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Distribution and storage of crop residue carbon in aggregates and its contribution to organic carbon of soil with low fertility

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ABSTRACT

Long-term intensive cultivation leads to the decrease of soil organic carbon (SOC) and soil fertility. Crop residue amendment to soil is documented as an effective measure to increase SOC and improve soil productivity. However, there is limited information on the turnover and storage of crop residue carbon (C) in soil aggregates after the residue is added to soil with low fertility. The objectives of this research were to investigate the distribution and storage of residue C in soil aggregates and its contribution to different physical fractions of SOC, and to quantify the turnover of residue C in soil with low fertility. Soil samples added with ^{13}C-labelled maize straw residue were put into carborundum tubes for two-year long *in-situ* incubation. Soil aggregates were separated by wet sieving and then physically fractionated. During the whole incubation process, 12–15% of residue C was stably distributed to 2000–250 μm aggregates, while the percentage of residue C distributed to microaggregates (<250 μm) increased with incubation time. The contribution of residue C to particulate organic C (POC) fractions decreased from average 63% on day 60 to average 43% on day 720 and that to mineral-associated organic C (mSOC) fraction increased from average 23% on day 60 to average 28% on day 720. More than 50% of fine POC (fPOC) was derived from residue C, especially 71% in microaggregates on day 360. Within aggregates, the percentages of residue C distributed to free light organic C (fLOC) and coarse POC (cPOC) reduced and these to fPOC and mSOC strengthened with incubation time. Mean residence time (MRT) of residue C was shortened with the increase of the aggregate sizes. MRT of mSOC was longer compared to other SOC physical fractions. These results suggest that microaggregates could provide favorable conditions for microbial activities and conduce to fPOC accumulation in a low fertility soil amendment with crop residue.

1. Introduction

Aggregates serve as a stable pool of soil organic carbon (SOC) (Blanco-Canqui and Lal, 2004) and the basis of soil fertility (Chen et al., 2001). SOC is protected from microbial decomposition by physical occlusion within aggregates (Elliott, 1986; Ingram et al., 2005; Six et al., 2000; McCarthy et al., 2008), or by chemical adsorption on the surfaces of clay particles (Hassink et al., 1993; Hassink and Whitmore, 1997; Oades, 1988). While free organic carbon (C) located outside of aggregates is susceptible to be decomposed by microorganisms (John et al., 2005; Liao et al., 2006; Six et al., 2004). Therefore, the location of SOC in the hierarchical structure of soil aggregate system determines the sequestration and transformation of SOC (Golchin et al., 1994a; Yamashita et al., 2006; Guan et al., 2015).

The crop residue applied into soil provides substrate for microorganisms (An et al., 2015; Poirier et al., 2014). As the metabolic products of microorganisms, the residue C is stored in different fractions of soil aggregates or attached on clay particles during the processes of organic transformation and aggregate formation (Guggenberger et al., 1995; Six et al., 2004). Residue addition could alter the distribution of SOC in aggregates and increase the SOC content in aggregates, especially in macroaggregate (>250 μm) (Guan et al., 2015; Hao et al., 2013; Liu et al., 2010;

Abbreviations: SOC, soil organic carbon; POC, particulate organic carbon; mSOC, mineral-associated organic carbon; fPOC, fine POC; fLOC, free light organic C; cPOC, coarse POC; MRT, mean residence time.

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Sun et al., 2012). The dynamics of SOC sequestration in soil aggregates have been studied widely (Anaya and Huber-Sannwald, 2015; Chung et al., 2008; Gulde et al., 2008; Steffens et al., 2011). However, the majority of these studies did not differentiate the residue C from native SOC after the incorporation of residue into soil. Residue C is preferentially accumulated in the macro-aggregates in the form of particulate organic C (POC) after crop residue is mixed with soil with high clay content (Steffens et al., 2011). The distribution of residue C in fine fractions is related to the initial SOC content (Poirier et al., 2014). However, few studies have been conducted to address the distribution and sequestration mechanisms of crop residue C in soil aggregates with low clay and low SOC contents.

Long-term cultivation decreases SOC (Qiu et al., 2009; Wang et al., 2002; Yu et al., 2006). The amendment of crop residue to soil is thought as an effective measure to increase the content of SOC, create soil structure and improve soil fertility (Courtier-Murias et al., 2013; Hu et al., 2013; Jiang et al., 2012; Xu et al., 2009). However, it is not clear about the distribution and dynamics of residue C sequestrated in the aggregates with low soil fertility. Previous studies have mostly focused on laboratory incubation for short-term (no longer than one year) under constant temperature and moisture conditions (Aminiyan et al., 2015; Guan et al., 2010; Hou et al., 2015; Wang et al., 2015). The obtained results might not be sufficient to evaluate the long-term process of residue C sequestration and transformation in the field, where soil thermal and moisture conditions substantially change during years. Therefore, the objectives of this study were to investigate the distribution of residue C in different sizes of aggregates with ^{13}C-labelled maize straw residue and to quantify the contribution of residue C to soil aggregation and the turnover of residue C in soil aggregates. This research would provide theoretical insights for mechanisms of SOC sequestration at aggregate scales.

2. Materials and methods

2.1. Experimental materials

Soil samples were taken from a long-term experimental site (41°49′ N, 123°34′ E) of Shenyang Agricultural University, Shenyang, Liaoning Province, China. The long-term tillage experiment was established in a monoculture maize field in 1987. The site has a typical continental monsoon climate with mean annual temperature of 7.9 °C and mean annual precipitation of 705 mm. The mean annual accumulated temperature above 10 °C is 3350 °C. Approximately 85% of annual precipitation occurs from April to September. The soil is classified as Hapli-Udic Cambisol (FAO Classification). Maize (*Zea mays* L.) was sown in early May and harvested in early October every year (Wang et al., 2006).

Soil samples were collected from the no fertilizer plot, whose fertility was low in terms of the content of SOC as compared to the average level of the same soil type in the region, at the depth of 0–20 cm in the spring of 2011. After sampling, crop roots and other debris were removed, and the soil was air-dried prior to passing through a 2 mm sieve. The soil samples contained 9.0 g kg^{-1} SOC, 1.2 g kg^{-1} total nitrogen, 7.5 ratio of carbon to nitrogen (C/N), pH (H_2O) 6.4, 17.3% clay, and −18.4‰ δ^{13}C value (An et al., 2015).

^{13}C-labelled straw residues were obtained from matured maize plants, which were pulse-labeled using $^{13}CO_2$ for four times throughout the whole growing stage in 2005 (Xue, 2007). The collected maize straw residue was dried at 60 °C for 12 h, and then finely ground (<0.5 mm) for storage in sealed jars. The ^{13}C-labelled straw residue had 401 g kg^{-1} total C, 9.96 g kg^{-1} total nitrogen, and 138‰ δ^{13}C value.

2.2. In-situ *incubation experiments*

Air-dried soil samples (100 g) were thoroughly mixed with 5 g of maize straw residue and then put into the carborundum tubes, which were cylindrical and had the flat base. As described in the research of An et al. (2015), the carborundum tubes had dimensions of 3.8 cm inner diameter, 5.5 cm outer diameter, and 15.5 cm height, and were perforated with pores of 70 μm × 140 μm. The pores could prevent crop roots and soil animals (e.g., earthworm) from entering into the tubes while allowing the exchange of water, gas and dissolved organic matter across the tubes (Lin et al., 1981). In order to activate soil microorganism, all tubes were immersed with the soil slurry to adjust soil moisture content to water holding capacity according to the method by Wang et al. (1995) and An et al. (2015). Soil without the addition of maize straw residue was processed with the same way as the soil added with maize straw residue. All tubes were sealed with carborundum lids, and then vertically buried into the no fertilizer plot (5 cm distance from soil surface to the top of tube) on May 6, 2011. The tubes of the two treatments (soils added with and without straw residue) were kept at 2 m distance for one another. The total of 12 tubes were randomly and destructively sampled as replicates from each treatment on July 5, 2011, November 2, 2011, April 30, 2012 and April 25, 2013. That is, the 60th day, 180th day, 360th day and 720th day from the beginning of incubation. Soil sub-samples were air-dried, weighed, and then used for soil aggregate extraction.

2.3. Soil aggregate extraction

Soil aggregates were extracted by wet sieving soils through 2000, 250, and 53 μm sieves (Elliott, 1986). Aggregate extraction was performed using a Soil Aggregate Analyzer (Model SAA 8052, Shanghai, China). Briefly, 100 g soil sub-sample was submerged with deionized water on the top of a 2 mm sieve for 5 min at room temperature (20 ± 1 °C). And then the series of sieves were automatically moved up and down 3 cm at a speed of 30 repetitions per min for 30 min. Four size classes of aggregates were collected in turn, air-dried, and weighed. A portion of soil aggregate samples were ground (<0.25 mm sieve) for analysis of organic C content and δ^{13}C value, while the remaining aggregate samples were oven-dried at 60 °C for subsequent organic C fractionation.

2.4. Organic carbon fractionation

The free light organic C (fLOC) fraction, particulate organic C (POC) fraction and mineral-associated organic C (mSOC) fraction were separated from 2000 to 250 μm size class aggregates and 250 to 53 μm size class aggregates according to the method described by Golchin et al. (1994b) and Six et al. (1998). A 5 g soil aggregate sample was immersed in 35 mL of a 1.85 g mL sodium iodide (NaI) solution in a conical centrifuge tube (50 mL). Tubes were gently shaken for several times by hand, and materials remaining on the inside wall of the tubes were washed with 10 mL NaI. Tubes were then placed under vacuum of −138 kPa for 10 min to exhaust air enclosed in the soil aggregates. After 15 min equilibration, the tube was centrifuged for 1 h at 1807 × *g* at 25 °C. The supernatant was obtained by vacuum filtration using a 0.45 μm membrane. Remaining NaI was removed by washing with deionized water. The floating substances remaining on the filter were fLOC. The sample passing through the filter was dispersed in 5 g L^{-1} hexametaphosphate sodium by shaking for 18 h on a reciprocal shaker. The dispersed fraction was passed through 250 μm and 53 μm sieves to collect coarse POC (cPOC, >250 μm), fine POC (fPOC, 250–53 μm), and mSOC (<53 μm). All of the physical