

Effect of reclamation on soil organic carbon pools in coastal areas of eastern China

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Abstract The coastal wetlands of eastern China form one of the most important carbon sinks in the world. However, reclamation can significantly alter the soil carbon pool dynamics in these areas. In this study, a chronosequence was constructed for four reclamation zones in Rudong County, Jiangsu Province, eastern China (reclaimed in 1951, 1974, 1982, and 2007) and a reference salt marsh to identify both the process of soil organic carbon (SOC) evolution, as well as the effect of cropping and soil properties on SOC with time after reclamation. The results show that whereas soil nutrient elements and SOC increased after reclamation, the electrical conductivity of the saturated soil extract (EC_e), pH, and bulk density decreased within 62 years following reclamation and agricultural amendment. In general, the soil's chemical properties remarkably improved and SOC increased significantly for approximately 30 years after reclamation. Reclamation for agriculture (rice and cotton) significantly increased the soil organic carbon density (SOC_D) in the top 60 cm, especially in the top 0–30 cm. However, whereas the highest concentration of SOC_D in rice-growing areas was in the top 0–20 cm of the soil profile, it was greater at a 20–60 cm depth in cotton-growing areas. Reclamation also significantly increased heavy fraction organic carbon (HFOC) levels in the 0–30 cm layer, thereby enhancing the stability of the soil carbon pool. SOC can thus increase significantly over a long time period after coastal reclamation, especially in areas of cultivation, where coastal SOC pools in eastern China tend to be more stable.

Keywords soil organic carbon (SOC), reclamation time,

land use, coastal wetlands, heavy fraction organic carbon (HFOC), light fraction organic carbon (LFOC)

1 Introduction

Coastal wetlands are an important global carbon pool (Post et al., 1982; Chmura et al., 2003; Zhang, 2010). In 2003, the Earth's total area of salt marshes was $2.2 \times 10^4 - 4 \times 10^5$ km², sequestering at least 44.6 Tg C·yr⁻¹ (Chmura et al., 2003). However, because coastal wetland ecosystems are fragile, they have been affected by a combination of reclamation, rising sea levels, and halophytic plant degradation. Indeed, in recent years coastal wetlands have been reclaimed extensively to increase food production and accommodate more people. This is especially true in the developing world, where the extent of wetlands has been reduced considerably (Nicholls, 2004). Previous studies have revealed that soil organic carbon (SOC) in coastal wetlands may be mineralized quickly due to reclamation, thus influencing the global carbon budget and balance (Cui et al., 2012).

Anthropogenic activities in coastal zones (such as reclamation and dyke construction) have had a significant effect on SOC. In the Bay of Biscay (Spain), levels of soil organic matter (SOM) have tended to increase remarkably after reclamation (Fernández et al., 2010), a finding in line with those of both Iost et al. (2007) and Sun et al. (2011). However, Bai et al. (2013) reported that the conversion from natural coastal wetland to cropland in China led to a significant decrease in SOC. Such inconsistent conclusions might be caused by a variety of factors, such as differences in tillage regimes, cultivation practices, soil physico-chemical properties, and reclamation stages (Tripathi et al., 2006; Khorramdel et al., 2013; Li et al., 2014a, 2015a). Analytical techniques, such as the establishment of

chronosequences, can potentially reveal the evolutionary process of soil physico-chemical properties (Grunzweig et al., 2004; Sun et al., 2011). For example, Li et al. (2013) reported that soil physico-chemical properties tended to be stable in coastal areas 33 years after reclamation, agreeing with the findings of Sun et al. (2011). Nevertheless, land use and cover changes induced by coastal wetland reclamation can have a significant impact on SOC evolution. Studies carried out in Jiangsu's salt marshes revealed SOC levels in bare saline soil, artemisia wasteland, and grass wasteland of 2.6, 5.8, and 8.2 g/kg, respectively (Kang et al., 2012). After reclamation, halophytic vegetation is typically replaced by crops, including wheat, corn, cotton, grapes, and rice (Laegds-gaard, 2006; Fernández et al., 2010; Li et al., 2014b). Crop cultivation, organic/inorganic fertilizer application, and a change in soil properties all directly affect SOC enrichment and decomposition, thus resulting in a further change in SOC content. Bai et al. (2013) found that in comparison with that found in bare saline soil, SOC in ditches usually increased after reclamation in the Pearl River Delta. Li et al. (2013) reported SOC levels in croplands and forests that were considerably higher than that in bare saline soil. Studies undertaken in the Yangtze River Delta revealed that SOC levels in coastally reclaimed paddy fields are generally higher than those recorded in soil under other land-use types, such as forests and vegetable fields (Zhou et al., 2009). In addition, the carbon sequestration rate is significantly higher in agricultural soils after reclamation than in natural areas.

Extensive research has been conducted on the impact of land use on coastal SOC (Bai et al., 2013), yet few studies have focused on the evolution processes of coastal SOC over time after reclamation. But in fact, coastal land-use change (especially for agricultural use) was dominated by reclamation time which significantly affects the evolution of soil physico-chemical properties (soil salinity, soil water content, pH, etc.) (Li et al., 2017). As a result, information obtained on the effects of reclamation and subsequent crop growth on SOC and its fractions in coastal areas is limited, with consistent conclusions seldom reached (Fernández et al., 2010). Even less is known on the effects reclamation has had on the evolution of coastal SOC and its fractions (Bai et al., 2013; Li et al., 2014a). The substantial coastal wetlands of Jiangsu have been reclaimed for agriculture since 1949, resulting in a rapid change in land use that has destroyed the structure and function of the wetland ecosystems. Research into the coastal wetlands of Jiangsu could therefore provide useful information that may help guide coastal wetland development in other regions, especially in the developing world. Four reclamation areas in Rudong County, Jiangsu Province, eastern China were selected to investigate the effect of reclamation on the SOC pool, with the aim of (i) determining the processes of SOC evolution after reclamation and (ii) investigating the effect of land use (crops) on SOC.

2 Materials and methods

2.1 Study area

This study was conducted in Rudong County, Jiangsu Province, eastern China (120°41'22.84"E–121°35'24.962"E, 32°10'11.92"N–32°38'15.789"N; Fig. 1), an area with a north subtropical oceanic monsoon climate, an average annual temperature and rainfall of 14.8 °C and 1028.6 mm, respectively, and a coastline 106 km in length. The primary soil types are Mollic Fluvisols. As a result of the region's unique submarine topography and the interaction between the Yangtze River and the sea, vast salt marshes have developed in the coastal area of Rudong, expanding seaward at a rate of –25–200 m per year. Four reclamation areas (viz. Old Beikan, reclaimed in 1951; New Beikan, reclaimed in 1974; Dongling, reclaimed in 1982; and Yudong, reclaimed in 2007) and a reference salt marsh were investigated, in addition to sampling sites in salt marshes situated in the high-tide zone (inundated twice a day) outside the sea embankment.

The coastal wetlands of Jiangsu are one of the largest in the world, with a total area of 5×10^6 ha. The area of built-up land in the reclamation region is small, consisting of rural residential areas and transport infrastructure. Cotton, corn, and rice are the main (summer) crops grown in Old Beikan (1951), New Beikan (1974), and Dongling (1982), although a number of aquaculture ponds are found north of New Beikan. The highest concentration of uncultivated land is in Yudong (2007), where halophytic plants grow profusely.

2.2 Sampling and chemistry analysis

Samples were obtained every km². The study area was thus divided into 1 km×1 km plots, with 56 sample sites identified (including eight in the salt marsh). Five samples from each site were collected at five different depths (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–60 cm) from 20–28 September 2012, representing a total of 280 samples. Upon collection, each sample was packed into a polyethylene bag and transported back to the laboratory.

All samples were air-dried at room temperature for 30 days before being ground in an agate mortar and passed through a 2 mm sieve, thereby removing coarse roots and stones prior to the determination of available nitrogen (AN), available potassium (AK), available phosphorus (AP) and electrical conductivity of a saturated soil extract (ECe). Afterwards, all samples were ground once more and passed through a 0.25 mm sieve (to determine total nitrogen (TN) and cation exchange capacity (CEC)) and a 0.149 mm sieve (to determine total phosphorus (TP), total potassium (TK), and SOC). 1) TN was determined via the potassium bichromate-sulfuric acid digestion method and AN via the alkaline solution diffusion method; 2) TP was determined via the molybdenum-antimony anti-spectro-

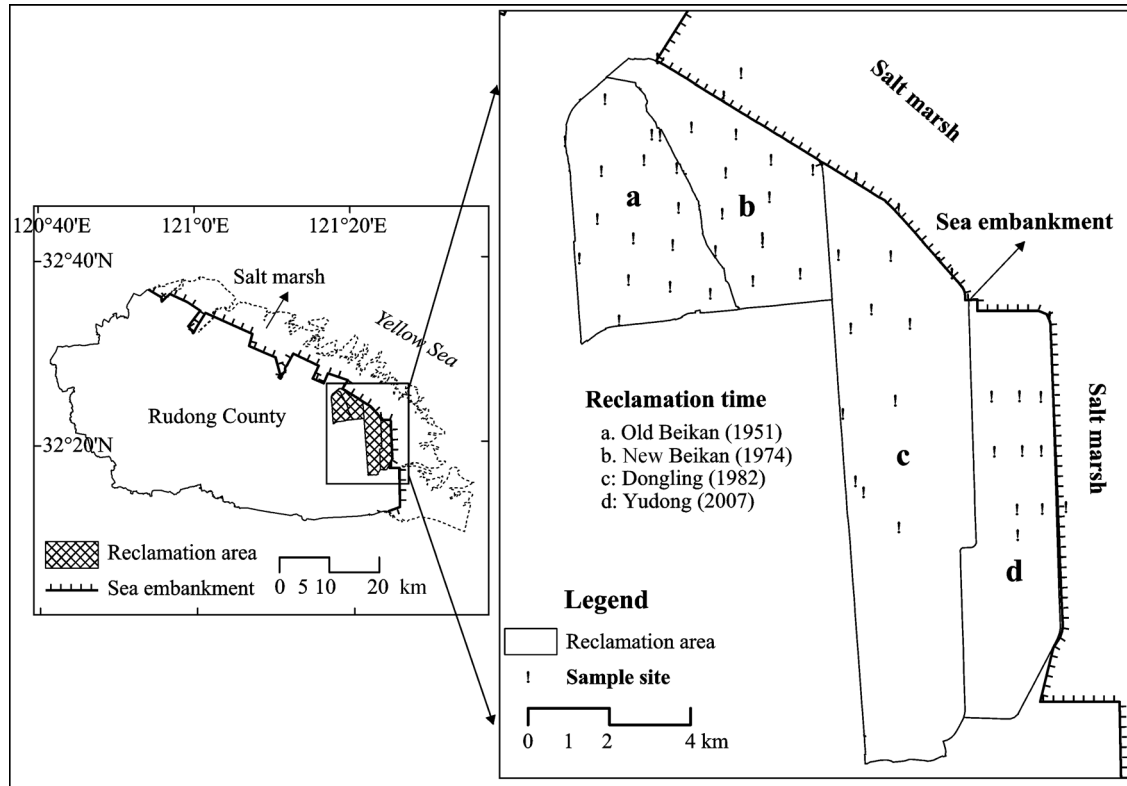


Fig. 1 Study area and sampling site locations. The study area is located in eastern China, and has a north subtropical oceanic monsoon climate. Rudong's coastal beach expands seaward at a rate of about 150 m per year. At present, about 20 reclamation zones have been built for agricultural use with a total area of approximately 260 km².

photometric method and AP via the Olsen NaHCO₃ extraction method; 3) TK and AK were determined via the flame photometric method; and 4) CEC via the method outlined by Hendershot and Duquette (1986). Soil water pH (water:soil ratio of 1:5) was measured using a pH meter (PH_S-3C, China), EC_e using a salinity meter (VWR Scientific, USA), SOC with a C/N analyzer (Vario EL III, Germany), and Ti and Cr using an X-ray fluorescence spectrometer (Niton, USA). Each air-dried sample was dispersed in a 10% sodium hexametaphosphate solution and then submitted for particle size analysis in a laser particle analyzer (Microtrac S3500). Two sampling sites in each reclamation area were selected for bulk density analysis from March 27–29, 2013. Five bulk density cores were collected at five different depths (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–60 cm) at each sampling site, before being oven-dried for 24 h at 105°C and weighed for bulk density and soil moisture determination. The mean bulk density recorded at the two sampling sites in each reclamation area was then used to estimate the soil organic carbon density (SOC_D) in the corresponding reclamation area. Light fraction organic carbon (LFOC) and heavy fraction organic carbon (HFOC) were determined using the soil density fractionation technique developed by Christensen (1992). Six sampling sites in each reclamation area were chosen to measure soil LFOC and HFOC. To this

end, a sub-sample of 10 g (passed through a 2 mm mesh sieve) from each soil sample was placed in a 100 mL centrifugal tube, with 50 mL NaI (1.80 g·mL⁻¹) then poured into the tube. The tube was then shaken at 200 revolutions per minute (rpm) for 1 h and centrifuged for 20 min at a relative centrifugal force of 1000×g. The light fractions of the SOC, as the suspended matter after centrifugation, were decanted into a Büchner funnel with 0.45 µm filter paper. The collected suspended matter was then washed in 100 mL CaCl₂ (0.01 mol·L⁻¹) and distilled water and transferred to a beaker. Finally, the washed suspended matter was dried at 60°C for 72 h and then weighed. The aforementioned procedures were repeated twice, with the dried matter ground to pass through a 60-mesh sieve for LFOC determination (Vario EL III, Germany). Distilled water (50 mL) was poured into the tube with the remaining sediment, shaken for 10 min (200 rpm), and centrifuged for another 20 min at 3000×g. The sediment was washed with CaCl₂ (0.01 mol·L⁻¹) at least five times and then washed twice more with distilled water. Finally, the washed sediment was transferred to a beaker to dry at 60°C for 48 h. The weight of HFOC was obtained after passing through a 60-mesh sieve (Vario EL III Germany).

SOC_D and SOC_D(storage) were calculated using the following formulae:

$$\text{SOCD} = \sum D_i \times \text{SOC}_i \times T_i, \quad (1)$$

$$\text{SOC}(\text{storage}) = \text{SOCD} \times A_i, \quad (2)$$

where SOCD is the soil organic carbon density ($\text{kg C} \cdot \text{m}^{-2}$); D_i is the soil bulk density of soil layer i ($\text{kg} \cdot \text{m}^{-3}$); T_i is the thickness of soil layer i (m); SOC(storage) is the soil organic carbon storage; and A_i is the area of the study region.

2.3 Statistical analysis

Descriptive statistics and a correlation matrix (CM) were produced using SPSS 17 software to identify soil physico-chemical properties and the factors that influence SOC in the selected reclamation areas. One-way analysis of variance (ANOVA) was applied to investigate the differences in SOC among the different treatments, with ordinary kriging used to predict the spatial pattern of SOCD in the study area using ArcGIS 10 software.

3 Results

3.1 Descriptive statistics of soil properties in the study area

Table 1 shows that soil salinity and pH both decreased over time since reclamation. Soil ECe fell to $2.04 \text{ dS} \cdot \text{m}^{-1}$ 62 years after reclamation (Old Beikan, 1951), considerably lower than the $48.78 \text{ dS} \cdot \text{m}^{-1}$ recorded in the salt marsh. Soil particle size decreased gradually, characterized by a falling percentage of sand and an increase in the percentages of clay and silt. Soil bulk density fell from $1720 \text{ kg} \cdot \text{m}^{-3}$ (salt marsh) to $1640 \text{ kg} \cdot \text{m}^{-3}$ (1951), although the lowest value ($1570 \text{ kg} \cdot \text{m}^{-3}$) was measured in Dongling (1982). TN, TP, and SOM in the salt marsh were recorded at 0.02%, 0.06%, and 0.45%, respectively, increasing to 0.07%, 0.07%, and 0.75% 62 years after initial reclamation.

3.2 Variation in SOC among reclamation areas

Figure 2 reveals that SOC tended to increase in the top 60 cm of soil with time after reclamation, but decreased down the soil profile from 0 to 60 cm depth. In the top 10 cm, salt marsh SOC was recorded at $2.6 \text{ g} \cdot \text{kg}^{-1}$, increasing by 66.92% to $4.34 \text{ g} \cdot \text{kg}^{-1}$ in Old Beikan (1951). In the 10–20 cm soil layer, SOC increased from $1.92 \text{ g} \cdot \text{kg}^{-1}$ (salt marsh) to $4.07 \text{ g} \cdot \text{kg}^{-1}$ in Old Beikan (1951), representing a rise of 111.98%. In the 40–60 cm soil layer, the highest SOC value of $2.18 \text{ g} \cdot \text{kg}^{-1}$ was measured at New Beikan (1974) and the lowest of $1.47 \text{ g} \cdot \text{kg}^{-1}$ was measured in the salt marsh soil. Table 2 also shows that HFOC in the top 30 cm increased after reclamation; especially marked in the top 10 cm. HFOC in Old Beikan soil (1951) was recorded at 3.08, 2.6, 1.97, and $1.69 \text{ g} \cdot \text{kg}^{-1}$ in the 10–20 cm, 20–30 cm, 30–40 cm, and 40–60 cm soil layers, respectively. Although LFOC increased significantly after reclamation in the 0–10 cm and 40–60 cm soil layers, the standard deviations of these values are larger than those of HFOC at the same depths, especially in the top 10 cm where LFOC increased significantly 62 years since reclamation. Whereas the percentage of HFOC increased gradually down the soil profile from 0 to 60 cm depth, LFOC levels decreased.

3.3 SOC in soil under different land-use types

Agricultural soils in New Beikan were investigated about 40 years after initial reclamation, with soil physico-chemical properties maintaining a stable state according to Liu et al. (2013), Li et al. (2014a), and Sun et al. (2011). Therefore, an analysis was undertaken in the present study regarding the effect of land use on SOC. To this end, five samples from six sites (at 0–10, 10–20, 20–30, 30–40, and 40–60 cm depth), covering each land-use type in New Beikan, were collected to determine the effect of land use on SOC. Figure 3 shows that SOCD in the top 0–60 cm of

Table 1 Descriptive statistics of soil physico-chemical properties in the study area (0–10 cm)

Properties	1951 (<i>n</i> = 14)	1974 (<i>n</i> = 14)	1982 (<i>n</i> = 10)	2002 (<i>n</i> = 10)	Salt marsh (<i>n</i> = 8)
ECe/($\text{dS} \cdot \text{m}^{-1}$)	2.04a	6.72a	11.73a	50.08b	48.78b
pH	8.26a	8.22a	8.48b	8.70c	8.63c
Sand silt clay	15:75:10	31:64:5	31:63:6	44:52:04	42:53:05
Bulk density/($\text{kg} \cdot \text{m}^{-3}$)	1640a	1640a	1570c	1700b	1720b
TN/%	0.07a	0.05b	0.05b	0.03c	0.02c
TP/%	0.07a	0.07a	0.06ab	0.06b	0.06b
TK/%	11.52a	12.57a	12.15a	12.86a	13.16a
OM/%	0.75a	0.84a	0.72a	0.45b	0.45b
Ti/Zr	14.08a	14.37a	14.37a	14.81a	15.19a

abc: the different lower-case letters indicate significant differences at the $P < 0.05$ level among treatments.

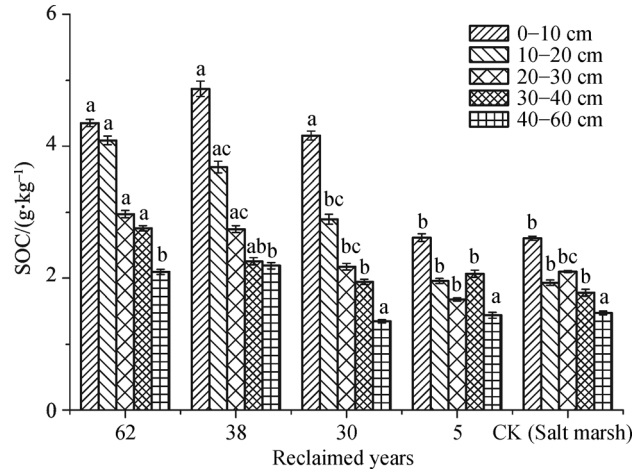


Fig. 2 SOC shown in different soil layers and treatments (1951, 1974, 1982, 2007 and the salt marsh). SOC tends to decrease down the soil profiles from depths of 0 to 60 cm within about 60 years of reclamation. abc: The lower-case letters indicate significant differences ($P < 0.05$), at the same depth, among treatments.

Table 2 Effect of reclamation on the fraction of SOC in the study area

Year		SOC/(g·kg ⁻¹)				
		0–10 cm	10–20 cm	20–30 cm	30–40 cm	40–60 cm
1951 (n = 6)	H	2.9±0.06a	3.08±0.04a	2.6±0.1a	1.97±0.08a	1.69±0.08a
	L	1.03±0.23A	0.88±0.23A	0.44±0.09A	0.33±0.24A	0.14±0.1A
	L:H	0.26:0.74	0.22:0.78	0.15:0.85	0.15:0.85	0.08:0.92
1974 (n = 6)	H	3.92±0.25a	2.04±0.03a	1.84±0.09a	1.58±0.1a	1.32±0.03a
	L	0.99±0.1A	0.74±0.44A	0.4±0.28A	0.23±0.4A	0.15±0.14A
	L:H	0.2:0.80	0.26:0.74	0.18:0.82	0.13:0.87	0.11:0.89
1982 (n = 6)	H	2.57±0.06a	2.15±0.15a	1.65±0.01a	1.88±0.08a	2.02±0.03a
	L	0.66±0.16A	0.73±0.28A	0.47±0.06A	0.35±0.26A	0.12±0.14B
	L:H	0.20:0.80	0.25:0.75	0.22:0.78	0.16:0.84	0.06:0.94
2002 (n = 6)	H	0.96±0.05b	1.08±0.03b	1.03±0.08b	1.14±0.1a	0.98±0.007a
	L	0.41±1.48A	0.19±0.02A	0.1±0.15A	0.13±0.2A	0.09±0.09A
	L:H	0.30:0.70	0.15:0.85	0.09:0.91	0.11:0.89	0.09:0.91
Salt Marsh (n = 6)	H	1.15±0.03b	0.78±0.12b	1.33±0.02b	1.29±0.06a	1.84±0.16a
	L	0.17±0.17B	0.14±0.09A	0.1±0.06A	0.08±0.04A	0.02±0.03B
	L:H	0.13:0.87	0.15:0.85	0.07:0.93	0.05:0.95	0.01:0.99

Values represent mean±SD. H: Heavy fraction organic carbon; L:Light fraction organic carbon. ab: Different lower-case letters indicate significant differences of HFOC among treatments at the $P < 0.05$ level. AB: Different capital letters indicate significant differences of LFOC among treatments at the $P < 0.05$ level.

soil in both cotton-growing and rice-growing areas was higher than that at the aquaculture pond, at 2.91 kg·m⁻², 2.83 kg·m⁻², and 1.66 kg·m⁻², respectively. However, all three of these values are higher than the 1.56 kg·m⁻² recorded in salt marsh soil. In the top 0–20 cm of soil, SOCD followed the sequence: rice-growing area (1.62 kg·m⁻²) > aquaculture pond (1.16 kg·m⁻²) > cotton-growing area (0.91 kg·m⁻²) > salt marsh (0.55 kg·m⁻²). No significant differences in SOCD values were found between the top 60 cm of the rice- and cotton-growing areas.

4 Discussion

4.1 Variation of soil properties in reclamation areas and their relation to SOC

The method of substituting space for time using chronosequences was employed to study SOC pool evolution following reclamation in the selected coastal areas of Jiangsu Province. The first step was to identify the homogeneity of soil sources observed at the different sites. In this regard, trace metal analysis is considered one

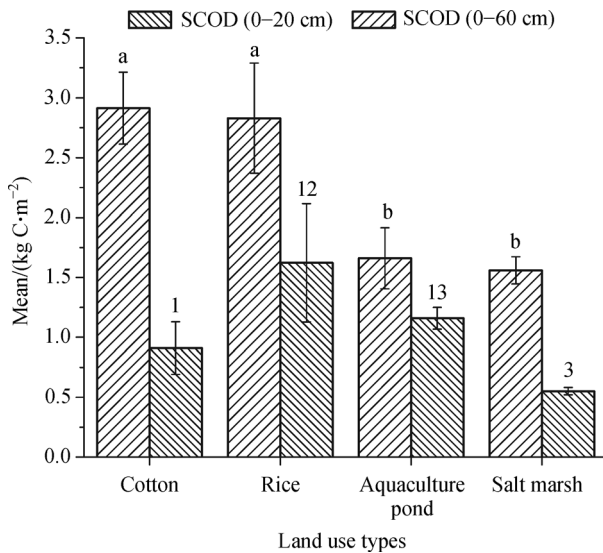


Fig. 3 Effect of land use on SOCD in the study area. ab: The lower-case letters indicate significant differences ($P < 0.05$), at a depth of 0–60 cm, among land use types. 123: Numbers indicate significant differences ($P < 0.05$), at a depth of 0–20 cm, among land use types.

of the most effective methods (Tsai et al., 2000), with the ratio of Ti to Zr (Ti/Zr) typically used to test such homogeneity in coastal areas (Cui et al., 2012). As shown in Table 1, Ti/Zr at the five sites was recorded at 14.08 (1951), 14.37 (1973), 14.37 (1982), 14.81 (2007), and 15.19 (salt marsh), with subsequent ANOVA indicating homogeneity across all sites. Therefore, based on these findings, the soils at the five sites can be considered to share the same source.

Soil chemical properties typically enter a new stage of evolution about 30 years after initial reclamation (Iost et al., 2007; Li et al., 2014a). In the present study, there was a remarkable improvement in reclaimed soils, with a significant increase in SOC. Alternatively, even though soil nutrient levels may increase over time, no significant increase was observed (Table 1). These insignificant increases ca. 30 years after reclamation may be explained by multiple factors, including sampling design and soil properties (Bai et al., 2013). The CM constructed to identify the factors influencing SOC is shown in Table 3, with a total of 112 samples taken in the top 20 cm of all sampling sites analyzed to obtain the correlation coefficients between SOC and other soil properties. Analysis of this table reveals that SOC in the study area is significantly and positively related to TN, AN, TP, and AP. Soil N and P concentrations are related to organic and inorganic

fertilizer additions, with high levels significantly increasing above-ground biomass and the amount of plant residues, roots and microbes, which are the main sources of SOC (Zhang et al., 2011b). Soil salinity can negatively affect crop growth, thereby reducing organic matter input, but it can also decrease microbial activity and biomass, preventing SOC decomposition (Bai et al., 2013). Nevertheless, high salinity levels generally reduce SOC (Setia et al., 2012), which is reflected in the negative correlation coefficient observed here between ECe and SOC (Table 3). A negative relationship was also recorded between the percentage of clay and SOC; one possible explanation for this is that clay generally increases SOM by absorbing the latter in its free state (Zhou et al., 2007a). In contrast, soil moisture was positively related to SOC, based on the former likely protecting the latter from contact with air (Bai et al., 2013). Soil pH was found to be significantly and negatively related to SOC; the former decreasing and the latter increasing with time since reclamation. However, as there is no direct practical relationship between these two parameters, the significant and negative correlation coefficient between them is likely only a numerical reflection of two distinct variational tendencies. Consequently, fertilization after reclamation can significantly promote SOC concentrations.

4.2 Evolution of SOC pools in the top 60 cm within ~60 years after reclamation

SOC in the study area generally increased after reclamation, in line with the findings reported by Fernández et al. (2010), but to a lower extent than found in Europe, North America, and in estuaries (Laudicina et al., 2009). The main reason for this discrepancy is that a thick peat horizon composed of a considerable amount of plant residue is found in coastal areas of Europe and North America due to the low rate of deposition (Portnoy and Giblin, 1997), while the high SOC levels recorded in estuaries are primarily derived from suspended particulate matter (SPM) and marsh plant residues (Zhou et al., 2007a).

Whereas reclamation significantly increased SOC in the top 30 cm of soil across the study area, levels at 30–60 cm depth were reduced within five years (Yudong) after reclamation. One possible explanation for this is that SOC in this layer decomposed and mineralized due to aeration after dyking (Gebhart et al., 1994) (Fig. 4). Consequently, a sequence of SOC evolution can be described as SOC in the deep soil profile coming into contact with air due to a lack of seawater protection and organic matter input, and is then decomposed and mineralized, resulting in low SOC levels

Table 3 Correlation coefficients between soil organic carbon levels and different soil properties (0–20 cm)

	Moisture	Ece	%Clay	TN	AN	TP	AP	TK	CEC	pH
SOC ($n = 112$)	0.09	-0.30	0.01	0.74**	0.52**	0.68**	0.45**	-0.17	-0.12	-0.60**

within about 10–20 years after dyking (Cui et al., 2012). Even though SOC increased after the commencement of crop cultivation and organic fertilizer addition, the greatest concentration of the increase was in the top 30 cm of soil. As previous studies have reported, an increase in soil nutrient content may accelerate the emission of N_2O (Muñoz-Hincapié et al., 2002), and thus, various cultivation management practices should be carried out at different stages of reclamation to regulate the emission of this important greenhouse gas (GHG).

SOCD in the study area was estimated via ordinary kriging. Figure 5 shows that current SOCD levels rise gradually with distance from the sea, increase with time after reclamation. SOCD levels in the top 60 cm of soil were recorded at $1.7 \text{ kg} \cdot \text{m}^{-2}$, $1.67 \text{ kg} \cdot \text{m}^{-2}$, $2.03 \text{ kg} \cdot \text{m}^{-2}$, $2.58 \text{ kg} \cdot \text{m}^{-2}$, and $2.65 \text{ kg} \cdot \text{m}^{-2}$ in the salt marsh, Yudong (2007), Dongling (1982), New Beikan (1974), and Old Beikan (1951) sites, respectively. A previous study reported that the total area of reclaimed land in Jiangsu during the periods of 1951–1955, 1956–1975, 1976–1985, and 1986–2010 was around 2.4×10^5 ha, 9×10^5 ha, 6×10^5 ha, and 6×10^5 ha, respectively (Zhang et al., 2011a), with a total of 1.2 Tg carbon, and thus sequestered in the top 60 cm of reclaimed soil since 1951.

4.3 Effect of tillage practices on SOC pools

Crop cultivation has a significant effect on SOC (West and

Post, 2002). In the study area, SOC in the top 60 cm of the soil in both cotton- and rice-growing areas is higher than at the aquaculture pond and salt marsh sites, indicating that aquaculture pond amendment is not an effective way to increase SOC. SOC in rice-growing areas is mainly concentrated in the top 20 cm of soil, potentially reflecting the presence of ploughed soil (plough pan), resisting the infiltration of organic matter (Jamison and Thornton, 1960). Indeed, SOC levels in rice-growing areas are generally high (Tan et al., 2006). However, in the present study, the difference in SOC between cotton and rice soils was not significant, likely due to an inconsistency in crop rotation. Due to poor soil quality, farmers usually switch to corn and soybean after planting rice and cotton the previous summer. As a result, SOC in cotton- and rice-growing areas is also affected by the other crops involved in the rotation. An earlier study showed that the soil carbon sequestration rate in cropland was significantly higher than that in salt marsh (Jin, 2016), increasing from $93 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{yr}^{-1}$ in natural salt marsh to $288 \text{ kg C} \cdot \text{hm}^{-2} \cdot \text{yr}^{-1}$ in paddy-upland rotation cropland after reclamation the latter value 2.85 times higher than in upland-upland rotation soil. Thus, the application of paddy-upland rotation after reclamation is an effective tillage practice that can improve carbon sequestration in coastal areas. This is largely due to the restoration of environment found in paddy fields (Zhang et al., 2014, 2015). In addition, previous studies have shown that NPK treatment is an effective and realistic option with

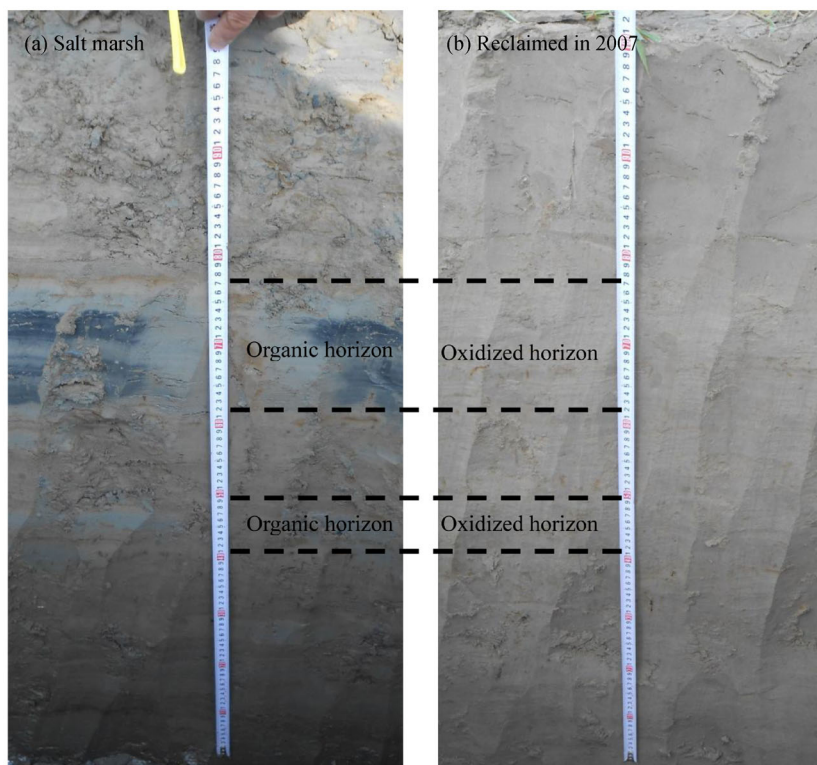


Fig. 4 Organic horizon in the salt marsh and oxidized horizon at Yudong (2007). The soil profiles with a depth of 100 cm of salt marsh (a) and Yudong (b) were built. The two soil profiles were very close, separated only by an embankment (as shown in Fig. 1 to eliminate the influences of other factors). The land-use/cover in salt marsh and Yudong are bare, flat, and barley-growing areas.

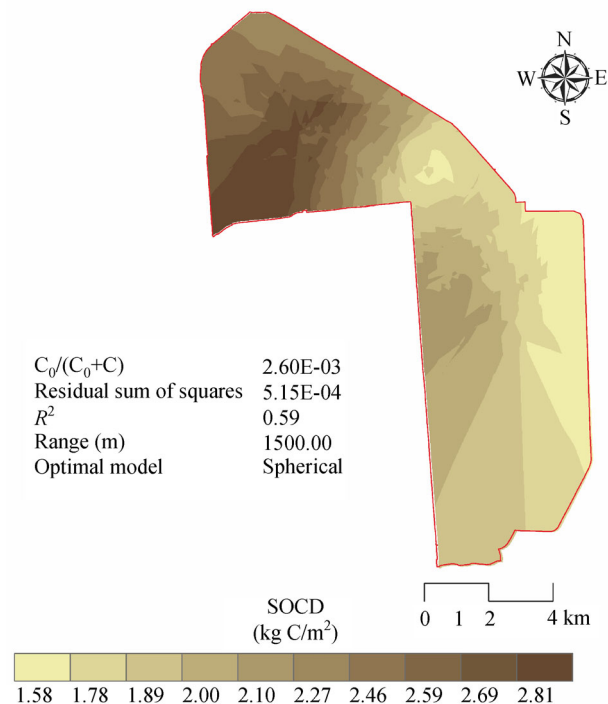


Fig. 5 Spatial distribution of SOCD in the study area. The geostatistical analysis of the ArcGIS 10 software is used to predict the SOCD in the study area. The SOCD map was made by the spherical model; the main parameters of the model indicating prediction precision are collected. The parameters of $C_0/(C_0+C)$ and R^2 are 0.0026 and 0.59, respectively.

which to increase SOC (Gong et al., 2009). In Jiangsu's coastal areas, the typical land-use conversion pathway is salt marsh → aquaculture pond → forest/cropland → built-up land (Li et al., 2015b). This pattern is typically related to reclamation time and soil property changes since rice and cotton can only be planted after approximately 30 years post-reclamation. In the present study, SOC in rice-growing areas was higher than in soil under other crops; in agreement with the findings reported by Wu et al. (2008). Therefore, popularizing rice planting in long-term reclaimed zones can potentially increase SOC levels significantly.

As is well known, LFOC is a free state of SOC, which includes both partly and undecomposed organic residues and micro-biomass (Wang et al., 2009). LFOC is generally composed of low-density plant residues and roots, charcoal, and micro-organisms. LFOC is easily decomposed and mineralized, releasing a quantity of greenhouse gases (Laik et al., 2009). In contrast, HFOC is a high-density organo-mineral complex absorbed onto the surface of mineral granules and is hard to decompose (Wang et al., 2009). Whereas tillage can increase LFOC significantly in the top 10 cm of soil due to fertilizer input (organic) and the decomposition of plant and animal residues (Janzen et al., 1992), here HFOC increased significantly after reclamation, which was helpful in enhancing the stability of the SOC pools in the studied coastal areas. The percentage of LFOC in the study area ranged from 1%–

30%, less than in forest areas and grassland, as a result of low net primary productivity (NPP; Christensen, 1992; Zhou et al., 2007b). Furthermore, whereas the percentage of HFOC in the top 60 cm of soil across the study area gradually increased down the soil profile, LFOC decreased; a pattern in agreement with that reported by Wang et al. (2009).

In summary, after the reclamation of coastal areas, there could be an increase in the amount and instability of the carbon pools. Due to the significance of tillage 30 years after reclamation, rice planting should be encouraged in those relevant areas. Reducing the rotation frequency, promoting no-till, deep ploughing or organic fertilizer application, and enlarging the area of forest and grass are alternative choices for increasing carbon pool stability (Christensen, 1992; Gong et al., 2009).

5 Conclusions

A tendency for an increase in SOC with time after reclamation has been observed in the study area, with a significant improvement in soil chemical properties after approximately 30 years. Reclamation has significantly increased SOC levels in the top 60 cm of soil, particularly in the uppermost 30 cm. SOC in the top 60 cm of soil in both cotton- and rice-growing areas is also higher than that recorded at the aquaculture pond and salt marsh sites,

indicating that reclaiming salt marshes for growing cotton and especially rice was a wise choice to enhance SOC. Reclamation has also significantly increased HFOC levels in the top 30 cm of soil, potentially enhancing the stability of SOC pools in the studied coastal areas. Furthermore, fertilization may be the most effective way to increase SOC in coastal reclaimed areas.

Finally, a total of 1.2 Tg carbon has been sequestered in the top 60 cm of soil across Jiangsu since 1951 due to reclamation. However, a significant reduction in SOC levels within about 10 years after initial reclamation was observed, indicating that the presence of decomposed and mineralized SOC may lead to the emission of a huge volume of GHGs during this early period.

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