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No-tillage with continuous maize cropping enhances soil aggregation and organic carbon storage in Northeast China

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ABSTRACT

In Northeast China, conventional tillage practices involve removal of crop residue after harvest and prior to moldboard plowing; this has been shown to cause a decline of soil organic carbon (SOC) and degradation of soil structure. No-tillage has been suggested to be an effective way to increase SOC storage but its effectiveness in some soils and climates has been questioned. Different cropping systems also influence SOC storage. Hence, we established an experiment to evaluate how a combination of different tillage and cropping systems could improve soil aggregation and organic carbon storage. We included five treatments: a) NTMS: no tillage with maize (*Zea mays* L.)-soybean (*Glycine* max Merr.) (MS) rotation; b) MPMS: moldboard plowing with maize-soybean rotation; c) NTMM: no tillage with continuous maize (MM); d) MPMM: moldboard plowing with continuous maize; e) CTMM: conventional tillage with continuous maize (the conventional farming practice in Northeast China). All crop residues were returned to the soil except in the CTMM treatment. Returning residue to the soil significantly increased SOC storage in all tillage/cropping systems with NTMM having the highest increase in rate of SOC storage at 0.80 Mg C ha^{-1} yr^{-1} relative to the start of the experiment. The CTMM depleted SOC storage at rate of 0.52 Mg C ha^{-1} yr^{-1} relative to the start of the experiment. Soil under NTMS exhibited a significant SOC decline deep in the soil (5–30 cm) but overall SOC storage in 0–30 cm profile was equal to that under MPMS. The NTMM had the highest SOC storage and the highest proportion and associated organic carbon (OC) in occluded micro-aggregates (53–250 μm, inside of 250 μm aggregates) across all experimental treatments. The OC in occluded micro-aggregates was much higher than that associated with unprotected micro-aggregates (53–250 μm, outside of 250 μm aggregates). The effects of tillage on aggregate size and OC concentration occurred mainly in the surface layer (0–5 cm) whereas the effect of cropping system on aggregate size and OC concentration occurred at deeper depths. The MS cropping system increased the proportion of silt-clay (< 53 μm, outside of 250 μm aggregates) over MM while occluded silt-clay (< 53 μm, inside of 250 μm aggregates) in MM was greater than in MS in all layers. The NTMM treatments improved SOC storage and aggregation over the other treatments.

1. Introduction

Northeast China is a key area of commercial grain production in China, and thus plays a crucial role in China's food security (Yang et al., 2007). However, in recent years, substantial losses of soil organic carbon (SOC) have been observed, which has resulted in a significant reduction in soil fertility (Yu et al., 2006). This phenomenon has been reinforced by conventional tillage (CT) practice which included removal of crop residue after harvest and moldboard plowing (Zhang et al., 2015). This type of practice has caused the decline of SOC, degradation of soil structure and extensive wind and water erosion (Liu et al., 2010). Conservation tillage, particularly no tillage (NT), has been suggested to be an effective practice to control soil erosion and increase the SOC content in Northeast China (Zhang et al., 2007).

However, the effect of NT on increasing SOC levels is not always clear and consistent. Some studies (West and Post, 2002., Ogle et al., 2005., Kumar et al., 2012) suggest that NT is more effective than CT for increasing SOC, whereas other research suggests that this is not always

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the case (Baker et al., 2007; Blanco-Canqui and Lal, 2008; Powlson et al., 2014). This discrepancy has been attributed to differences in cropping systems, duration of tillage, soil type and environmental conditions (Blanco-Canqui, 2013).

Cropping systems can change SOC levels by affecting the amount and characteristics of crop residue and soil aggregation (Yang and Kay, 2001; Zuber et al., 2015). Crop residue binds soil particles together into aggregates and protects SOC from mineralization (Stetson et al., 2012). Different cropping systems contribute post-harvest residues varying in quantity and quality (chemical composition) which will control the carbon (C) inputs to soils (Ogle et al., 2012), thereby affecting SOC storage (Poeplau et al., 2015). Another fundamental characteristic of NT compared to CT is reduced soil disturbance (Paul et al., 2013). Soil disturbance disrupts soil aggregates and exposes physically-protected SOC (Six et al., 2000), promoting its decomposition and loss of C within aggregates, which is essential for long-term SOC storage (Yoo et al., 2011).

Soil aggregates play an important role for SOC storage; aggregate separation methods are useful to investigate the influences of tillage on SOC dynamics (Six et al., 1999; Poeplau et al., 2017). Soil aggregates have been used to evaluate SOC changes in agro-ecosystems (Cates et al., 2016). The size, quantities and composition of aggregate fractions have been suggested to be sensitive to changes in SOC and thus can serve as potential indicators of C sequestration under different tillage practices (Duval et al., 2013). More specifically, the quantity of C associated with occluded micro-aggregates was shown to account for the decrease in SOC under CT compared with NT (Six et al., 1999; Denef et al., 2004). Six and Paustian (2014) identified occluded micro-aggregates as a robust indicator for management-induced SOC changes over decadal time scales.

Maize is one of the most common crops in Northeast China usually grown under continuous cropping and accounts for around 20% of the total national maize area and 31% of the total national maize production (Wang et al., 2014a, 2014b). The potential of SOC storage with cropping systems based on legume crops under NT also needs to be explored (Conceição et al., 2013) because the type of cropping system could cause different changes in SOC storage (West and Post, 2002). In addition, previous studies about the effects on occluded micro-aggregates were mainly focused on tillage (Du et al., 2015; Singh et al., 2015; Sheehy et al., 2015) or cropping systems separately (Cates et al., 2016). There has been little research to evaluate the influence of tillage and cropping systems together on the occluded micro-aggregates. In this study we evaluated different tillage practices with maize-soybean rotation and continuous maize in a long-term study. Our objectives in this study were: 1) to identify a tillage practice that enhances SOC storage; 2) to evaluate the effects of tillage and cropping system on soil aggregates, especially occluded micro-aggregates.

2. Materials and methods

2.1. Experimental site

The tillage and crop system field experiment was established in the Experimental Station (44°12′N, 125°33′E) of Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, in Dehui County, Jilin Province, China in fall 2001. The experimental site is located in North Temperate Zone and has a continental monsoon climate. The coldest month is in January ($-19.5\,^\circ$C) and the warmest month is in July (24.5 °C) and the mean annual temperature is 4.4 °C. The mean annual precipitation is 520 mm with > 70% occurring during the growing season from June to August. The clay loam soil is classified as Typic Hapludoll according to the USDA Soil Taxonomy. The site had been under conventional tillage management and continuous maize production for > 15 years prior to 2001. The average soil pH is approximately 6.5, total nitrogen (N) 1.40 g kg^{-1}, available P 15.5 mg kg^{-1} and available K 110.2 mg kg^{-1} in 0–20 cm layer. Other details about physical and chemical properties of the experimental site are provided by Liang et al. (2007).

2.2. Field experimental design

The long-term tillage experiment was a completely randomized design with four replications for each treatment. Five treatments were studied: a) NTMS: no tillage with two year maize-soybean (MS) rotation (maize: *Zea mays* L.; soybean: *Glycine max* Merr.); b) MPMS: moldboard plowing with two year maize-soybean rotation; c) NTMM: no tillage with continuous maize (MM); d) MPMM: moldboard plowing with continuous maize; e) CTMM: conventional tillage with continuous maize (this is the conventional farming practice in Northeast China where residue is removed and used for fuel or livestock feed). The soil in the NTMS and NTMM plots was not disturbed except for planting using a no-till planter (KINZE-3000NT, Williamsburg, Iowa). The MPMS, MPMM and CTMM included a ridge building in June with a modified lister and one fall moldboard plowing (about 20 cm deep) after harvest of the maize and soybean. For all treatments except CTMM, the maize residue was returned to soil after harvest. In NTMM and NTMS, 30–35 cm stubble was left standing and un-chopped maize stalks were left on the soil surface interspersed among the stubble to prevent water and wind erosion. Soybean residue in NTMS and MPMS was directly returned to the soil surface. In the MPMS and MPMM treatments residue was removed prior to plowing, and then manually replaced after plowing to prevent the soil erosion from wind over the winter. Before sowing in the following spring, all the surface residues were cut into about 30 cm pieces with a heavily ballasted disk when the soil was partially frozen. Residue from the previous year was incorporated during spring cultivation, and subsequently, incorporated to a deeper depth with moldboard plowing in the autumn in MPMS and MPMM. Therefore, the only difference between MPMM and CTMM was residue replacement in the MPMM treatment. Both the MPMS and MPMM treatments were a departure from traditional farming practices (CTMM) in northeast China where all residues are removed after harvest and stockpiled for subsequent use as animal feed or fuel for heating and cooking. The experimental field had been farmed in this way for many years prior to initiation of the experiment.

Maize and soybean in all five treatments were planted on May 10, 2013. The fertilizer strategy was different for the maize and soybean phases of the rotation. For maize, N, P and K fertilizers were applied at 100, 45.5 and 78 kg ha^{-1}, respectively, as starter fertilizers. At the V-6 growth stage, an additional 50 kg N ha^{-1} was applied as top dressing. For the soybean, starter fertilizer was applied at 40 kg N ha^{-1}, 60 kg P ha^{-1} and 80 kg K ha^{-1}. Starter fertilizers were applied with the side-banding attachment on the no-till planter.

2.3. Soil samples

Seven soil samples were collected from each plot in the maize phase down to a depth of 30 cm in the beginning of the experiment (2001) and after harvest in 2013. The samples were taken using a hand auger with 2.64 cm internal diameter, which allowed cores to be taken without compaction. Each soil core was separated into four segments corresponding to depths of 0–5 cm, 5–10 cm, 10–20 cm and 20–30 cm. Soil samples were gently broken and air-dried. The seven samples were combined to form a composite sample for each depth and each plot. Air-dried soil samples were sieved to pass a 7 mm sieve and stubbles and stones were removed.

2.4. Soil analysis

a) *Bulk density*, *SOC storage*, *SOC storage change rate*

In fall 2013 (after harvest and before fall moldboard plowing), two replications of undisturbed soil samples from each plot were collected