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Soil organic carbon dynamics within density and particle-size fractions of Aquic Cambisols under different land use in northern China

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ABSTRACT

A long-term crop residue incorporation and tillage experiment was initiated in 1999 on cropland that was converted from natural grassland in 1974. Three management factors included in the experiment were land use, tillage systems (tillage/no-till) and methods of maize (*Zea mays* L.) straw incorporation (whole straw, and pulverized straw and no straw). Soil samples were obtained in 2010, and ^{13}C natural abundance analysis was used to estimate the maize-derived C in density fractions (light fraction, LF; heavy fraction, HF), particle-size fractions (>50 μm, 50–5 μm, 5–2 μm, 2–0.2 μm and <0.2 μm), and original SOC decomposition. There occurred a 14–23% decrease in the SOC concentration or a loss of 0.166–0.225 Mg C ha^{-1} yr^{-1} upon conversion of natural grassland to cropland. Organic carbon (OC) in the LF was a sensitive indicator reflecting this reduction in SOC concentration. Conversion to no-till did not significantly increase the SOC concentration, compared with tillage systems. The data on OC concentration in particle size fractions and those on maize-derived OC in clay and silt fractions indicate that the most stable OC was associated with the silt fraction, while OC bound to clay was important in the short to medium term. Incorporation of pulverized straw over 11 years contributed 2 to 2.4 Mg of maize-derived C ha^{-1} into the SOC stock, significantly higher than that by incorporation of whole straw. However, because the whole straw incorporation retained more of the antecedent SOC, it effectively increased the SOC stock. These data suggest that incorporation of whole straw combined with tillage could be an effective practice for improving the SOC stock in croplands of the North China Plain.

1. Introduction

Land use change, especially from natural grassland to cropland, can significantly impact soil organic carbon (SOC), often decreasing both the SOC concentration and stock (Lal, 2004; Puget and Lal, 2005). Numerous studies have also been conducted to assess changes in SOC by incorporation of crop residues and tillage methods (Luo et al., 2010). Straw incorporation can sequester SOC at the rate of 0.21 to 0.69 Mg C ha^{-1} depending on ambient conditions and experimental treatments (Paustian et al., 2000). Over the last 40 years, a large proportion of non-agricultural lands (mainly saline–alkaline soils and wetlands) in the North China Plain (NCP) have been converted to cropland for cereal production. Grain yields have been greatly increased with increasing application of nitrogen (N) and water and by the introduction of high-yielding cultivars. However, there have been limited studies on assessing the dynamics of the SOC concentration under changing agricultural practices, particularly in relation to soil density and particle-size fractions in the NCP.

With increasing urbanization, mechanical straw incorporation and tillage are two among the major agricultural techniques widely adopted to improve soil fertility and increase grain yields. Maize (*Zea mays* L.) straw is either mechanically pulverized into small pieces (<5 cm) or incorporated into the soil as a whole. An essential question is whether these two contrasting methods of straw incorporation with conventional tillage (CT) or no-till (NT) have different effects on the SOC stock.

Natural isotope carbon (^{13}C) abundance has been widely used to study SOC transformations and distribution in soils affected by land use change, tillage methods and straw management (Balesdent et al., 1987; Bonde et al., 1992; Gregorich et al., 1995; Wick et al., 2009). The conversion of grasslands, formerly under native C-3 vegetation and subsequent introduction of or succession by C-4 plants, is an in situ labeling process of newly incorporated organic carbon (OC) into the soil (Cerri et al., 1989; Balesdent et al., 1987; Gregorich et al., 1995; Solomon et al., 2002), especially in terms of the density and particle-size fractions (Schwendenmann and Pendall, 2006). Physical fractionation of SOC, based on either density or particle size, is less destructive compared with chemical fractionation, and the data obtained are more sensitive and directly related to the in situ functions of SOC

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(Golchin et al., 1994; Gregorich et al., 1995; Six et al., 2002). Besides total SOC stock, the quantity, structure and stability of different SOC pools are necessary to accurately detect the mechanisms of changes in SOC under different farming systems (John et al., 2005). Consequently, the impact of agricultural management on the distribution of OC within different soil fractions can be more accurately estimated by the integration of ^{13}C analysis with density and particle-size fractions (Schwendenmann and Pendall, 2006; Wick et al., 2009).

Total land area in the NCP is approximately 31 million ha (M ha), most of which (18 M ha) is used for agriculture. The predominant cropping system in the NCP is a winter wheat (*Triticum aestivum* L.)-summer maize rotation, covering up to 60% of arable land in this region. The NCP supplies more than 50% of the nation's wheat and 33% of maize (Liang et al., 2012). Obviously, agricultural sustainability including the SOC concentration in the NCP could have a large impact on China's food security and the environment. Therefore, the purpose of the present study was to assess the impact of land use, maize straw incorporation and tillage methods on the distribution of SOC in different density- and particle-size-associated fractions in widely distributed Aquic Cambisols in the NCP. In addition, the distribution pattern of newly incorporated OC from C-4 crops and the turnover of antecedent OC from C-3 crops in different soil fractions were also assessed. We hypothesized that: i) conversion of natural grassland to cropland decreases the SOC concentration and stock; ii) adoption of NT sequesters more SOC compared to tillage treatments; and iii) incorporation of pulverized rather than whole straw increases the SOC stock.

2. Materials and methods

2.1. Experimental site

The experimental site is located at the Quzhou Experimental Station of China Agricultural University in Quzhou County, Hebei Province, north China (36°52′N, 115°01′E, 40 m a.s.l.). The climate of the region is warm, semi-arid, continental temperate monsoon. The mean annual temperature is 13.1 °C, and the frost-free period is 201 days. The mean annual rainfall is 556 mm and occurs mainly from July to September. Originally, the region was largely covered by saline–alkaline soils with long periods of shallow groundwater and the lack of efficient drainage systems. Drainage systems were introduced in the 1970s to lower the groundwater table and reduce salt concentrations in the root zone. In 1975, salt concentration in soil was 3.8%, comprising 41% $CaCl_2$ and 29% $MgCl_2$ (Shi et al., 1991). In 1999 (Kong et al., 2003) salt concentration in soil declined to 0.2%. Rates of fertilizer application increased drastically, and high-yielding varieties were introduced. Wheat and maize yields in the experimental county (Quzhou County) increased from 1500 kg ha^{-1} in the 1970s to 7425 and 8535 kg ha^{-1} in 2010, respectively (Xin and Li, 1990; Quzhou Statistic Bureau, 2012).

Between 1974 and 1999, predominant crops in the region were winter wheat and cotton (*Gossipium hirsutum*). After 1999, cotton was replaced by summer maize, leading to wheat–maize as the principal rotation in the NCP. The long-term field experiment was established to compare the impacts of tillage and crop residue incorporation on soil quality and agronomic yield. At the beginning of the experiment in 1999, the physico-chemical properties of the soil were pH of 7.8, SOC concentration of 7.5 g kg^{-1}, $CaCO_3$ of 0.64%, total nitrogen (N) concentration of 0.37%, Olsen phosphorus of 10 mg P kg^{-1}, and available potassium of 92 mg K kg^{-1}. Sand, silt and clay content were 49.0%, 40.8% and 10.2%, respectively. Soil of the experimental site is classified as an Aquic Cambisol according to FAO/WRB (Shi et al., 1991; Liang et al., 2012).

2.2. Experimental design

Natural grassland (NL, 300 × 200 m^2) was chosen to represent the native undisturbed reference plot without any cropping or other anthropogenic perturbation since 1974. Being the baseline, the plot was intentionally reserved to observe the impact of land use change and farming practices on soil properties including the SOC concentration. Naturally occurring plant species on NL were mainly C-3 plants such as green bustle grass (*Setaria viridis* L.), speak grass (*Imperata cylindrica* L.), Asian hazel (*Corylus heterophylla* L.), and stipe (*Stipa grandis* L.). In 1999, the long-term experiment on the cropland that was converted from natural grassland in 1974, was established with five treatments: 1) SW: whole maize straw incorporation, fertilization and no till (NT); 2) SC: maize straw mechanically pulverized and incorporated, fertilizer use and NT; 3) SCT: maize straw mechanically pulverized and incorporated, fertilizer use and tillage; 4) SWT: whole maize straw incorporation, fertilizer use and tillage; and 5) T: no maize straw incorporation, only fertilizer use and tillage. Different straw incorporation and tillage for the five cropland treatments were applicable for the wheat season only. For maize season, all practices, including straw incorporation, tillage, fertilizer use, and irrigation, were the same. Rate of application of fertilizer for wheat and maize was in accord with the local conventional practices, i.e., 264 kg N ha^{-1} and 108 kg P_2O_5 ha^{-1} for wheat and 254 kg N ha^{-1} and 80 kg P_2O_5 ha^{-1} for maize. The dimensions of each plot were 6 × 20 m. Details of agricultural management for all treatments are listed in Table 1. A 500-m wide buffer strip was established between NL and the cropland treatments. Before 1999, crop straws (wheat and cotton) were harvested from the experimental fields and used as household fuel by farmers. All treatments were laid out in triplicate according to the completely randomized design.

2.3. Soil sampling and analysis

After maize harvest in September 2010, five sub samples were collected at random from each plot from 0 to 20 cm depth, and were composited. Three composite soil samples, each consisting of five soil cores, were also obtained from NL as pseudo-field replicates. Visible plant detritus, roots, and gravel (>2 mm) were removed by hand. Soil samples were air dried, ground to pass through a 2-mm sieve, and stored at room temperature pending analyses. Soil bulk density (BD) was measured by the core method, using a 100-cm^3 cylinder (5 cm height × 5 cm diameter) (Lu, 2000).

2.3.1. Soil density fractionation

Twenty-gram air-dried samples were sieved through 2-mm mesh and placed into a polyethylene centrifuge tube with tap. NaI was used because it is less expensive than sodium polytungstate (SPT) and has similar recovery of LF at high density of 1.8 Mg m^{-3} (Sequeira et al., 2011). 80 cm^3 of NaI was added into the 20-g of soil. The centrifuge tube with soil and NaI was ultrasonicated (Model CX-250, Beijing Medical Equipment Factory) for 30 min to destroy soil aggregates and then dispersed on a reciprocal shaker at 190 rpm for 60 min. The solution was centrifuged at 1000 rpm for 15 min, and the supernatant was filtered through a 0.45-mm acetate microporous film (Beijing Henggao Engineering Company). The filter film was placed on a Buchner funnel connected to a vacuum pump. The filter and film were thoroughly rinsed with deionized water. The soil on the film was transferred into a beaker with deionized water, and this fraction was termed the light fraction (LF). Likewise, sediment in the tube was transferred into a beaker with deionized water, and this fraction was termed the heavy fraction (HF). The two soil fractions were oven-dried at 60 °C to a constant weight. Soil samples were treated with a 0.5 M HCl solution to remove carbonates prior to further analysis.

2.3.2. Soil particle-size fractionation

The composite samples were separated by ultrasonic dispersion into the following particle-size-associated OC fractions (hitherto referred to as particle-size fractions), i.e., >50 μm (sand and floatable organic matter), 50 to 5 μm (coarse silt), 5 to 2 μm (fine silt), 2 to 0.2 μm (coarse clay), and <0.2 μm (fine clay) (Anderson et al., 1981; Tiessen and