with NTS-treated (59%) and NTM-treated (54%) soils, respectively, while lower values of MicAOC (34% vs. 42 and 46%, respectively) were measured. On average, the CMacAOC and MesAOC pools contained 8 and 92% of the total MacAOC, while CMicAOC and ‘silt + clay’ OC accounted for 58 and 42% of the total MicAOC, respectively. CT treatment resulted in greater MesAOC (63%) compared with the NTS (52%) and NTM (49%) treatments. In addition, the aggregated C (<2.0 mm) was found to account for 98, 94 and 94% of the total aggregated OC for the CT, NTS and NTM treatments, respectively. The aggregated C (<2.0 mm) was found to be distributed among MesAOC, CMicAOC and ‘silt + clay’ OC at a ratio of ~3.2:1.4:1 and contributed 58, 24 and 18%, respectively.

4. Discussion

Generally, under NT systems, the upper soil tended to display increased BD due to greater compaction when compared with CT. Bhattacharyya et al. (2009) found that NT increased the BD, MWD and the proportion of macroaggregate fractions (>0.25 mm) in soil compared with CT in the surface layer of soil. In contrast, a decline in BD in the 0–20 cm layer in the NTS- and NTM-treated plots relative to the CT-treated plots was observed in the present study. Similar compaction occurred during sowing and harvesting under CT, NTS and NTM systems in our long-term experiments. The decrease in BD was not significant under NTS and NTM treatments compared with CT, which may be partially attributed to the increase in SOC content resulting from application of crop residue (NTS) or manure (NTM) (Table 4). SOC likely directly impacted the BD, as the particle density of organic matter is considerably lower than that of mineral soil (Pikul and Zuzel, 1994; Franzluebbers, 2010). Arvidsson (1998) reported a lower BD in soils with higher levels of organic matter. A decrease in BD in the 0–10 cm layer under NT treatment with higher crop-residue levels was also observed by Blanco-Canqui and Lai (2007) and Ghuman and Sur (2001).

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of dry manure (3.46 Mg ha$^{-1}$) was found to be 76.6% higher than that in shallow tillage (CT) was found to receive less C input aboveground compared with NTS and NTM, no difference in SOC content overall was observed in the 0–60 cm soil profile among treatments. Angers et al. (1993) reported a similar total SOC content in soils to a depth of 60 cm after 10 years of conservation tillage at eight sites and attributed these results to increased levels near the surface and lower values in the deeper layers. Although NT usually leads to the accumulation of SOC in untilled soil. In the present study, while NTS and NTM systems of SOC was transferred into the stable SOC pool in tilled soil compared with untilled soil. In general, more of the root-derived C remains in soil than that of residue-derived C (52% vs. 4%) (Kong and Six, 2010). Greater root density was observed near the soil surface under NT compared with CT and an opposite trend was observed in the subsoil (Ball-Coelho et al., 1998; de Rouw et al., 2010; Wang et al., 2003). Within the soil profile, the root length density (RLD) was found to be significantly higher under NT than under CT at a depth of 5 cm, whereas it was higher under CT than under NT below 10 cm. Below 50 cm, no difference was observed in RLD between the tillage systems (Qin et al., 2006). In Quzhou, China, the root amount of wheat in the deep tillage (CT) was found to be 76.6% higher than that in shallow tillage (10–12 cm depth), while the root biomass in 15–100 cm profile in this field was 1.22 times higher than that in shallow tillage (Lei et al., 2011). Baker et al. (2007) found that the differences in the distribution of wheat and maize roots between the NT and CT systems could result in different SOC distributions with depth. However, lack of data regarding crop roots hampers accurate interpretation of SOC profiles in the present study. Further investigations into crop root development and distribution under the three tillage systems in the studied area should be considered in future work.

Results in the present study also showed that a small amount of dry manure (3.46 Mg ha$^{-1}$ yr$^{-1}$) can potentially replace crop straw inputs (wheat straw 5.9 Mg ha$^{-1}$ of wheat straw plus 4.9 Mg ha$^{-1}$ yr$^{-1}$ of maize straw) to compensate for the C of 4.6 Mg ha$^{-1}$ yr$^{-1}$ due to residue removal. In the 20–60 cm layers, no significant difference was observed in SOC content between the NTS and NTM treatments. The higher OC contents of soil at 20–60 cm in plots treated with NTM may be attributed to leaching and accumulation of soluble organic carbon from the manure. The addition of manure may have promoted microbial activities and the production of soluble carbon (Huang et al., 2011).

5. Conclusion

NTS and NTM treatments in the YRD were shown to promote soil water infiltration in the surface soil. NTS- and NTM-treated plots were also found to accumulate the highest amounts of SOC near the soil surface, which was accompanied by both higher macroaggregate content and higher macroaggregate C concentrations. SOC sequestration in the 0–60 cm layers was not observed to be significantly different between treatments. SOC in 40–60 cm soil layers for CT plots and 20–40 cm layers for NTS plots was higher compared with that measured under NTS. Compared with NTS and NTM, CT treatment promoted both the proportion of the mesoaggregate (0.25–2 mm) fraction and the associated C concentration throughout the soil profile. These results demonstrated that the use of organic matter inputs (crop straw or manure) together with a reduced urea rate under NT did not significantly increase SOC under the winter wheat/maize double cropping system in the YRD.

The findings indicate that a combination of NT with organic fertilizer may act to increase macroaggregate formation and improve soil physical properties at the soil surface. These impacts can be attributed to decreased soil disturbance and the addition of crop residues or manure. The positive effects of CT on SOC in deeper soil were attributed to crop root development in deeper soil layers. Future work should include observation of crop root distribution in the deeper soil profile and an evaluation of SOC dynamics in different tillage systems under the wheat–maize cropping system in the YRD.

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References


