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16-Year fertilization changes the dynamics of soil oxidizable organic carbon fractions and the stability of soil organic carbon in soybean-corn agroecosystem

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ABSTRACT

Oxidizable organic carbon is a valuable indicator of soil quality, early changes in soil organic carbon (SOC) content, and changes in stabilities of SOC induced by soil fertilization practices. To improve SOC accumulation under soybean-corn cropping system in flat farmland on the Loess Plateau, we examined the effects of nine fertilization treatments [bare land (BL), control (CK), nitrogen (N), phosphorus (P), N + P (NP), manure (M), M + N (MN), M + P (MP), M + N + P (MNP)] on dynamics of SOC and four fractions of oxidizable organic carbon (OC) [very labile (C_{VL}), labile (C_L), less labile (C_{LL}) and recalcitrant (C_{NL})], and stability of SOC over the period of 1997 to 2013. Although SOC content in treatments without fertilization or with inorganic fertilization remained relatively stable between 1997 and 2013, long-term no fertilization or inorganic fertilization caused a depletion of the very labile C (C_{VL}) fraction and increased the stability of SOC. Long-term application of manure promoted an accumulation of SOC in the topsoil between 1997 and 2013, mainly by sequestering labile C (C_{VL} and C_L) in the 0–20-cm soil layer, and the dynamics of SOC and C_{VL} contents under these treatments fitted a logistic regression model, which decreased the stability of SOC between 2008 and 2013. SOC content in the subsoil (20–40 cm) under cultivation with organic fertilization increased between 1997 and 2006, but then decreased between 2007 and 2013. Organic fertilization increased C_{VL} and C_L contents in the 20–40-cm layer between 1997 and 2010, but then decreased them between 2010 and 2013, and increased the stability of SOC between 2011 and 2013. Our findings indicated that manure fertilization was more effective in promoting SOC enrichment of the soil surface layers by increasing C_{VL}, relative to inorganic fertilization and no fertilization, whereas long-term manure fertilization was associated with a risk of decreasing labile carbon in the 20–40-cm layer and the stability of SOC in the 0–20-cm layer. Manure fertilizer should thus be used cautiously in farmland on the Loess Plateau to guarantee long-term soil carbon stock.

1. Introduction

Soil organic carbon (SOC) content is very important for maintaining soil fertility, soil sustainability, and crop yield in agroecosystems (Ghosh et al., 2010). SOC is also the sink and source of atmospheric CO_2, and thus promoting SOC sequestration in agricultural soils contributes to mitigate the increase of atmospheric CO_2 concentrations (Lal, 2004a,b,c). Therefore, maintaining an optimum level of SOC is conducive to ensure food safety and mitigate climate warming. Fertility maintenance by application of inorganic fertilizers and organic manures can manage optimum SOC levels in agroecosystems (Bhattacharyya et al., 2008, 2011). Numerous studies suggested that continuous use of inorganic fertilizers and organic manures promotes SOC sequestration (Schuman et al., 2002; Kundu et al., 2007; Majumder et al., 2008; Gu et al., 2017). Inorganic fertilization may indirectly enhance SOC storage by increasing crop residue input to soils (Tian et al., 2015), whereas manure application can increase soil organic matter (SOM) through the direct inputs of processed organic materials to soils (Hai et al., 2010).

The SOC stock comprises a labile pool and a recalcitrant pool that

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differ in their turnover rates (Majumder et al., 2008). The labile C pool belongs to SOC with rapid turnover rates, which serves as an energy source for soil food webs, and thus improves nutrient cycling, soil quality and its productivity (Chan et al., 2001). Moreover, its oxidation determines the flux of CO_2 to the atmosphere, thus affecting global climate (Majumder et al., 2007). In contrast, the recalcitrant pool of SOC is very resistant to microbial decomposition (Sherrod et al., 2005b), and plays a vital role in long-term C storage (Neff et al., 2002; Jiang et al., 2014). Walkley and Black (1934) offered a method for measuring the C content of soil and Chan et al. (2001) improved the Walkley-Black method to divide SOC into four fractions with different labilities and oxidizabilities: very labile C (C_{VL}), labile C (C_L), less labile C (C_{LL}), and recalcitrant C (C_{NL}). The C_{VL} and C_L fractions are the most readily oxidizable fractions and mainly composed of polysaccharides, decaying young organic matter, fungal hyphae, and other microbial products, which contribute to the formation of macroaggregates and availability of nutrients (Janzen, 1987; Maia et al., 2007). The C_{LL} and C_{NL} fractions are related to compounds of high chemical stability, and are slowly decomposed by soil microbe (Chan et al., 2001; Sherrod et al., 2005a). Most studies suggested that long-term manure fertilization promotes the accumulation of SOC mainly through increasing the amounts of labile oxidizable organic C due to the high labile carbon inputs by the manure (Majumder et al., 2007; Ghosh et al., 2010; Yang et al., 2012). However, different results were also observed. Bhattacharyya et al. (2011) observed that long-term manure fertilization simultaneously increases both labile and recalcitrant oxidizable C fractions, whereas Majumder et al. (2008) suggested that long-term manure fertilization mainly increases the content of recalcitrant oxidizable C fractions. These inconsistent results are partly related to differences in the quality of manure, climatic conditions, soil type, and cropping system among study sites (Mi et al., 2016). Additionally, the cultivation time largely affects fertilization effect on SOC and soil oxidizable OC fractions, because short-term manure fertilization mainly increased labile oxidizable C but long-term manure fertilization tended to promote the accumulation of recalcitrant oxidizable C (Wu et al., 2004; Ghosh et al., 2010). SOC content increased follow equilibrium dynamics after manure fertilization (Shang et al., 2011; Triberti et al., 2016), and labile C contained by manure directly contributes to the rapid increase of SOC, and recalcitrant C might accumulated when SOC content reaches equilibrium because large amounts of labile C were decomposed into recalcitrant C. However, few studies have investigated the continuous inter-annual variation in soil oxidizable organic C fractions and the stability of SOC after fertilization, which is vitally important for enhancing quantity and quality of SOC and mitigating increases in atmospheric CO_2 concentrations in agroecosystems.

The Loess Plateau in the upper and middle regions of the Yellow River in China covers an area of approximately $58 \times 10^4\,km^2$, has a temperate semiarid climate, and is known for its long agricultural history and severe soil erosion (Chen et al., 2007). In order to control soil erosion and restore the ecological environment, 'the Grain for Green project' was launched by the Chinese Government in 1999, which converted unsuitable sloping farmland into forestlands or grasslands (Zhang et al., 2013). The yields in the flat farmland between valleys are thus very important to ensure regional food security because of the loss of sloped farmland, and fertilization is required to maintain yields in this area (Janzen et al., 1997). A long-term field experiment of fertilization established in 1998 on cultivated land of the Loess Plateau offered a good opportunity for the study of the effects of fertilization on oxidizable organic carbon (OC) fractions, particularly the continuous inter-annual variation in soil oxidizable OC fractions. In this study, we measured the contents of SOC and oxidizable OC fractions between 1997 and 2013 under nine fertilization regimes. We aimed to evaluate the long-term effect of fertilization on SOC and oxidizable OC fraction sequestration with a view to modelling the SOC retention potential of a soybean–corn agroecosystem on the Loess Plateau and to determine C stabilization at two soil depth intervals. We hypothesized that (1) cultivation with balanced and imbalanced fertilization in combination with or without manure influences the SOC stock, size of oxidizable OC fractions, and the stability of SOC over time, and that (2) soil depth and the interaction between soil depth and fertilization affects the SOC stock, size of oxidizable OC fractions, and the stability of SOC.

2. Materials and methods

2.1. Experimental site

This study was part of a long-term fertilization field experiment set up at the Ansai Station of the Institute of Soil and Water Conservation, Chinese Academy of Sciences (109°19′23″E, 36°51′30″N). The station is located at an attitude of 1068–1309 m in a typical hilly region of the Loess Plateau. This region has a temperate semi-arid climate, with a mean annual temperature of 8.8 °C, an average annual rainfall of 500 mm, a frost-free period of 159 d, and 2416 h of sunshine annually. The soil is mainly composed of wind-deposited Huangmian soil (calcaric cambisols, FAO), characterized with yellow particles, absence of bedding, silty texture, looseness, and wetness-induced collapsibility (Zhang et al., 2011). The initial soil properties of the 0–20-cm soil layer were as follows: SOC content of 5.57 g kg^{-1}, total N content of 0.57 g kg^{-1}, available N content of 28.99 mg kg^{-1}, total phosphorus (P) content of 0.63 g kg^{-1}, available P content of 2.49 mg kg^{-1}, pH 8.6, and soil bulk density of 1.25 g cm^{-3}.

2.2. Field experiment

The long-term field experiment on fertilization was conducted from 1997 to 2013. This long-term experiment had a triplicate randomized complete block design, and each plot was 2.33 × 6 m in size (Fig. S1). The experiment consisted of the following nine treatments: unfertilized bare land (BL), unfertilized control (CK), nitrogen fertilizer (N), phosphorus fertilizer (P), nitrogen and phosphorus (NP), farmyard manure (M), farmyard manure and nitrogen (MN), farmyard manure and phosphorus (MP), and farmyard manure and nitrogen plus phosphorus (MNP). Each treatment consisted of three replicates. N was added as urea and P as superphosphate, and the farmyard manure contained the faeces and urine from domestic sheep. The N, P, and manure fertilizers were applied at the rates of 97.5, 75, and 7500 kg hm^{-2}, respectively. The experiment was performed under a 3-year rotation, with a sequence of *Glycine max* (Linn.) Merr.–*Zea mays* Linn.–*Zea mays* Linn., beginning with *G. max* in the autumn of 1998. These crops were manually harvested, and the aboveground crop residues were removed in October.

2.3. Sampling

Soil from the 0–20-cm layer in each treatment was sampled annually from 1998 to 2013. Similarly, soil from the 20–40-cm layer in each treatment was sampled in 2000, and from 2003 to 2013. A soil sample from the same duplicate of each treatment was only collected from each soil layer between 1998 and 2010. Three samples from three duplicates of each treatment were collected from each soil layer between 2011 and 2013. Soil samples were collected from the 0–20 and 20–40-cm layers at five points in each plot after harvest using the S-sampling method, and then the five soil samples from each plot were mixed to produce a composite sample. Soil sampling was conducted using a soil auger (diameter, 4 cm). Visible plant residues were removed, and the samples were immediately transported to the laboratory, air-dried and crushed to pass through 2-, 1-, and 0.25-mm sieves, and then stored in glass bottles separately, which were placed in a soil bank. The physical and chemical properties and OC fraction contents of all soil samples were analysed in 2014.