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Variations in cropland soil organic carbon fractions in the black soil region of China

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ABSTRACT

The use of three discrete soil organic carbon (SOC) pools proposed by the CENTURY model to study the SOC dynamics helps to understand the changes in cropland SOC pool and its stability. This study focuses on a typical black soil (mollisol) region in Northeast China. Based on historical soil data from samples that were collected in the 1980s, we selected 44 sampling points and collected 88 soil samples from the surface (0–20 cm) and subsurface (20–40 cm) layers in 2010. A 100-day laboratory incubation for each sample was conducted to measure the decomposition rates of SOC at different times, and data from the incubation experiment were fitted to a three-pool first-order model that divided the total SOC into active (C_a), slow (C_s) and resistant (C_r) SOC fractions. A method for predicting the concentrations of the three SOC fractions was developed and used to obtain the concentrations of SOC fractions in the 1980s at each sampling point. The results showed that a power function model ($D_{soct} = a \times t^b$) could be used as the universal SOC decomposition curve model. Using the universal model, the predictive method accurately estimated the concentrations of C_a, C_s and C_r of upland soils in this black soil region, which effectively solved the problem of a lack of soil samples and SOC fractions data in previous studies of the spatial-temporal variations of SOC fractions in regional soils. From 1980 to 2010, the estimated variations of the C_a, C_s and C_r in the surface upland soil were +0.37, −5.53 and −6.32 g kg^{-1}, and the corresponding contributions to the loss of the total SOC were -3.2%, +48.2% and +55.1%, respectively, while the variations of the C_a, C_s and C_r in the subsurface soil were +0.19, −0.43 and −2.45 g kg^{-1}, and the corresponding contributions to the loss of the total SOC were −7.1%, +16.0% and +91.1%, respectively. The decrease in the total SOC is primarily attributed to the decrease of the C_s and C_r fractions in the region, although the C_a fraction has significantly increased. The overall variations in the SOC fractions suggest a declining stability of the SOC pool in the black soil region of Northeast China.

1. Introduction

Soil organic carbon (SOC) is an important component of the global carbon cycle, and its huge pool size means that a small change may cause significant variations in atmospheric CO_2 concentrations (Schlesinger, 1997). Cropland SOC is the most active C pool in the terrestrial ecosystems, which is directly perturbed by anthropogenic activities, such as cropping systems, fertilization and irrigation, and indirectly affected by environmental factors, such as climate change, N deposition and soil erosion (Smith et al., 2005; Yan et al., 2011). Consequently, cropland SOC can change over a short time period (Yan et al., 2011).

Previous articles focused more on the changes in total SOC storage in Chinese cropland soils. Using the DNDC model, Li (2000) estimated that China's cropland soils lost 73.8 Tg C yr^{-1} (to a depth of 30 cm) due to a lower percentage return of crop residues (< 20%), compared with an estimated 72.4 Tg C yr^{-1} increase in US croplands. However, over the same period, some other reports came to the same conclusion that China's croplands played a role as carbon sink with a total SOC increase (0–20 cm) from the 1980s to the 2000s by using different estimation methods, in which, the cropland soils in most regions or provinces in China were sequestering C, but the upland soils in Chinese black soil

Abbreviations: BD, bulk density; C_a, active soil organic carbon; Clay, soil clay content; C_r, resistant soil organic carbon; C_s, slow soil organic carbon; C_{soc}, the total soil organic carbon; DNDC, DeNitrification-DeComposition; MAT, mean annual temperature; MRT, mean residence time; RMSE, root-mean-square error; Sand, soil sand content; Silt, soil silt content; SOC, soil organic carbon; SSSSC, the Second State Soil Survey of China; TK, total kalium; TN, total nitrogen; TP, total phosphorus

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(mollisol) region (Northeast China) were losing C over the last 30 years (Huang and Sun, 2006; Xie et al., 2007; Yan et al., 2011).

However, the SOC is a complex compounds that consists of multiple pools differing considerably in their physical, chemical, and biological properties (Tian et al., 2015), which results in much difficulty to determine the SOC dynamics and reveal its sequestration mechanism (Dou et al., 2016). In the CENTURY model, the SOC in mineralizable soil was divided into active SOC (C_a), slow SOC (C_s) and resistant SOC (C_r) fraction pools, according to the differences in mean residence time (MRT) (Parton et al., 1987). Different fraction pools respond differently to changes in management practices (Davidson and Janssens, 2006). Collins et al. (2000) studied the US Corn Belt soils and found that no-till significantly increased the C_a and C_s concentrations compared to conventional tillage. Wang et al. (2016) observed increases in all of the C_a, C_s, and C_r through an estimation of 1980 vs. 2010 in paddy soils of southwest China (0–20 cm), in which the C_s and C_r contributed more than 90% of the total SOC increase, due to the specific SOC stabilization mechanism in paddy soils. Compared with the paddy soil, Shao et al. (2006) concluded that the upland soil tended to be lower in C_a concentration but higher in C_s concentration in the same region. Also in the long-term tillage experiments, Zhao et al. (2012) found that no-tillage increased the C_a but decreased the C_s. As a result, how the three fraction pools changed with the total SOC decrease in Chinese black soils under long-term management, and the contributions of different fractions to the changes in the total SOC are still unclear, due to a lack of historical soil samples and SOC fraction data.

To solve these problems, this study collected 88 soil samples from four types of upland soils in the black soil region of Northeast China in 2010, based on the soil information from the Second State Soil Survey of China (SSSSC) conducted in the early 1980s, and aimed to (1) reveal the variation characteristics of different SOC fraction pools in the upland soils, (2) quantify the contributions of different SOC fractions to the loss of the total SOC in the black soil region, and (3) develop a method to predict the concentrations of the SOC fractions that can be used to study the spatial-temporal variations of cropland SOC fractions.

2. Materials and methods

2.1. Study area

The black soil (mollisol) region of Northeast China, an important national base for marketable grain production, is well known for its high soil organic matter content and fine properties, which is one of "*the world's three major mollisol regions*" along with the Ukraine Great Plain and the US Mississippi River Basin (Fan et al., 2005). Beian County and Kedong County in this black soil region were chosen as the study area (47°35′–48°33′ N, 126°01′–127°53′ E). This study region covers a total area of $\sim 9.3 \times 10^3$ km^2, including almost 70.1% of the total area of mollisols. It is located in a continental monsoon climate zone varying from a mid-temperature zone to a cold temperate zone from south to north, with a long-term mean temperature of 0.2–1.2 °C and average annual rainfall of 500–550 mm. Most of the terrain in this region is rolling plain and piedmont plain, with an altitude varying from 12 to 411 m. The rolling farmland here easily forms a large catchment area and often experiences alternate freezing-thawing, both of which aggravate the gully erosion and surface erosion in the study area. The erosion continually thins the black soil layer, and even exhausts it, which is one of the main reasons of SOC loss in this area (Huang and Sun, 2006; Xie et al., 2007; Yang et al., 2016).

Since the 1980s, most croplands in the area were cultivated as upland-crop fields, and were managed in a summer soybean/maize-winter wheat rotation, with the NPK fertilization converted from the single N fertilization. Mechanized farming was widely used with an average tillage depth of 18 cm, including deep ploughing of ~30 cm (Beian Soil Survey Office, 1984; Kedong Soil Survey Office, 1985).

2.2. Data collection in the 1980s

China conducted a state soil survey from 1979 to 1982. The main survey results for Beian County and Kedong County were published in the two books "*Beian Soils*" and "*Kedong Soils*", which contain soil-forming processes, locations, areas and soil physicochemical properties from different types of upland soils. In the study area, the upland fields were developed on 4 types of soils, including black soils (mollisols), dark brown forest soils (alfisols), meadow soils (haplocryolls), and meadow bog soils (humaquepts), and the corresponding sampling points were 23, 8, 3, and 10 (total of 44), respectively. The soil physicochemical properties of each sample included the total SOC, soil bulk density (BD), pH, total nitrogen (TN), total phosphorus (TP), total kalium (TK) and soil mechanical composition (i.e., sand, silt and clay), etc.

2.3. Data collection and analysis in the 2010s

After the harvest of crops in November 2010, sampling points were set in the original croplands, if possible, based on the geographic locations of the sampling points from the SSSSC. Soil samples (a total of 88) were collected from the surface layers (0–20 cm) and subsurface layers (20–40 cm) in the 4 types of upland soil profiles in the study area. Meanwhile, some information of each sampling field on cropland management was investigated and recorded, including cropping system, fertilization, straw return and topographic condition. Fresh soil samples were air dried, the visible litter and roots were removed by hand, and the soil then ground to pass through a 2-mm sieve.

Each sample was analysed for total SOC (dichromate oxidation method), soil pH (determined electrometrically using a pH electrode), soil TN (Kjeldahl method), soil TP (HF-$HClO_4$-HNO_3 digestion-Mo-Sb colorimetric method), soil TK (HF-$HClO_4$-HNO_3 digestion-flame photometric method), and soil particle size distribution (measured using the pipette method). Soil bulk density (BD) was determined by cutting ring sampling, with samples then oven-dried at 105 °C until reaching a constant weight. Each measurement was conducted with three replicates (Lu, 2000). The C_r content was determined through the residue of acid hydrolysis (6 M HCL), also was measured using dichromate oxidation method (Paul et al., 2001a, b).

The soil incubation method was used to measure the amount of SOC decomposition per unit time (Collins et al., 2000; Yang et al., 2007). Soil carbonates were removed through the addition of 100 ml of 250 mM HCL to 20 g soil and shaking for 1 h, and then the soils were washed by using deionized water to remove excess Cl^{-1} (Collins et al., 2000). 100 g of each pretreated soil sample were adjusted to 60% water holding capacity (Elliott et al., 1994) and incubated in a 250 ml glass jar in the dark at 25 °C for 100 days. On the top of the jar, a respiration tube was installed and filled with soda lime to filter out possible mixed CO_2 in the incoming air. The released CO_2 from SOC decomposition was absorbed by 20 ml, 0.5 M NaOH. The absorbing liquid was measured every 2 days during the first week, every 7 days in the following weeks till the end of the incubation period. New absorbing liquid was replenished immediately when the old absorbing liquid was extracted for measuring. Released CO_2 was precipitated by adding 20 ml of 1 M $BaCl_2$ and measured by titrating the residual sodium hydroxide to pH 7.0 with 0.4 M HCL. Finally, we calculated the amounts of SOC decomposition at different times during the 100 days incubation.

2.4. Model fitting of SOC fractions

The SOC pool is divided into the C_a, C_s and C_r fraction pools. The three pools follow a three-pool first-order model (Paul et al., 2001a, b), which can be expressed as the following equation:

$$Csoct = Ca \times \exp(-Ka \times t) + Cs \times \exp(-Ks \times t) + Cr \times \exp(-Kr \times t) \quad (1)$$