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Variation of soil aggregation and intra-aggregate carbon by long-term fertilization with aggregate formation in a grey desert soil

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ABSTRACT

A long-term field experiment was established in 1990 to evaluate the impact of mineral fertilizer (N and NPK) and organic material (manure and crop residues) application on soil aggregation and organic carbon (C) accumulation in an intensively cultivated grey desert soil in northwestern China. The long-term addition of organic materials with balanced inorganic NPK inputs significantly increased the mass proportion of macroaggregates from 10% in the CK treatment to 34% and 24% in the 1.5MNPK and SNPK treatments (the application of inorganic NPK combined with organic sheep manure and the return of crop residues to the field, respectively). In contrast, the addition of inorganic fertilizer (the N and NPK treatments) had no obvious effect in promoting the percentage of macroaggregates. The application of inorganic fertilizer and abandonment (the CK_0 treatment) only sustained the soil organic carbon (SOC) content. However, the SOC contents were significantly increased by 197% and 19% in the 1.5MNPK and SNPK treatments, respectively, relative to the CK treatment over a 24-year period. Amending the soils with N and NPK mainly increased the organic C concentrations in the silt + clay fraction. In contrast, the application of manure accelerated the accumulation of organic C in all of the aggregate fractions, particularly by increasing the amount of C in the fine intra-aggregate particulate organic matter (iPOM) fraction rather than the coarse iPOM or the silt + clay subfraction. The organic C concentration in the silt + clay fraction was significantly correlated with the mass proportion of macroaggregates ($R^2 = 0.9488$, $P < 0.01$), and with the ratio of macroaggregates to microaggregates ($R^2 = 0.9477$, $P < 0.01$). These results indicated that macroaggregates and the silt + clay fraction were more sensitive to fertilization in the grey desert soils. We consider that increases in the organic C concentrations in the silt + clay fraction and shifts in the stored C towards microaggregates may play important roles in soil aggregation and SOC sequestration in grey desert soils.

1. Introduction

Soil aggregation conserves and protects soil organic matter, which functions as a plant nutrient and energy reservoir (Bronick and Lal, 2005). In addition, the soil structure affects a wide range of soil properties, including soil porosity, compactability and water retention (Cheng et al., 2015; Regelink et al., 2015). In addition, aggregate stability is a soil property that determines the resistance of a soil to erosion (Chaplot and Cooper, 2015). It is generally accepted that organic materials affect soil aggregation (An et al., 2010; Smith et al., 2014). Thus, organic matter amendments may influence the formation and stability of soil aggregates by binding soil mineral particles, which would influence the mechanical strength of soil aggregates and the effectiveness of interparticle binding agents (Six et al., 2004; Mizuta et al., 2015).

The conservation and storage of SOC in cropland soils have been widely considered as important components of soil quality for sustaining crop productivity and the long-term stability of agricultural systems (Riley et al., 2008; Banger et al., 2009). In addition, SOC sequestration has long been recognized as a promising measure for mitigating global climate change through C storage in soils (Yu et al., 2013; Lehmann and Kleber, 2015). SOC can be further classified into several C fractions with variable physical and biochemical properties, including differential stabilities and turnover rates (Guimaraes et al., 2013). Physical fractionation is based on the different protection mechanisms of SOC and depends on the interactions between organic and inorganic soil components during organic matter turnover (Nascente et al., 2013). These C fractions (i.e., intra-aggregate particulate organic matter-carbon, iPOM-C) are likely more sensitive to measurable soil quantities than the total soil C pool and can serve as potential indicators of increasing C sequestration under different management practices (Smith et al., 1999; Duval et al., 2013). Using this approach, Six et al. (2002) proposed using a physical fractionation procedure and the associated conceptual SOC model, which were used to explain the formation of aggregates and to understand the dynamics

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and accumulation processes of SOC under different management practices (Smith et al., 2002). Aggregate-associated organic C pools with more rapid erosion may potentially arise more readily from macroaggregates than microaggregates (Zhao et al., 2012). The above-mentioned studies were usually conducted to develop better strategies based on the premise of improving SOC and soil quality.

Cultivation with organic and inorganic nutrient sources applied differently over a long period may influence the regeneration and rejuvenation of the soil structure (Liang et al., 2012; Naveed et al., 2014). Previous studies have shown that different organic amendments, such as manure (farmyard manure or green manure), could improve organic C concentrations and soil aggregation (Bandyopadhyay et al., 2010). Furthermore, the addition of organic residues to soils could enhance C sequestration and increase aggregate stability (Hati et al., 2008; Zhang et al., 2014). Although significantly lower C sequestration was observed in treatments with direct root residue and straw input relative to treatments with added manure, the ability of straw and crop residues to store C was similar to that when mineral fertilizer was added to soil (Tong et al., 2014; Wang et al., 2014b). Several studies have indicated that the application of mineral fertilizers to soil promotes macroaggregation and increases SOC concentrations (Lugato et al., 2010; Egodawatta et al., 2012). Fonte et al. (2009) and Bi et al. (2015) observed that long-term mineral fertilization decreased the SOC content and reduced aggregation. Interestingly, several authors have reported that the application of balanced inorganic fertilizer (NPK) can only sustain SOC concentrations and does not significantly affect the SOC content or soil macroaggregation (Huang et al., 2010; Bandyopadhyay et al., 2010; Ayuke et al., 2011). These different effects of returning straw or adding mineral fertilizers to the soil on the SOC contents and soil aggregation may depend on specific soil characteristics, plant types and climate conditions. Physical fractionation of soil aggregates may be a useful approach to understand the dynamics and functional attributes of SOC.

Grey desert soils represent the most important soil resource in the typical continental arid climate regions of northwestern China. Up to 52,528 km^2 of grey desert soils are cultivated across China, and more than one quarter of cultivated grey desert soils are located in Xinjiang (Jiang et al., 2015). However, because some inherent unfavorable properties have resulted from intensive weathering and minimal external input, with inappropriate land use, grey desert soils are generally characterized by poor nutrition, low productivity and a high erosion risk (Wang et al., 2014a). Population growth and the food crisis in China have resulted in an urgent need to improve the quality and productivity of grey desert soils. A long-term fertilization experiment was established in an intensively cultivated grey desert soil where maize-wheat-cotton crop rotation was practiced to monitor changes in the plants and soil fertility under manure, straw-return and mineral fertilizer treatments. Although the effects of fertilization on the quality of grey desert soils have been well documented, previous studies have mainly focused on the total soil C pool (Xu et al., 2014), the biodiversity of soil fauna (Jiang et al., 2015), greenhouse gas emissions (Lv et al., 2014) and soil phosphorus accumulation (Wang et al., 2014a). To further understand the influence of physical aggregate fractionation resulting from fertilization on the mechanisms of SOC accumulation and functional attributes, a long-term experiment was required. Consequently, our objectives were to (1) document the spatial and temporal subfraction-associated organic carbon characteristics of grey desert soil by aggregate formation and (2) determine the effects of long-term fertilization on soil aggregation and aggregate-associated organic carbon pools in intensively cultivated grey desert soil.

2. Materials and methods

2.1. Study site

This study is a continuation of the study conducted by Jiang et al. (2015). A long-term field experiment located at Urumqi farm in Xinjiang, with a typical grey desert soil, was established as part of the National Long-term Monitoring Network of Soil Fertility and Fertilizer Effects in 1990 to investigate the effects of climate, crop rotation and inorganic and organic fertilizer application on crop yield and soil fertility, and this experiment was used in this study. The experimental site (43°58′ N, 87°25′ E, 600 m a.s.l.) has a typical continental arid climate, and the typical oasis farmland with maize-wheat-cotton crop rotation was used to prevent the deterioration of soil quality. The mean annual precipitation is 242 mm, with 70% of the precipitation occurring during the winter and summer. During the study period, the mean annual temperature was 7.6 °C, and the lowest and highest mean monthly air temperatures were −15 °C in January and 27.2 °C in July, respectively. The average amount of sunshine is 2454 h per year, and the annual frost-free period is approximately 156 days. The annual evaporation in the study area is approximately 2570 mm (Jiang et al., 2015), and the soil, which was classified as a grey desert soil according to the China soil classification system and as a calcareous desert soil according to the FAO soil classification (FAO, 2014), contains 30, 53 and 17% clay, silt and sand, respectively, in the upper 20 cm of the soil profile. The main soil properties in the plough layer (0–20 cm) of the experimental site were as follows: a soil pH (water:soil = 2.5:1) of 8.1, an organic matter content of 8.8 g C kg^{-1}, a total nitrogen (N) content of 0.87 g N kg^{-1}, a total phosphorus (P) content of 0.67 g P kg^{-1}, a total potassium (K) content of 23.0 g K kg^{-1}, an alkaline hydrolysable N content of 55.2 mg N kg^{-1}, an Olsen-P content of 3.4 mg P kg^{-1} and an ammonium acetate (NH_4OAc) extractable K content of 288.0 mg K kg^{-1} (Jiang et al., 2015).

2.2. Experimental design and sample collection

Long-term fertilizer treatment was conducted using a randomized complete block design with three replicates with a size of 468 m^2 each plot. The plots were hydrologically isolated by partitioning walls extending to a depth of 70 cm and filled with cement to prevent the movement of species between the individual plots. Five treatments were designed for the long-term fertilization experiment: (1) CK (control, without any fertilizer application); (2) N (the application of inorganic nitrogen fertilization only); (3) NPK (the application of an inorganic nitrogen, phosphorus and potassium fertilizer); (4) 1.5MNPK (the application of inorganic NPK application combined with 1.5 times organic sheep manure); (5) SNPK (the application of inorganic NPK combined with the return of crop residues to the field); (6) CK_0 (abandonment, nature and without any fertilizer application). Detailed information regarding the treatments is provided in Table 1. Nitrogen fertilizer (as urea) was applied using two split applications, with 60% N applied as basal fertilizer and 40% N applied by topdressing. All phosphorus (P) and potassium (K) fertilizers (as calcium superphosphate and potassium sulfate, respectively), and organic fertilizers (including straw and manure) were applied as basal fertilizers. The sheep dung applied in the study area was collected from the same sheep farm. The fertilizer

Table 1
Treatments of different mineral, organic manure, and straw application rates in a long-term fertilization experiment in the grey desert soil.

Treatment	Sheep manure ($kg\ ha^{-1}$)	Straw ($kg\ ha^{-1}$)	N ($kg\ ha^{-1}$)	P_2O_5 ($kg\ ha^{-1}$)	K_2O ($kg\ ha^{-1}$)
CK	0	0	0	0	0
CK_0	0	0	0	0	0
N	0	0	241.5	0	0
NPK	0	0	241.5	138	58.5
SNPK	0	4500–9000	216.7	116.6	52
1.5MNPK	60,000	0	151.8	90.4	19.0

Treatments represent habit types and are labelled as follows: control and without any fertilizer application (CK), inorganic nitrogen fertilization only (N), combined inorganic nitrogen, phosphorus and potassium fertilization (NPK), inorganic NPK application combined with 1.5 times organic sheep manure application (1.5MNPK), inorganic NPK application combined with the return of crop residues to the field (SNPK), and abandonment, nature and without any fertilizer application (CK_0).