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Soil organic carbon of an intensively reclaimed region in China: Current status and carbon sequestration potential

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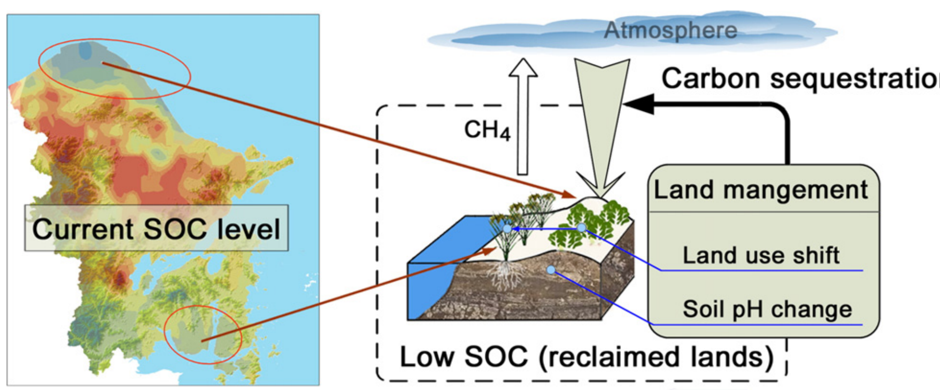
HIGHLIGHTS

- SOC density of reclaimed land is low and has a great carbon sequestration potential.
- SOC recovery in land reclaimed >290 years ago is negligible.
- SOC recovery is highly associated with soil pH and cropping systems.
- Flooded land with vegetable-rice cropping is recommended for carbon sequestration.

GRAPHICAL ABSTRACT



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ABSTRACT

Land reclamation has been highly intensive in China, resulting in a large amount of soil organic carbon (SOC) loss to the atmosphere. Evaluating the factors which drive SOC dynamics and carbon sequestration potential in reclaimed land is critical for improving soil fertility and mitigating global warming. This study aims to determine the current status and factors important to the SOC density in a typical reclaimed land located in Eastern China, where land reclamation has been undergoing for centuries. A total of 4746 topsoil samples were collected from 2007 to 2010. The SOC density of the reclaimed land (3.18 ± 0.05 kg C m^{-2}; mean ± standard error) is significantly lower than that of the adjacent non-reclaimed land (5.71 ± 0.04 kg C m^{-2}) ($p < 0.05$). A Random Forest model is developed and it captures the relationships between the SOC density and the environmental/anthropogenic factors ($R^2 = 0.59$). The soil pH, land use, and elevation are the most important factors for determining SOC dynamics. In contrast, the effect of the reclamation age on the SOC density is negligible, where SOC content in the land reclaimed during years 1047–1724 is as low as that reclaimed during years 1945–2004. The scenario analysis results indicate that the carbon sequestration potential of the reclaimed lands may achieve a maximum of 5.80 ± 1.81 kg CO_2 m^{-2} (mean ± SD) when dryland is converted to flooded land with vegetable-rice cropping

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system and soil pH of ~5.9. Note that in some scenarios the methane emission substantially offsets the carbon sequestration potential, especially for continuous rice cropping system. With the optimal setting for carbon sequestration, it is estimated that the dryland reclaimed in the last 50 years in China is able to sequester 0.12 million tons CO_2 equivalent per year.

1. Introduction

Coastal marshes are important land resources for agriculture around the world (Li et al., 2014). In coastal marshes, land reclamation by the construction of dikes, in order to enclose tidal wetlands, used to be popular in developed countries, such as the Netherlands (Hoeksema, 2007), European Atlantic coast (Fernández et al., 2010), and Japan (Suzuki, 2003). In developing countries such land reclamation is still very active (Li et al., 2014). In Eastern China >50% of the natural coastal wetlands have been reclaimed since year 1949, resulting in 13,380 km^2 of reclaimed lands during 1950–2008 (Wang et al., 2014). Urban expansion and increasing food demands are the primary purposes for land reclamation (An et al., 2007). Reclamation of coastal marshes for agricultural production usually affects soil organic carbon (SOC) dynamics through processes, such as loss to the atmosphere, decomposition of peat horizon or mineralization of organic matter. These effects have been observed in Europe, North America, and Eastern Asia (Iost et al., 2007; Laudicina et al., 2009; Li et al., 2014).

In general SOC dynamics are influenced by climatic conditions, soil properties, topography and anthropogenic factors (Jobbagy and Jackson, 2000; Schimel et al., 1994; Six et al., 2000). SOC content tends to be higher in areas with more precipitation and lower temperature (Burke et al., 1989; Post et al., 1982). For soil properties, e.g., soil pH, moderate alkaline conditions favor decomposition of soil organic matter (SOM) by stimulating the activity of soil microorganisms (Whittinghill and Hobbie, 2012). Anthropogenic activities, such as land use changes, tillage practices, and cropping systems, also play an important role in SOC dynamics through carbon input (Yan et al., 2012) and SOC loss (Turner and Lambert, 2000). For instance, the SOC content decreased >50% after converting grassland was converted to farmland (Post and Kwon, 2000).

SOC dynamics in reclaimed lands not only depend on environmental factors but also the land use and cropping system after reclamation (Chmura et al., 2003; Cui et al., 2012; Fernández et al., 2010). Similar to general SOC dynamics, temperature influences SOC decomposition rates (Chmura et al., 2003). Soil salinity is a major limiting factor to plant growth resulting in low organic carbon input to newly reclaimed lands (Li et al., 2014). SOC dynamics can be strongly influenced by land management practices (Cui et al., 2012; Fu et al., 2014). After reclamation the SOC content can increase as a result of fertilizer application and accumulation of organic residues (Iost et al., 2007; Li et al., 2014). Due to more stubble return and better mineral protection of SOC, flooded land planted with paddy rice was found to have higher SOC content than dryland planted with vegetables (Cui et al., 2012). Other studies have found that reclaimed land planted with vegetables, cotton, oil rape, or wheat have low SOC concentrations (Fu et al., 2014; Wang and Zhou, 2011), indicating higher carbon sequestration potential.

Agricultural soil has great potential to sequester carbon from the atmosphere (Smith, 2004). This potential is usually evaluated with long-term field experiments (Tan and Lal, 2005) or model simulations (Izaurralde et al., 2006). A sequestration amount of 32.5 Tg C year^{-1} was estimated under the scenario of 50% no-tillage + 50% crop residues in China cropland (Yan et al., 2007). Another field experiment indicated a great carbon sequestration potential (760 kg C ha^{-1} year^{-1}) through proper land management practices (Jarecki et al., 2005). Nevertheless, these studies were only conducted for non-reclaimed croplands (Tornquist et al., 2009; Yan et al., 2007), and carbon sequestration potential in reclaimed land has not been comprehensively evaluated. It is important to simultaneously consider the effects of environmental and anthropogenic factors on SOC dynamics in reclaimed land, especially for cases with centuries of agricultural activity.

Coastal reclamation along the Eastern China seaboard is mainly for the generation of agricultural land, and is still rather active today (Li et al., 2014). Draining, ditching, and dewatering were common practices for desalination and to improving soil structure (Cheng et al., 2009). Cultivation in the reclaimed lands lasted for centuries, and during this time soil properties are expected to have evolved due to agricultural practices (Fu et al., 2014; Wang and Zhou, 2011). In this study, the SOC density and related environment/anthropogenic factors were investigated in a typical reclaimed region in Eastern China. A Random Forest model was developed for identifying important factors related to the SOC density and for predicting the carbon sequestration potential. The objectives of this study are (1) to investigate the current SOC level across reclamation ages; (2) to identify important drivers of the spatial heterogeneity of SOC distribution; and (3) to estimate carbon sequestration potential under various land management scenarios. The results of this study provide valuable guidance on land management in reclaimed lands to improve soil fertility and mitigate global warming.

2. Materials and methods

2.1. Study area

The study area (28°43′N–30°27′N, 120°52′E–122°26′E; ~9800 km^2) is an insensitively cultivated region in Eastern China, where approximately 1030 km^2 land were reclaimed from tideland (Fig. 1). The main soil types distributed from the coastal line to inner lands are Solonchak, Cambisols, and Gleysols (ZJSSO, 1994; Wang and Zhou, 2011). The surface elevation is lower than 50 m across the whole reclaimed land. This reclaimed area is located within a subtropical monsoon climate zone, with an annual mean temperature of 17.69 ± 0.18 °C [mean ± SD] and an annual cumulative precipitation of 1263 ± 57 mm [mean ± SD]. The precipitation and temperature in the northern area are higher than those in the southern area (Fig. S3).

The reclaimed lands along the seaboard, especially in the southern Hangzhou Bay, have been reclaimed since the 5th century (Wang and Zhou, 2011). To meet the increasing land demand for agricultural production and urban development (An et al., 2007), the coastal land reclamation in this study area is expected to continue for the next few decades (Fig. 1). A total of 12 dikes have been constructed since the year 1047. The land reclamation mainly took place in 1047–1341, 1724, 1815–1918, 1945, 1970, and 2004 (ZJSSO, 1994; Wang and Zhou, 2011). The rest of the reclaimed lands along the coastal region of Ningbo were gradually formed after 1945 (Wang and Zhou, 2011). Initially, the reclaimed lands were mainly used for fishery and the salt industry. After the soil salinity was alleviated, rice, cotton, wheat, barley, oil rape, broad bean and vegetables were grown on the reclaimed lands (Cheng et al., 2009; Wang and Zhou, 2011).

In the study area, land use and cropping systems changed dramatically in the recent decades. From the 1950s to the 1980s, reclaimed lands in the southern Hangzhou Bay were mainly planted with cotton/rice rotations. Since 1996, a large part of flooded land planted with paddy rice has been converted to dryland planted with vegetables (e.g., water bamboo, cabbages, and pak choi), orchards (e.g., pear, grapevine, and peach), broad bean, and nursery stock. The area of paddy rice was halved by year 2010 (NBS, 2015). At present, paddy