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Long-term fertilization effects on organic carbon fractions in a red soil of China

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ABSTRACT

Long-term fertilization has a significant impact on total soil organic carbon (SOC) stock. However, fertilization impact on physical fractions of SOC is still poorly understood for red soils in southern China. This study assessed the impact of 17 years (1990–2007) of long-term fertilization on the changes in different SOC fractions under an intensive maize (*Zea mays* L)–wheat (*Triticum Aestivium L*) cropping system in a red soil of southern China through various treatments: the unfertilized control (CK), the recommended applied rates of N (N), NP (NP), NPK (NPK), NPK + manure (NPKM), NPK + straw (NPKS) and manure only (M), and a 150% recommended applied rate of NPK + manure (1.5NPKM). Soil samples from 0 to 20 cm soil layer taken in September, 2007, were separated into free particulate organic C (fPOC), intra-microaggregate particulate organic C (iPOC), and mineral associated organic C (MOC) with physical fractionation. In comparison with CK, all the C fractions and maize and wheat yields were significantly increased, except for N and NP treatments. The treatments with manure (M, NPKM, and 1.5NPKM) showed higher C sequestration rates in MOC (323–515 kg ha^{-1} yr^{-1}), fPOC (291–408 kg ha^{-1} yr^{-1}) and iPOC (162–179 kg ha^{-1} yr^{-1}). It was estimated that 8.0 to 35.7% of the gross C input from manure and crop residues over a period of seventeen years contributed to the increase of total SOC stock. Both MOC C sequestration efficiency (CES) and C sequestration distribution (CSD) were the highest among the C fractions for all the treatments. Significantly positive linear correlations were observed between accumulated C sequestrations in all fractions with gross C input and both maize and wheat yields. Our result indicated that MOC was the primary fraction of C sequestration in the red soils. The most efficient fertilization practice for sequestering C in each fraction in the red soils was continuous applications of either manure or manure plus mineral fertilizers.

1. Introduction

Red soil occupies an area of 1.13 million km^2, accounting for 6.5% of the total arable land in China (Xu et al., 2006b). Unfavorable intrinsic properties and inappropriate land use may be responsible for lower productivity in red soils of tropical and subtropical regions of southern China (Zhang et al., 2009a). Soil organic carbon (SOC) plays an important role in cycling plant nutrients, increasing grain yield and improving the physical, chemical and biological properties of soils (Bhattacharyya et al., 2008, 2010; Manna et al., 2007; Rasool et al., 2008). Therefore, understanding the dynamics and mechanism of carbon sequestration under different management practices in the red soils was a primary way to improve soil fertility and to sustain grain yield production in this region.

Soil organic matter (SOM) is a heterogeneous and dynamic substance that varies in C and N content, molecular structure, decomposition rate and turnover time (Oades, 1988). In most current SOM studies, SOM was classified into different pools by their intrinsic decomposition rates and controlling factors, such as microbial biomass C (MBC) (Wu et al., 2005), particulate organic C (POC), potentially mineralizable C (Cambardella and Elliott, 1992), and $KMnO_4$ oxidizable C ($KMnO_4$-C) (Blair et al., 1995). These C fractions are likely to be more sensitive to management practices than the total SOC and could serve as indicators of future changes in total SOC stock (Campbell et al., 1997). However, these fractions are generally loosely associated with measurable quantities (Six et al., 2002a). Several studies have elucidated the relationship between aggregate and associated SOC dynamics (Jastrow, 1996; Six et al., 1998, 2000). A hypothesis on aggregate hierarchy was proposed, i.e. microaggregates are bound together into a macroaggregate and microaggregates are much more stable and less dependent on agricultural managements than macroaggregates. Further, free

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primary particles are bound together into microaggregates (50–250 μm) by persistent binding agents (e.g. humified OC). Six et al. (2002a) proposed a physical fractionation procedure and the associated conceptual SOC model that separated the bulk SOC pool into conceptual fractions according to different protection mechanisms: free particulate organic C (fPOC, unprotected SOC inter-aggregate), intra-microaggregate particulate organic C (iPOC, physically protected SOC) and mineral-associated organic C (MOC, chemically and biochemically protected SOC). This conceptual model gave an opportunity to understand the process and mechanism of C sequestration with different management practices (Smith et al., 2002).

Several studies have reported the relative increases in SOC contents within different particle-size fractions (Tong et al., 2009) and $KMnO_4$ oxidizable C (Xu et al., 2006a) under long-term fertility experiments in red soils of southern China. None of these studies, however, used fractionation techniques which specifically aim at isolating fractions that can be linked to the conceptual SOC model. We took soil samples, in the plough layer from different treatments of a long-term fertilization experiment in southern China, and fractionated into size and density fractions using a methodology similar to the one proposed by Six et al. (2000). The objectives of this study were: (i) to determine C changes in the C fractions; (ii) to estimate the conversion rate of C input to SOC over a 17-year period (1990–2007); and (iii) to explore the relationships between crop yields and C sequestrated in these SOC fractions.

2. Materials and methods

2.1. Site description

A long-term fertilization experiment was initiated in September 1990 at the experiment station of the Chinese Academy of Agricultural Sciences, Qiyang (26°45′N, 111°52′E, 120 m altitude), Hunan Province, China. The climate was subtropical humid monsoon, with mean annual precipitation of 1431 mm and mean annual temperature of 18 °C.

Prior to the experiment, the field was under maize–wheat rotation for three years with recommended mineral fertilization to ensure no apparent spatial difference in soil physical and chemical properties in the plowing zone over the field. The soil was classified as Ferralic Cambisol (FAO, 2006), with clay texture. The initial (1990) topsoil (0–20 cm) had a total SOC of 8.58 g kg^{-1}, total N 1.07 g kg^{-1}, total P 0.45 g kg^{-1}, total K 13.28 g kg^{-1}, bulk density 1.1 Mg m^{-3}, pH (1:1 w:v) 5.7, and available N, P, and K of 79, 10.8, and 122 mg kg^{-1}, respectively. More details on the soil properties have been addressed elsewhere (Zhang et al., 2009b).

2.2. Experimental design and crop management

This experiment consisted of 11 fertilizer treatments, of which eight treatments were chosen for this study (Table 1). These were unfertilized control (CK), 100% recommended rate of N (N), 100% recommended rate of N and P (NP), 100% recommended rate of N, P and K (NPK), 100% recommended rate of N, P and K with straw (NPKS), manure only (M), 100% recommended rate of N, P and K with manure (NPKM) and 150% recommended rate of N, P and K with manure (1.5NPKM). Minerals N, P and K were urea, calcium superphosphate and potassium chloride, respectively. The manure was pure pig manure with an average composition of 413.2 g kg^{-1} C and 16.7 g kg^{-1} N (on a dry weight basis). In the NPKM and 1.5NPKM treatments, P and K were applied through mineral fertilizers and N was applied through manure and mineral fertilizer together (following the ratio of 2.3:1). Aboveground biomass was removed from the fields except in the plots under the NPKS treatment, where entire straws were returned to the plots. Wheat and maize residues (i.e. root and straw) contained 399 and 444 g kg^{-1} C (on an oven-dry basis), respectively (NCATS, 1994). The contents of N and P were 6.1 and 0.81 g kg^{-1} in wheat residues, 9.5 and 1.3 g kg^{-1} in maize residues. However, the N content from the residues did not compensate the amount of N application in the NPKS treatment.

Table 1
Annual application of inorganic N, P, and K fertilizers and pig manure under various fertilization treatments.

Treatments	Inorganic N (kg ha^{-1})	Inorganic P (kg ha^{-1})	Inorganic K (kg ha^{-1})	Pig manure (Mg ha^{-1})[Ψ]
CK	0	0	0	0
N	300	0	0	0
NP	300	53	0	0
NPK	300	53	104	0
M	0	0	0	13.3
NPKM	90	53	104	13.3
1.5NPKM	134	79	157	20.0
NPKS	300	53	104	6.6[Φ]

[Ψ] In dry weight.
[Φ] Wheat and maize straw return to the soil.

Each treatment was replicated twice (plot size 20 m × 9.8 m) in a randomized block design. Each plot was isolated by 100 cm cement baffle plates. For each year, winter wheat (*Triticum Aestivium* L.; cultivar 'Xiangmai 4') was sown in strips around November 10 each year and harvested in early May in the following year. Summer maize (*Zea mays* L.; hybrid 'Yedan 13') was sown between the wheat strips in early April, and harvested in July of the same year. No irrigation was given to both crops because the plots received high annual rainfall (mean = 1431 mm; n = 17) during the experimental period. Herbicides and pesticides were applied during crop growth periods when required. Crops were harvested manually by cutting straws close to the ground. Thus, stubble left in the field was negligible. Mineral fertilization was applied before sowing of each crop (30% of mineral N, P and K were applied for the wheat crop and 70% for the maize crop). However, the entire amount of manure was applied before wheat seeding. Grains and straws were air dried, threshed, oven dried at 50 °C to a uniform moisture level, and then weighed separately.

2.3. Soil sampling

Samples from the topsoil (0–20 cm) were taken in September 2007, using a soil auger (5 cm diameter). Crop residues on the soil surface were carefully removed before soil sampling. Three separate composite soil samples were collected from each plot by taking 20 cores for each composite sample in a stratified random design. That means there were six samples for each treatment. In the laboratory, bulk densities were determined for each soil core. Another set of fresh soil samples were gently broken apart by hand and were passed through a 5 mm sieve to break down large macro-aggregates. The samples were then air dried.

Archived initial soil samples, which were taken in 1990 just before the experiment stared from the 0–20 cm layer, were obtained for analysis of SOC fractions. These crude subsamples were stored at room temperature until further analysis.

2.4. Physical fractionation of SOC and C content analysis

Soil samples from each plot of the treatments were used for the physical fractionation using the modified method reported by Gale et al. (2000). Briefly, a 10 g of soil sampled soil was prewetted overnight in a refrigerator. Then, the prewetted soil was wet sieved based on the procedure described by Six et al. (2000) (Fig. 1). The soil was placed on a 250 μm sieve and gently shaken with 4 mm glass beads by hand and a constant water flow through the sieving column avoiding further disruption of the microaggregates by the beads. The water + soil fraction was wet sieved through a <53 μm sieve, and the fraction passed through the 53 μm sieve was collected in buckets. The coarse free particulate organic C (cfPOC) and sand which had been retained on the 250 μm sieve was collected, dried at 60 °C and weighed. The same procedure was followed