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

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ABSTRACT

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 and stocks (0–5 cm) were significantly greater for NTS and NTM compared with CT, while CT led to a greater OC accumulation in the 20–60 cm soil layer compared with NTS and in the 10–20 cm compared with NTM. The mesoaggregate fraction (2–0.25 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.

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). Cavalieri 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 CO_2 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; Kou 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

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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 (Fliebbach et al., 2007; Karami 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 sequestered a higher fraction of SOC compared with the control.

Although the separate effects of tillage, cropping systems, and fertilizer on soil physical quality and SOC sequestration have been previously documented, there is limited information available regarding the combined effects of these practices. Wang and Dala (2006) evaluated the combined effects of NT, stubble retention (SR) and N fertilization (NF) on SOC sequestration. When NT, SR, or NF was applied alone, no significant effect on SOC was measured in the 0–10 cm layer. However,maximum SOC sequestration was achieved under a combined NT + SR + NF treatment, suggesting that the long-term sustainability of corn production under manure application can be mainly attributed to the improved soil quality. In order to promote soil C sequestration and sustainable agricultural production, reduced tillage systems should be developed in conjunction with judicious organic management (Guo and Zhou, 2007; Pathak et al., 2011). Although no-tillage and other conservation tillage practices have the potential to increase the SOC pool by increasing residue and manure inputs and decreasing C loss, these practices may also increase N_2O emission and nitrate leaching (Mkhabela et al., 2008). There is a need for research related to the capacity of N in straw and manure as a crop nutrient to reduce the use of mineral N fertilizer 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–Uneso system, the soil is classified as a calcaric 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 N_2O emissions and NO_3-N leaching loss in YRD. However, the feasibility of NT in YRD depends if the quality of a soil being conversed 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 convention 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 total 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 m^2 (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 (NHH 2BXF-9 planter with width of 1570 mm) between 10 and 15 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
General soil characteristics for the surface soil (20 cm) at the experimental site.

pH (H_2O, 1:2.5)	8.3 (0.1)
EC1, 5 (dS m^{-1})	0.12 (0.0)
CaCO3 (%)	6.8 (1.1)
Total N (g kg^{-1})	0.76 (0.05)
Olsen P (mg kg^{-1})	16.8 (3.4)
CEC (cmol kg^{-1})	12.0 (2.5)
Water retention (kg kg^{-1})	
33 kPa	0.16
1500 kPa	0.05

Numbers in parentheses are standard errors.