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Effects of long-term cropping regimes on soil carbon sequestration and aggregate composition in rainfed farmland of Northeast China

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ABSTRACT

Soybean (*Glycine max* L.)–maize (*Zea mays* L.) rotation has been recommended as a good cropping practice for soil quality improvement and crop productivity enhancement. However, its impacts on carbon sequestration in soil are not well documented. The main objective of this study was to learn whether soybean–maize rotation can promote soil organic carbon (SOC) sequestration. Based on a long-term field experiment (started in 1990) in Northeast China, we investigated the differences in soil organic carbon (SOC) and soil aggregate composition between cropping patterns. This experiment included four treatments: continuous maize cropping (CMC), maize–soybean rotation (MSR), continuous soybean cropping (CSC) and farmland fallow (FALL) in a Haplic Phaeozem soil. All treatments showed a sustained trend toward increasing SOC storage since 1990. The contents of SOC in the topsoil and in the profile to the 1 m depth were in the following order of CMC > MSR > CSC ≥ FALL, suggesting a greater potential of C sequestration under cropping with manure application than under the farmland fallow without any fertilizer application. In the 1 m soil profiles, SOC levels decreased with soil depth with a major part (around 60–71%) being distributed in the 0–40 cm layer, whereas different practices led to great differential of SOC distribution. The CMC had the highest SOC levels (47.3 Mg ha^{-1}) in the topsoil (0–20 cm) among the four systems. Meanwhile, maize cropping system (e.g. CMC and MSR) promoted more SOC allocation in >40 cm soil layers. Moreover, cropping pattern also differently influenced the formation and transformation of soil aggregates and the distribution of SOC in the aggregates. Macro-sized aggregate and the associated C (18.6 Mg ha^{-1}) dominated in the FALL, while the micro-sized fractions (44.0% and 52.5%, respectively) and corresponding associated C (14.8 Mg ha^{-1} and 19.2 Mg ha^{-1}, respectively) were maximized in the MSR and CSC. The CMC had the greatest silt + clay-sized aggregate fraction (42.0%) and associated C in the macro- (13.4 Mg ha^{-1}) and silt + clay-sized aggregate (12.9 Mg ha^{-1}) fractions when compared with the MSR and CSC. Thus, maize–soybean rotation may be not the best cropping practice for C sequestration in the rainfed farmland Mollisol (Cumulic Hapludoll) in Northeast China, and intensive cropping with manure application can sustain the soil fertility for a long-term with high crop yield.

1. Introduction

Farmland soil is an important carbon (C) pool of the biosphere (Buyanovsky and Wagner, 1998) and a potential sink of atmospheric C (Lal, 2004; UNFCCC, 2009). Previous observations have showed that there were negative or positive effects of cropping practices on carbon storage and stability in farmland soils (Paustian et al., 1997; Bruce et al., 1999; Six et al., 2002). Mostly, inappropriate cropping practices (e.g. excessive cultivation) can induce dramatic SOC losses and significant soil quality degradation (Elliott, 1986; Six et al., 2002; Yu et al., 2006). Rational cropping practices, such as crop residue recycling (Aoyama et al., 1999; Blair et al., 2006), manure application (Hao et al., 2003; Rudrappa et al., 2005), conservation tillage (Gale and Cambardella, 2000; Six et al., 2000a), and farmland fallow (Paustian et al., 1997; Unger, 2001; Nair et al., 2009; UNFCCC, 2009), can significantly increase SOC storage and soil quality. As an important recommended cropping practice, crop rotation (e.g. maize–soybean rotation) has been considered as an effective approach to sequestrate C in farmland soil and to

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enhance soil fertility (Huggins et al., 1995; Jarecki and Lal, 2003; Lal, 2004; Madari et al., 2005; Smith et al., 2007). However, other observations showed adverse conclusions about C sequestration in soil under maize–soybean rotation system (Eghball et al., 1994). The incompatible results imply that further attentions should be paid to the impacts of crop rotation on soil carbon sequestration and its stability.

Soil aggregates are important agents of SOC retention (Carter, 2002; Haile et al., 2008) and protection for decomposition (Elliott, 1986; Jastrow et al., 1996; Six et al., 2000b). Generally, SOC protected by the macro-aggregates shows a short-term storage, and the most stable C is stored in the smallest silt + clay size fraction (<0.053 mm) (Six et al., 2002). Thus, soil aggregate fractionation has been widely applied to evaluate the SOC stability and the impacts of land use on SOC dynamics (Christensen, 1992; Cambardella and Elliott, 1994; Christensen, 2001). Cropping pattern, the integration of anthropogenic disturbances on farmland, can significantly affect soil aggregate stability and distribution (Elliott, 1986; Six et al., 2002; Pinheiro et al., 2004; Lichter et al., 2008). Previous investigations have been conducted to learn the effects of crop rotations on soil aggregation and SOC storage, such as the maize (*Zea mays* L.)–wheat (*Triticum aestivum* L.) rotation (Lichter et al., 2008), barley (*Hordeum vulgare* L.)–wheat rotation (Álvaro-Fuentes et al., 2008a), wheat–fallow and maize–soybean (*Glycine max* L.)–wheat rotation (Six et al., 2000b), and the wheat or pea (*Pisum sativum* L.) or lentil (*Lens culinaris* Medicus)–soybean rotation (Wright and Hons, 2004; Bhattacharyya et al., 2009). These investigations have greatly enhanced our understanding of the impacts of crop rotation on soil aggregation and SOC stability. However, there is limited information about the effects of maize–soybean rotation on soil aggregates and their aggregation processes, which is very important to understand the mechanisms underlying soil carbon sequestration.

Commercial grain production in Northeast China plays a crucial role in Chinese food security (Yang et al., 2007). In this region, the long-term intensive maize cropping with all stover harvested for rural fuel has resulted in great decreases of SOC and rapid declines of soil fertility (Yu et al., 2006). In order to improve soil quality, maize–soybean rotation plus manure application has been widely recommended since the 1990. During the past decades, many efforts have been paid on the impacts of the rotation on crop yield and soil chemical–physical conditions (Huggins et al., 1995; Six et al., 2000b; Jarecki and Lal, 2003; Yang et al., 2007; Álvaro-Fuentes et al., 2008a), but little is known about its impacts on soil aggregation and SOC situations (Eghball et al., 1994; Huggins et al., 1995). Theoretically, there are great differences in the inputs of soil organic carbon as crop stubble and root and in its outputs as carbon decomposition between cropping patterns. As compared with the continuous corn or soybean cropping, maize–corn rotation system may have different impacts on SOC storage and stability. Meanwhile, soil aggregation and SOC sequestration are both long-term processes and a short-term (less than 5 years) field experiment cannot fully present the effects of crop rotation. Based on a long-term maize–soybean rotation experiment started in 1990 in Northeast China (Liu et al., 2007), we performed an investigation to compare the differences in SOC stability and soil aggregation between different cropping regimes. Our objectives were to assess and quantify the long-term effects of maize–soybean rotation on (1) SOC contents, (2) soil aggregate composition and transformation, and (3) SOC distribution in the aggregates. We hypothesized that long-term maize–soybean rotation could promote soil carbon sequestration when compared with continuous cropping and farmland fallow.

2. Materials and methods

2.1. Experimental site

The study site is located at the Gongzhuling Experiment Station (N 43°30′23″, E 124°48′33.9″; 220 m above sea level) of Jilin Academy of Agricultural Sciences, Jilin Province, China. The long-term field experiment has been conducted in a rainfed farmland since 1990. The historical cropping background was monoculture maize cropping without manure application before 1990. The mean annual precipitation is 450–600 mm with about 70% falling between June and August, and the mean annual temperature is 4–5 °C ranging from −35 °C in January to 34 °C in July. The soil is classified as Thermo-Black Soil in Chinese classification, Haplic Phaeozem in FAO-Unesco classification, and Cumulic Hapludoll (Mollisol) according to the US classification (Boerma et al., 1995; Soil Survey Staff, 2003). The soil properties at the start of the experiment were as follows: pH 6.7, organic carbon 28.0 g kg^{-1}, total N content 1.9 g kg^{-1}, and total P content (as P_2O_5) 0.6 g kg^{-1}, silt content 37.5%, clay content 29.1%. Further details of the experimental site could be found in Chen et al. (2010).

2.2. Experimental design

The long-term experiment included four treatments: continuous maize cropping (CMC); maize–soybean rotation (MSR); continuous soybean cropping (CSC); and continuous farmland fallow (FALL). The treatments were arranged in a completely randomized design with three replicates. Every plot covered around 667 m^2. Primary tillage was followed by a pass of stubble crushing machine to a depth of 0–20 cm about three day before planting in late April every year in the three cropping plots. Maize (52,500–60,000 plant ha^{-1}) or soybean (120,000–150,000 plant ha^{-1}) was planted in ridge-till and harvested in late September. The above-ground biomass was removed following harvest except for the FALL treatment. Organic manure (horse (*Equns caballus* L.) manure) and inorganic fertilizer were applied in the CMC, MSR and CSC every season. Approximately 23,100 kg ha^{-1} horse manure was applied before tillage as basal fertilizer in the cropping plots. Phosphorus (82.5 kg P_2O_5 ha^{-1}) and potassium (82.5 kg K_2O ha^{-1}) were applied as basal fertilizer and seed fertilizer by dividing the doses in the ratio 2:1, respectively. Urea (nitrogen fertilizer, totaling 165 kg N ha^{-1}) was added as seed fertilizer and supplemental fertilizer in the ratio 1:2, respectively. Weed control mainly associated with fertilizer topdressing with a fertilizing-tillage machine at jointing stage in the three cropping systems. Disease and inspect pests of maize or soybean were cured through applying pesticide during the growth periods. The plots of the FALL treatment were fallow as a natural succession field without any fertilizer or pesticide application. Local weeds and shrubs are the dominant plants in the FALL plots, and all litters of the weeds and shrubs were kept on the plot surfaces without any anthropogenic disturbance.

2.3. Soil sampling and analysis

Soil samples were collected with soil auger (3 cm in diameter) after crop harvest in early October 2008. The samples were collected from five depths (0–20, 20–40, 40–60, 60–80, and 80–100 cm) in three randomly selected sampling points for each plot. The three sub-samples at each sampling point and depth class were blended to get one composite sample for each depth class per plot. After being transferred to the laboratory, the field-moist soil samples were passed through an 8 mm sieve, and air-dried and mixed thoroughly. Then, every sample was divided into two parts. One part was used to determinate SOC through a 0.149 mm sieves,