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Original Articles

Dynamics and driving factors of the organic carbon fractions in agricultural land reclaimed from coastal wetlands in eastern China

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ABSTRACT

Soils are an important pool for storing organic carbon. Differences in soil managements, the effect of land use, and other factors are often evaluated to explain the dynamics and storage potential of the total soil organic carbon (SOC). As the SOC pool is composed of several subpools with different degrees of stability and turnover rate, insights into the dynamics and driving factors of the functional pools are essential for evaluating carbon sequestration or emission. In China, coastal wetlands are undergoing intensive reclamation due to the ever-increasing population. However, the dynamics and identification of key drivers of the functional SOC pools of reclaimed soils remain largely unclear. In this study, the concentrations of SOC and permanganate-oxidizable carbon (POxC) were determined for soils with different reclamation durations and land uses in an intensified reclamation region in eastern China. A random forest (RF) model was used to identify the importance of the potential drivers of the SOC and POxC at 241 sites in this study area. The result indicated that both SOC and POxC increased significantly with reclamation duration until 65 years of land reclamation. The human-dominated land uses had significantly ($p < 0.05$) higher levels of SOC and POxC than the tidal flats. For lands with identical reclamation durations, the paddy soils were superior to the upland soils in terms of sequestering the SOC and POxC. Soil total nitrogen (STN), pH and soil total phosphorus (STP) were identified as the most important factors impacting the spatial pattern of SOC, while the three most important drivers of POxC were STN, STP and Cl in coastal reclaimed lands. The relatively higher POxC contents and POxC/SOC ratios of the reclaimed soils in this study compared to previous studies suggest that reclaimed soils are potentially under the great threat of global warming due to the high sensitivity of POxC to environmental changes. However, paddy management practices are recommended as an efficient approach for minimizing the potential negative impacts of global warming because of the larger POxC sequestration ability of paddy soils than that of other land uses.

1. Introduction

Soil stores the largest amount of organic carbon (OC) in terrestrial ecosystems, with total amounts of OC two or threefold more than in either terrestrial vegetation or the atmosphere (Batjes, 1996; Eswaran et al., 1993; Lal, 2004; Schmidt et al., 2011). Preservation, or release, of this large carbon pool has been considered a key factor in controlling atmospheric CO_2 concentration (Pan et al., 2003). Recently, increasing attention to climate change, caused by exceeded emissions of greenhouse gases into the atmosphere, has strengthened interest in soil carbon sequestration as a strategy to offset anthropogenic CO_2 emissions (Lenka and Lal, 2013). Soils, especially those with low OC content but fine texture or those that have lost substantial amounts of OC, could have a high potential for OC sequestration by improving land management (Kalbitz et al., 2013; Wiesmeier et al., 2015; Wissing et al., 2011). Globally, agricultural soils have the potential to sequester approximately 5500–6000 Mt CO_2-eq.yr^{-1} by 2030 due to their current low level of OC (Smith et al., 2008). In addition, the soil organic carbon (SOC) is closely related to soil quality and productivity since a high content of SOC significantly improves soil structure conditions and nutrient levels (Hati et al., 2007; Tiessen et al., 1994). Therefore, strategies for enhancing the SOC pool are required not only to increase soil productivity but also to mitigate global warming, providing a “win-win” benefit (Lal, 2004).

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SOC is generally used as a sensitivity indicator to evaluate the effects of land use change and land management on soil quality (Cui et al., 2012; Tiessen et al., 1994). The SOC pool is divided into labile, intermediate, and passive pools based on their stability and residence time (Cheng et al., 2007; Von et al., 2008). Generally, these subpools respond differently to environmental changes. Changes in total SOC in the short- and medium-term are generally difficult to detect because of the large background volume of the relatively stable SOC (Gregorich et al., 1994; Wang et al., 2014a). The labile SOC pool, however, is more sensitive to environmental changes than the total SOC pool and thus has been suggested as an early indicator of changes in SOC caused by different soil management practices (Ottoy et al., 2017; Zhang et al., 2006; Weil et al., 2003; Yu et al., 2017). Permanganate-oxidizable carbon (POxC), released by the oxidation of soil with 333 Mm $KMnO_4$, accounts for a small proportion of the total SOC (Wang et al., 2015) but is the active SOC fraction that can be easily decomposed by soil microbes as their energy source for metabolic activity (Janzen et al., 1992). Thus, a comprehensive understanding of the soil POxC pool size and its driving factors in different ecosystems could have significant implications for SOC stability and thus land management practices (Wang et al., 2014a).

In eastern China, tidal flat reclamation is a common practice in coastal regions and plays a key role in the challenge to balance the growing population with limited land resources (Li et al., 2015; Zhang et al., 2013). Since the 1950 s, over 50% of the coastal wetlands in China have been enclosed by dikes between 1950 and 2008, resulting in approximately 13,380 km^2 of new land (Wang et al., 2014b). Coastal wetland reclamation may have notable impacts on the biogeochemical cycles of some elements due to changes in hydrology and land management practices (Li et al., 2014; Wang et al., 2014c). Numerous studies have analyzed the influence of reclamation duration on soil property dynamics using the space-for-time substitution method (Chatterjee et al., 2007; Cheng et al., 2009; Kölbl et al., 2014; Wang et al., 2014c; Wissing et al., 2014). Particularly, soil organic matter (SOM) has received considerable attention due to its significant role in soil quality and climate change (Bai et al., 2013; Fu et al., 2014; Lal, 2004; Zhang et al., 2016a). However, those studies focused mostly on total SOC changes, while the functional OC pool received little attention.

To manage soil carbon efficiently, we need to know more about the quantities of the functional carbon fractions and their primary controlling factors. For general soils, the dynamics of functional carbon pools were commonly related to land use changes, soil tillage intensity, soil management practices, and climate features (Leifeld and Kögel-Knabner, 2005; Janzen et al., 1992; Yang et al., 2012; Aguiar et al., 2013; Liu et al., 2016). However, in salt-affected reclaimed soils, the dynamics of SOC fractions are not only affected by general factors but also by specific factors, e.g., alkalinity and salinity (Li et al., 2014; Tang et al., 2017). Alkalinity and salinity play opposite roles in controlling SOC and its labile fractions by limiting plant growth, thus reducing OM input (Zweifel, 1999), and by limiting microbe activity, thus reducing OM decomposition rate in soils (Setia et al., 2012), respectively. Considering the complexity of the SOC fraction dynamics in coastal reclaimed lands, identifying the importance of each factor is essential for strategizing ways to increase the SOC pool.

In this study, we used a 90-year soil chronosequence developed from coastal wetlands in eastern China. The objectives of this study were to: (1) gain an insight into the impacts of reclamation durations and land use changes on the SOC and POxC dynamics, (2) identify the importance of the potential driving factors of the SOC and POxC using a random forest (RF) model, and (3) investigate the carbon pool management index (CMI) of soils with different reclamation durations.

2. Materials and methods

2.1. Study area

This study area, with an area of 1700 km^2, is located in Dafeng County, Jiangsu Province (33°00′ N–33°30′ N, 120°30′ E–121°00″ E). This area is characterized by a subtropical monsoon climate, with a mean annual temperature and rainfall of 14 °C and 1042 mm, respectively. This area is a marine deposit plain, with an elevation a few meters above sea level. Abundant terrestrial materials transported by the Yangtze River is carried into the Yellow Sea and re-accumulates on the coast of Dafeng. In addition, a considerable proportion of the deposit sediments in Dafeng originated from the Yellow River between 1495 and 1851, until its channel shifted northward (Zhang et al., 2013). Because of the high rate of sediment deposition and the high demand for land resources, intensive coastal tidal flat reclamation has been occurred in the past century. A common approach to reclaiming tidal flats in eastern China was dike building. The land enclosed by a certain dike was formed during approximately the same period. In this area, dikes built at different times formed a soil chronosequence. The approximately reclamation duration of the enclosed lands were 10, 30, 65, and 90 years (Fig. 1). The construction time of the dikes were obtained by reviewing local historical chronicles and interpreting satellite images (Landsat TM/ETM). The soil type of the newly reclaimed lands (< 50 years) were classified as Stagnic Gleyic Cambisol (Galcaric Siltic) according to the rules of the WRB system (IUSS Working Group WRB, 2007), and the lands with longer reclamation durations (> 50 years) were classified as Gleyic Cambisol (Eutric, Siltic).

In Dafeng, the natural tidal flats were partly covered with *Suaeda salsa*, *Spartina alterniflora*, and *Phragmites australis*. Once enclosed, the reclaimed lands (10 years old) were generally used for aquaculture, which would accelerate desalination process. Then, the lands (> 10 years old) were intensively used for cereal and cash crops when its salinity decreased to a suitable level for crop growth. The dominant crop rotation in 30- and 65-year-old lands was rice (*Oryza sativa*)-wheat (*Triticum aestivum*), with small proportions of maize-garlic (*Allium sativum*) and wheat-maize (*Zea mays*) rotations. The 90-year old land was dominated by upland crops such as wheat-maize, maize-rape (*Brassica campestris*) and wheat-cotton (*Gossypium hirsutum*) rotations.

2.2. Soil/sediment sampling and chemical analysis

Two hundred forty-one soil/sediment samples (0–20 cm) were collected using a soil auger in 2012 (Fig. 1). At each site, five randomly distributed subsamples within a 10-m radius were collected and combined into a representative sample. The soil/sediment sample were air-dried, gently ground to pass through a 2-mm sieve, and stored for chemical and physical analysis.

Soil/sediment texture was determined by the wet sieving and sedimentation method. Soil/sediment pH was measured in a 1:2.5 soil:-water ratio, after shaking for 1 h. X-ray fluorescence spectrometry (XFS) was used to measure elemental contents of Ca, Cl, Fe, Al, K_2O and Si. SOC was measured by wet combustion with $K_2Cr_2O_7$. Soil/sediment total nitrogen (STN) concentration was measured using the Kjeldahl method. Soil/sediment phosphorus (STP) concentration was measured by the molybdenum-blue method. The detailed measuring procedure of these soil/sediment attributes were described by Lu (2000).

The concentration of soil/sediment POxC was measured following Blair et al. (1995). Briefly, soil/sediment containing approximately 15 mg C, through a 0.25-mm sieve, was weighed into centrifuge tubes, to which 25 ml of 333 mmol L^{-1} $KMnO_4$ was added. The tubes were shaken for 6 h and then centrifuged for 5 min. Following dilution with deionized water, the absorbance of the supernatants at 565 nm was measured spectrophotometrically. Non-POxC was calculated from the difference between the SOC and POxC.