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Carbon sequestration and mineralization of aggregate-associated carbon in an intensively cultivated Anthrosol in north China as affected by long term fertilization

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ABSTRACT

Understanding organic carbon (OC) sequestration in aggregates and OC stability under different fertilization practices is of key importance in improving soil quality and crop productivity and in mitigating the causes of climate change. A long-term field experiment established in 1990 was used to assess the influence of organic and inorganic fertilizers on aggregate-associated OC and its mineralization and on the SOC stock at a soil depth of 0–20 cm under an intensive wheat-maize cropping system on Anthrosol in North China. The study involved three treatments: CK, control without fertilization; NPK, nitrogen (N), phosphorus (P) and potassium (K) fertilizers; MNPK, manure (M) combined with N, P and K fertilizers. Soil samples were collected and analyzed to determine the size distribution of aggregates, which were separated by dry sieving; the concentrations of OC and N in aggregates (>2, 0.25–2 and <0.25 mm) and bulk soils; and respiration from aggregates and bulk soils in the 0–10 and 10–20 cm layers after 21 years. Fertilization did not affect the size distribution of aggregates in the surface soil layer, but there was a significant change in the subsurface layer in response to manure addition. Application of NPK and MNPK significantly and evenly augmented OC and N sequestration in the three aggregate classes tested. However, the OC mineralization rate was substantially higher in micro- than in macro-aggregates. Application of NPK and MNPK considerably increased OC mineralization in both aggregates and bulk soils; MNPK yielded the highest values. OC mineralization rates in bulk soils were comparable among the three treatments for the surface layer, but they increased in the subsurface layer because of adding manure. Overall, soils treated for 21 years with NPK and MNPK showed increases in the OC pools in the top 20 cm of 7.42 and 22.83 Mg C ha^{-1}, respectively, compared with the control treatment, and had average sequestration rates of 353 and 1087 kg C ha^{-1} yr^{-1} respectively. Thus, appropriate application of NPK, alone or in combination with manure, can lead to improved OC sequestration by evenly augmenting aggregate-associated OC and providing the same degree of protection for OC in both macro-aggregates and micro-aggregates under a winter wheat-summer maize rotation on Anthrosol.

1. Introduction

Soil organic carbon (SOC) sequestration is of great interest, partly for the essential role that it plays in climate change and feedback processes, and partly because SOC is the most significant determinant of soil fertility, and thus of crop productivity and sustainability (Lal, 2004; Stockmann et al., 2013). The SOC level in a given soil is a result of the long-term balance between additions and losses of organic carbon. Various studies carried out under cropping systems have shown that increases in SOC levels in arable soils are directly related to the amounts of organic residues added to those soils, in the form of, for example, organic manure or straw return (Manna et al., 2013; Fan et al., 2014; Li et al., 2016; Zhang et al., 2015). On the other hand, the loss of OC from a given soil in a cultivated cropping system is related partly to the SOC content (Drury et al., 2004) and partly to soil aggregation, which can provide OC with physical protection against rapid decomposition (Pulleman and Marinissen, 2004).

Long-term application of mineral fertilizers and/or organic amendments change the size distribution and stability of aggregates (Holeplass et al., 2004; Wang et al., 2011; Yu et al., 2012a; Xie et al., 2015a, b); they increase the amount of aggregate-associated OC and modify the distribution of OC in aggregates (Holeplass et al., 2004; Yu et al., 2012a; Xie et al., 2015b). Yu et al. (2012a) reported that the addition of compost increased OC concentrations in all water-stable

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aggregates, but that adding synthetic NPK fertilizer increased OC accumulation mainly in the free silt and clay fraction. Sodhi et al. (2009) reported that the application of NPK and NPK plus manure increased OC and/or N concentrations more in water-stable macro-aggregates than in micro-aggregates. These results indicate that OC and N sequestration in aggregates varies between soil types. In addition, macro-aggregates were shown to produce more CO_2 than did micro-aggregates after combined application of manure plus NPK to an Aquic Inceptisol for 18 years (Yu et al., 2012b). However, Rabbi et al. (2013, 2014 and 2015) reported no significant difference in the content of potentially mineralizable carbon in macro- and micro-aggregates in Oxisols, and concluded that the extent to which OC was protected was similar in macro-aggregates and micro-aggregates. As with OC and N sequestration in aggregates, results for OC mineralization also vary among soil types, soil properties and climate conditions (Marinari et al., 2010). Carbon sequestration in different soils in response to fertilization practices may therefore be associated with different mechanisms of aggregate stabilization. Understanding how aggregates store and protect OC under long term fertilization practices in a specific soil type and under given climate conditions is, therefore, essential to develop appropriate management practices with which to sustain crop productivity and at the same time enhance SOC sequestration at regional and global scales.

The winter wheat-summer maize double cropping is the principal cropping system in northern China, occupying around 16 Mha, and the output from this system accounts for about a quarter of the total national food production (Yang et al., 2014). Previous studies showed that long term fertilization regimes had a profound impact on the dynamics of SOC concentrations (Yang et al., 2012, 2014) in Anthrosol and SOC sequestration in Aquic Inceptisol (Fan et al., 2014) under this cropping system. However, limited information is available about OC sequestration in aggregates and its stability (as estimated from carbon mineralization) in Anthrosol in response to long term fertilization regimes. The objectives of the present study were to assess the effect of 21 years' continuous application of mineral fertilizers with/without organic manure on aggregate-size distribution in the surface and subsurface soils; to evaluate levels of aggregate-associated OC and N; to estimate the stability of aggregate-associated OC by means of a mineralization incubation technique; and to quantify the rate of SOC sequestration in Anthrosol derived from loess.

2. Materials and methods

2.1. Study site and experimental design

A long-term experiment was established in October 1990 at the Chinese National Soil Fertility and Fertilizer Efficiency Monitoring Base for Loessial Soil (N 34° 17′51″, E 108°00′48″, with an altitude of 524.7 m a.s.l.), which is located on level land in Yangling, Shaanxi, China. The soil at the site is a silt clay loam (clay 32%, silt 52% and sand 16%; Anthrosols with a terric horizon derived from manure and loess material, WRB, 2014 or Earth-cumuli-Orthic Anthrosols, Chinese Soil Taxonomy, 2001). It is a major soil type in the Guanzhong Plain of north China, occupying an area of 97.6×10^4 ha (Guo, 1992) and accounting for 34.1% of the arable land in Shaanxi Province (Yao, 2013). On average, at the time of establishment the top layer of soil (0–20 cm) contained 7.44 g kg^{-1} organic C, 0.93 g kg^{-1} total N, 9.57 mg kg^{-1} Olsen P, 191 mg kg^{-1} exchangeable K and 92.5 g kg^{-1} $CaCO_3$, and it had a pH of 8.62 across all plots, with little inter-plot variation, as previously reported by Yang et al. (2012). The experimental site has a mean annual temperature of 13.0 °C and mean annual precipitation of ca. 550 mm, which falls mainly from June to September.

The field experiment included nine treatments in total, with each plot measuring 14 × 14 m; it is based on a winter wheat (*Triticum aestivum* L.)-summer maize (*Zea mays* L.) rotation with two crops per year, which is the most prevalent cropping system in the region. Three of the nine treatments were assessed in this work. The first treatment examined had no fertilizer or manure inputs (control, hereafter referred to as CK). The second treatment (NPK) consisted of annual inorganic fertilizer inputs of 165.0 kg ha^{-1} nitrogen (N), 57.6 kg ha^{-1} phosphorus (P) and 68.5 kg ha^{-1} potassium (K) in the winter wheat season and 187.5 kg ha^{-1} N, 24.6 kg ha^{-1} P and 77.8 kg ha^{-1} K in the summer maize season. The third treatment was NPK plus dairy manure (MNPK, where M refers to dairy manure). In the winter wheat season, the MNPK plot received 1.5-fold greater applications of N (30% from mineral N and 70% from organic manure) and inorganic P and K than the NPK plot. In the summer maize season, the MNPK plot received the same rates of N, P and K from inorganic fertilizers as in the NPK treatment, without any addition of organic manure. The C and N contents of the manure were about 26.45% ± 7.82 (SD) and 1.32% ± 0.91 (SD) respectively. In the MNPK treatment, the mean annual dry weight of organic manure applied was 20.6 t ha^{-1} ± 10.8 (SD) over the course of the experiment. All inorganic fertilizers and organic materials applied were incorporated into soil by rotary tilling to a depth of ca. 15–20 cm before the winter wheat was sown and about one month after the maize was planted; N was applied as urea, P as single super-phosphate and K as potassium sulfate. Winter wheat was sown in October and harvested in the following June, then summer maize was planted, and it was harvested about three months later at the end of September or early October. Each year the plots were irrigated, with ground water, 1 to 2 times during the winter wheat season and 1 to 3 times during the summer maize season, when necessary, with approximately 90 mm of water on each occasion. At maturity, crops were harvested manually with sickles, cutting close to the ground, from three areas, each of 8 m^2 and 20 m^2 for wheat and maize respectively, to estimate their yields for each treatment. All above-ground crop residues were removed after harvest. The fields were conventionally tilled.

2.2. Soil sampling and analysis

Undisturbed soil samples were collected on June 1st, 2011, one week before the winter wheat harvest. Each plot was divided into three sections of equal size, and three undisturbed soil cores (10 cm in diameter and 10 cm in height) were collected and bulked from each section to give three replicate composite samples. This sampling was carried out at two depths, 0–10 and 10–20 cm. Field-moist soil was weighed, subsamples were collected to measure bulk density, and the remainder was gently broken apart along natural break points and passed through a 10-mm sieve; plant and organic debris in the sieved soil was carefully removed with forceps, and the soil was air-dried. Subsamples of 200 g were then shaken through a motorized sieving device with pore diameters of 2 and 0.25 mm for 5 min to obtain three size fractions: > 2, 0.25–2 and <0.25 mm. The soil retained by each sieve was weighed.

The aggregate-associated OC and that of bulk soil were determined by potassium dichromate ($K_2Cr_2O_7$) oxidation at 170–180 °C followed by titration with 0.1 mol L^{-1} ferrous sulfate (Bao, 2005). Total N concentration was measured by the Kjeldahl method after H_2SO_4 digestion in the presence of K_2SO_4-$CuSO_4$-Se as a catalyst (Bremner, 1996). The mineralization of the bulk soil and of soil aggregates at depths of 0–10 and 10–20 cm was determined by incubating 100 g samples of the non-fractionated soil and of the >2 mm, 0.25–2 mm, and <0.25 mm aggregate size fractions in closed jars in a growth chamber at 25 °C and 60% of field water holding capacity. The respired CO_2 was trapped in 0.5 N NaOH and quantified by titrating the excessive NaOH with 0.4 N H_2SO_4. The CO_2 output from each sample was determined after 2, 4, 7, 10, 14, 21, 28, 35 and 42 days' incubation. Cumulative CO_2 production values (after 14 and 42 days) were used to make comparisons between aggregate size fractions and soils subjected to different fertilization regimes.