



Reclamation substantially increases soil organic and inorganic carbon stock in riparian floodplains

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Abstract

Purpose In recent decades, riparian floodplains have undergone intensive reclamation worldwide, which has potential to influence soil carbon (C) accumulation. Such influence generally varies based on reclamation duration. Therefore, a study on changes in soil C stock along the reclamation chronosequence can help reveal the impact of reclamation on terrestrial C cycling.

Materials and methods We chose natural floodplains (as the control) and croplands reclaimed for 13, 24, and 33 years in the lower reaches of the Yellow River and determined soil organic C (SOC) and soil inorganic C (SIC) contents at different depths and the stocks in 0–100 cm profiles.

Results and discussion The SOC and SIC stocks generally increased at average rates of 2.73 and 5.54 Mg C ha⁻¹ yr⁻¹, respectively, and the SIC stock was closely related with the SOC stock across the reclamation chronosequence. The SOC content increased more at 0–20 cm depth in the profile along the reclamation chronosequence, but the SIC content often had a higher rate of increase in the deep soil layers. Significantly, the contents of SOC and SIC were both positively correlated with the proportion of silt fractions.

Conclusions Our findings suggest that reclaimed croplands from riparian floodplain play an important role in C accumulation, highlighting the importance of soil inorganic C in C budget. Moreover, soil C accumulation relates closely to soil texture, which changes continuously along the reclamation chronosequence and often varies due to spatial heterogeneity.

Keywords Soil organic carbon · Soil inorganic carbon · Vertical distribution · Riparian floodplain · Reclamation duration

1 Introduction

Soil carbon (C), as the largest C pool in terrestrial ecosystems, plays an important role in the global C cycle (Lal 2004a). The top 100-cm soil layer stores approximately 1500 Pg soil organic C (SOC) and 950 Pg soil inorganic C (SIC) (Lal 2004b). In recent decades, the changes of SOC and its effects on greenhouse gas emission have been widely investigated, because SOC is highly sensitive to anthropogenic activities and

climate change (Lal 2004b; Knorr et al. 2005; Fang et al. 2018). However, much less attention has been paid to the SIC contribution to C accumulation and climate mitigation (Guo et al. 2016; Zhang et al. 2019), which often plays an equal or greater role as the SOC in C exchange between terrestrial ecosystems and the atmosphere (Batjes 1996; Shi et al. 2017; Zhang et al. 2019).

To relieve the pressures of population growth and urbanization, many riparian floodplains worldwide have been reclaimed over the past decades (Liu et al. 2017). Due to a strong C accumulation potential, reclamation of riparian floodplains deserves greater attention (Craft et al. 2018; Steger et al. 2019). Following reclamation, the amount of plant residue, together with the organic manure application, could directly increase the SOC stocks (Maillard and Angers 2014; Zhang et al. 2019). Moreover, the change of soil environments, such as soil texture, chemical properties, nutrient content, and microbial activities, may have indirect effects by regulating C stability and C efflux (Whitbread et al. 1998;

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Ewing et al. 2012; Wang et al. 2015b). In particular, crop presence generally increases the proportion of fine soil particles due to enhanced biochemical and chemical weathering, thus facilitating the absorption of organic matters (Hassink 1997; Wiesmeier et al. 2015). Additionally, reclamation, especially when it continues for a long time, also has potential to cause organic C stock decline due to soil acidification and leaching (Kindler et al. 2011; Zhang et al. 2019). At present, the effects of reclamation on SOC are still far from generalizable, often varying substantially due to floodplain types, soil properties, and reclamation duration (Wang et al. 2015a, b; Liu et al. 2017; Craft et al. 2018).

In addition to organic C, reclamation also has potential to affect inorganic C accumulation in soils (Jelinski and Kucharik 2009; Guo et al. 2016; You et al. 2020). Dissolution/precipitation of carbonate systems and leaching/absorption of atmospheric CO₂ are two major mechanisms of SIC sequestration (Wang et al. 2019). Agricultural activities, such as fertilization, irrigation, and tillage intensity, could affect soil physicochemical properties, thus interfering with the precipitation and leaching of SIC (Wang et al. 2015a; Guo et al. 2016; Shi et al. 2017; Zhang et al. 2019). In addition, the facilitated C mineralization following organic matter accumulation, together with the improved soil texture following reclamation, contributes to SIC accumulation (Gaines and Gaines 1994; Kindler et al. 2011; Shi et al. 2017; You et al. 2020). However, much less attention has been paid to the influence of reclamation on SIC stock, thereby limiting the accurate evaluation on total C stock in these ecosystems (Zhang et al. 2019).

The Yellow River contains the greatest sediment amounts in the world and is the fifth longest river in the world. In the lower reaches, a considerable area of riparian floodplains (~3154 km²) forms as the river slows down and deposits sediment. In recent decades, more than 70% of these riparian

floodplains have been reclaimed (Zhang 2018). However, the responses of soil C pools, including SOC and SIC, have rarely been studied in this area until now. Here, we selected croplands with different reclamation durations and a natural floodplain (as the control) in the lower reaches of the Yellow River and investigated SOC and SIC contents at different depths and the C stock in the 100-cm soil profile. Considering the effects of reclamation on organic matter inputs and soil environments, we hypothesized that (1) reclamation benefited both SOC and SIC stock, and such effects would be enhanced with reclamation duration; and (2) surface soils, i.e., the plow layer, responded more noticeably than deep soils.

2 Materials and methods

2.1 Study area and experiment design

The study area was located in the Langchenggang city (34.896°–34.952° N, 114.132°–114.178° E) of Henan Province in the lower reaches of the Yellow River (Fig. 1). This area has a temperate continental monsoon climate, with a mean annual temperature of 14.2 °C, precipitation of 616 mm (most falls in July and August), sunshine duration of 2366 h, and a frost-free period of 240 days. The soil corresponds to Eutric Fluvisol (FAO 1988).

Floodplains widely distributed in this area in the 1950s, but large amounts of floodplains were reclaimed in the following decades, especially after the Xiaolangdi Dam began operation (in 1999). The double cropping system of winter wheat and summer maize is typical for farmlands in this area. After wheat harvest in June, shoot straws are smashed and scattered on the soil surface and the stubble remains in the field. In October, the remaining wheat residue, together with the recently generated maize stubbles after harvest, are embedded

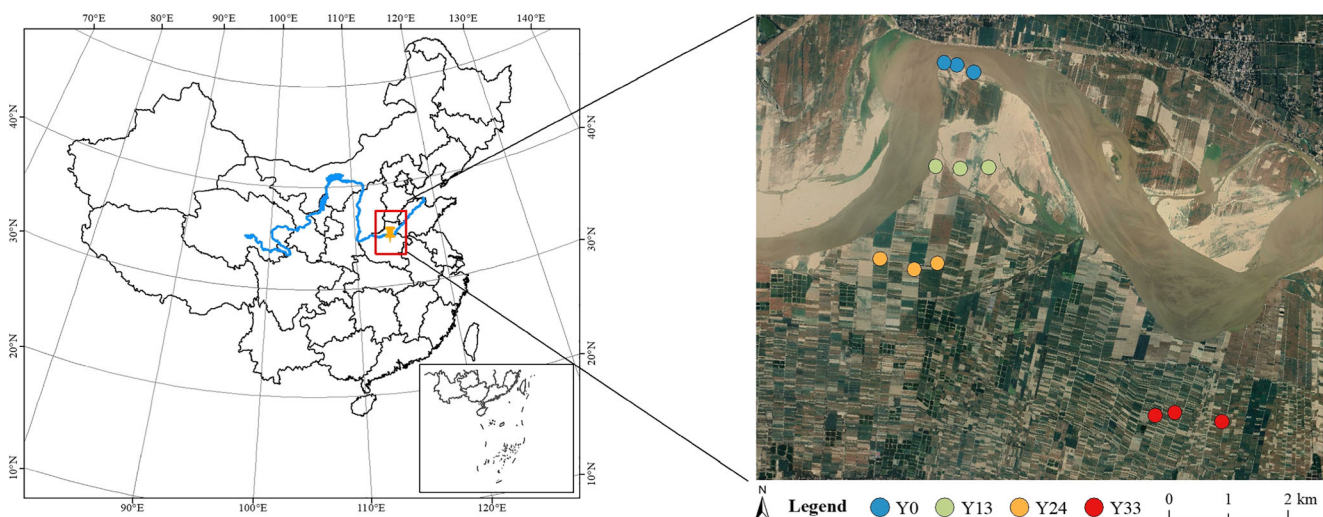


Fig. 1 A schematic of sampling locations

into the soil following plowing. These croplands need irrigation two or three times annually, with approximately $500 \sim 700 \text{ m}^3 \text{ ha}^{-1}$ each time. Before 1999, more than 80% of irrigation water was from the Yellow River, but the proportion gradually declined to less than 10% due to the operation of the Xiaolangdi Dam. In the study area, the water from the Yellow River contains $4 \sim 22 \text{ kg sediment m}^{-3}$ (Zhao et al. 2017), with fine particles ($< 25 \mu\text{m}$) accounting for $\sim 60\%$ (Sun et al. 2015). In addition, chemical fertilizers (including $\sim 150 \text{ kg N ha}^{-1}$, $\sim 33 \text{ kg P ha}^{-1}$, and $\sim 124 \text{ kg K ha}^{-1}$) and a small quantity of organic manure (varying greatly between years with $0 \sim 200 \text{ kg organic C ha}^{-1}$ equivalent) are applied annually as basal fertilizers and/or supplemental fertilizers.

River dynamics often cause high spatial variability of alluvial plains, which together with management practices (such as tillage methods, crop species, fertilizer regime, etc.) has critical effects on responses of soil C dynamics to reclamation duration. In this study, based on a consultation with the agriculture department and local farmers, we chose croplands reclaimed for 13 (Y13), 24 (Y24), and 33 (Y33) years, with natural floodplains (Y0) as the control (Fig. 1). These croplands have relatively consistent management practices, and similar starting soil conditions with the chosen natural floodplains, at least in the 0–40 cm layer. For each reclamation duration treatment, triplicate $50 \times 50 \text{ m}$ plots were randomly selected; the distance between any two neighboring plots was at least 200 m to minimize the potential for spatial autocorrelation.

2.2 Soil sampling and chemical analysis

Soil samples were collected in June 2018, after the winter wheat harvest. In each plot, we randomly dug three 100-cm soil profiles using a shovel, and soils at depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm were sampled. In these soil profiles, there were no visible rock fragments. After removing visible roots, organic debris, and fauna, soils at the same depth from the three profiles were thoroughly mixed to homogenize a sample, sieved to pass a 2-mm screen, and air-dried. Additional samples were collected using volumetric rings (5 cm in diameter) at the middle point of each layer, taken to laboratory, and oven-dried to calculate the bulk density.

The air-dried soils were divided into two groups of subsamples. One group was used to measure the soil texture and the pH (1:5 soil/water) with a glass electrode, and the other was ground ($< 0.25 \text{ mm}$) for analyses of soil total carbon (STC) and SOC. Soil texture was determined by a laser diffraction particle analyzer (Microtrac S3500, Malvern, UK), and soil particles were defined as sand ($> 20 \mu\text{m}$), silt ($2 \sim 20 \mu\text{m}$), and clay ($< 2 \mu\text{m}$). Generally, the soils in the investigated plots are sandy soil, sandy loam, loam, or silty loam (Table 1). The content of STC was analyzed with the dry combustion method (Vario PYRO cube, Elementar, German). After being acidulated with 1 mol L^{-1} hydrochloric

acid, the content of SOC was analyzed by using the same method as with STC. The SIC content was achieved by subtracting the SOC content from the STC content.

Considering the change of soil bulk density along the reclamation chronosequence, we used equivalent soil mass to calculate the soil C stock using the following equations (Lee et al. 2009):

$$M_i = BD_i \times T_i$$

$$C_{i, \text{fixed}} = O_i \times M_i$$

$$M_{i, \text{equiv}} = M_{i, \text{equiv}} - M_i$$

$$C_{i, \text{equiv}} = C_{i, \text{fixed}} + (O_{\text{bottom}} \times M_{i, \text{equiv}})$$

where M_i is dry soil mass of the i th soil layer (g cm^{-2}), BD_i is the bulk density (g cm^{-3}), T_i is the thickness (cm), $C_{i, \text{fixed}}$ is the C mass to a fixed layer (g cm^{-2}), O_i is the C content (mg g^{-1}), $C_{i, \text{equiv}}$ is the equivalent C mass to a fixed layer (g cm^{-2}), $M_{i, \text{equiv}}$ is the selected equivalent soil mass, $M_{i, \text{add}}$ is the additional soil mass used to attain the equivalent soil mass, and O_{bottom} is the C content of the additional soil mass, which is determined by the location of soil mass used for corrections. The mass of the heaviest soil layer is designated as the equivalent mass. In this study, the bulk density and C content of the 80–100 cm layer were used to calculate C mass combined with the additional thickness in the 100 cm equivalent mass.

2.3 Statistical analyses

SPSS 20.0 was used for statistical analysis, and the accepted significance level was $P < 0.05$. Data were tested for normality using the Shapiro-Wilk test. Two-way analysis of variance (ANOVA) was used to determine the effects of reclamation duration and soil depth on soil pH; bulk density; the contents and stocks of STC, SOC and SIC; and soil texture. Following one-way ANOVA, Tukey's (Tamhane's when equal variances not assumed) multiple comparison test was used to examine the differences in soil pH; bulk density; the contents and stocks of STC, SOC and SIC; and soil texture among reclamation chronosequence treatments. Multiple linear stepwise regression was performed to analyze the relationship between soil C contents and soil properties (including bulk density, pH, and soil texture) as well as the reclamation duration, and simple linear regression was used to assess the relationship between SIC stocks and SOC stocks.

3 Results

3.1 Soil pH, bulk density, and texture

The pH values, ranging from 7.79 to 9.13, generally decreased with reclamation duration, irrespective of the soil layer

Table 1 Soil properties at different soil layers across the reclamation chronosequence

Soil Property	Soil layer (cm)	Reclamation chronosequence			
		Y0	Y13	Y24	Y33
Bulk density (g cm ⁻³)	0–20	1.56 (0.02)aB	1.32 (0.07)aA	1.51 (0.01)B	1.53 (0.02)bB
	20–40	1.58 (0.01)abB	1.48 (0.04)bB	1.48 (0.01)B	1.43 (0.02)aA
	40–60	1.63 (0.01)cB	1.57 (0.04)bB	1.48 (0.01)A	1.43 (0.02)aA
	60–80	1.62 (0.01)bcC	1.51 (0.03)bB	1.43 (0.02)A	1.40 (0.03)aA
	80–100	1.56 (0.03)a	1.55 (0.01)b	1.45 (0.07)	1.49 (0.04)ab
pH	0–20	8.55 (0.04)aC	8.17 (0.04)aB	8.19 (0.03)B	7.79 (0.04)aA
	20–40	8.74 (0.03)abB	7.96 (0.10)aA	8.05 (0.10)A	8.01 (0.02)ba
	40–60	9.13 (0.18)cC	8.76 (0.02)cB	8.08 (0.03)A	8.08 (0.05)ba
	60–80	9.05 (0.05)bcC	8.63 (0.02)bcB	8.05 (0.02)A	8.07 (0.01)ba
	80–100	8.80 (0.29)abC	8.46 (0.08)bB	8.10 (0.03)A	8.26 (0.03)cAB
Proportion of sand (%)	0–20	90.17 (7.80)D	73.94 (0.95)aC	68.40 (1.61)bBC	40.50 (2.60)aA
	20–40	100.00 (0.00)B	88.31 (2.60)bbB	92.89 (1.07)cB	44.82 (12.80)aA
	40–60	99.82 (0.09)B	100.00 (0.00)bbB	90.14 (1.49)cB	48.87 (11.56)aA
	60–80	99.87 (0.03)C	99.61 (0.39)bcC	71.56 (5.80)bbB	44.98 (3.50)aA
	80–100	100.00 (0.00)B	92.02 (7.64)bbB	36.93 (8.71)aaA	95.84 (2.10)bbB
Proportion of silt (%)	0–20	9.81 (9.79)A	25.71 (4.70)bbB	31.37 (0.91)bbcC	56.02 (1.53)bbD
	20–40	0.00 (0.00)A	11.68 (2.92)aaA	7.11 (1.23)aaA	54.10 (4.00)bbB
	40–60	0.25(0.06)A	0.00 (0.41)aaA	9.86 (2.03)aaA	49.65 (9.19)bbB
	60–80	0.13 (0.03)A	0.39 (0.27)aaA	28.42 (5.72)bbB	53.68 (1.04)bcC
	80–100	0.00 (0.00)A	7.88 (6.56)aaA	60.70 (7.48)cbB	4.16 (3.74)aaA
Proportion of clay (%)	0–20	0.02 (0.02)A	0.35 (0.18)baB	0.23 (0.18)aaA	0.71 (0.00)B
	20–40	0.00 (0.00)	0.01 (0.02)aa	0.00 (0.00)aa	1.09 (0.23)
	40–60	0.00 (0.00)A	0.00 (0.00)aaA	0.00 (0.00)aaA	1.48 (1.21)B
	60–80	0.00 (0.00)A	0.00 (0.00)aaA	0.01 (0.00)aaA	1.34 (0.02)B
	80–100	0.00 (0.00)A	0.10 (0.12)abA	2.36 (1.43)bbB	0.00 (0.00)A

Note: Y0, natural floodplains free of reclamation; Y13, Y24, and Y33 represent croplands reclaimed for 13, 24, and 33 years, respectively

Values are means (SD in parentheses, $n = 3$). Different uppercase letters indicate significant differences between reclamation duration treatments at the same depth ($P < 0.05$), while different lowercase letters indicate significant differences between different soil layers in the same reclamation duration treatment ($P < 0.05$)

(Table 1). The bulk density ranged from 1.32 to 1.63 g cm⁻³ and showed the lowest values in the surface layer of Y13 croplands (Table 1). Moreover, the bulk density of 20–40 cm, 40–60 cm, and 60–80 cm layers gradually decreased along the reclamation chronosequence (Table 1). The proportion of sand generally decreased with reclamation duration for all soil layers, but the reverse trend was true for the silt proportion (Table 1). In summary, reclamation duration, soil layer, and their interaction significantly influenced soil pH, bulk density, and texture (Table 2).

3.2 SOC, SIC, and STC contents

The SOC contents were always highest in the 0–20 cm soil layer, and the SOC stocks in this layer accounted 32–52% of that in the 0–100 cm layer (Fig. 2a). Generally, the SOC, SIC, and STC contents declined with soil depth in natural floodplains (i.e., the Y0 treatment) and Y13 and Y33 croplands

(Fig. 2). However, for the Y24 croplands, the SIC and STC contents increased with soil depth in the 40–100 cm layer, and the SOC content was higher in the 40–100 cm soil layer than the 20–40 cm layer (Fig. 2). In summary, the contents of SOC, SIC, and STC varied greatly with the reclamation duration, soil depth, and their interaction (Table 2). Based on a multiple stepwise regression, the contents of SOC, SIC, and STC were closely related to the proportion of silt and the reclamation duration, especially the former (Table 3).

3.3 Soil C stock

Whether SOC or SIC, the stocks in the 0–100 cm layer significantly increased with reclamation duration, with the rates of 2.73 Mg C ha⁻¹ yr⁻¹ for SOC stocks and 5.54 Mg C ha⁻¹ yr⁻¹ for SIC stocks (Fig. 3). Thereinto, the SOC and SIC stocks of the plow layer, i.e., 0–20 cm, increased substantially with rates of 1.23 and 0.91 Mg C ha⁻¹ yr⁻¹, respectively.

Table 2 Results (*F* values) of two-way analysis of variance indicating the effects of reclamation duration (D), soil layer (L), and their interactions on the soil organic carbon (SOC), soil inorganic carbon (SIC), soil total carbon (STC), soil bulk density, pH values, and soil fractions

Treatments	df	SOC	SIC	STC	Bulk density	pH	Proportion of sand (%)	Proportion of silt (%)
D	3	87.6***	168.7***	364.3***	18.8***	171.4***	4.2*	66.5***
L	4	55.0***	9.6***	62.7***	1.84 ns	23.9***	0.7 ns	5.6**
D * L	12	11.0***	15.1***	21.4***	4.6***	8.1***	1.4 ns	11.9***

ns, not significant; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001

The SIC stocks showed a positive relationship with the SOC stocks (Fig. 4). By contrast, the SIC stocks were always greater than the SOC stocks, regardless of the reclamation duration (Fig. 3). However, the ratio of SOC to STC stock increased from 8.95% (the natural floodplain) to 25.53% (the Y33 croplands), with no significant difference between the Y24 and Y33 croplands, while the ratio of SIC to STC stock gradually decreased along the chronosequence. Compared to most studies regarding croplands, the soil C stocks (especially SOC stock) in the Y33 croplands were at a relatively higher level (Table 4).

4 Discussion

4.1 Changes of SOC with reclamation duration

In our study, the SOC stocks were found to increase with reclamation duration, which is consistent with our first hypothesis. Similar results were also found in previous studies (Ewing et al. 2012; Zhang et al. 2019), e.g., SOC content and stock exhibited an increasing trend with the chronosequence after tidal flat reclamation (Zhang et al. 2017). Such phenomenon is explained by the following mechanisms. First, plant-derived organic matter, including crop residue and root

exudates, directly increased SOC contents (Hati et al. 2007; Liang et al. 2012), and the application of organic manure further strengthens such effects (Steiner et al. 2007; Awale et al. 2013; Zhang et al. 2017). Second, the proportion of fine soil particles increased with the reclamation chronosequence, which is beneficial to the SOC-storing potential (Hassink 1997; Wiesmeier et al. 2015; Lal 2018) as well as a reduction of leaching (Six et al. 2000). Indeed, SOC contents in this study were found to increase synchronously with the silt fraction along the reclamation chronosequence. Similar to our study, Zhang et al. (2017) also verified the critical role of silt fraction on SOC accumulation in coastal reclaimed lands. Third, irrigation water from Yellow River also contributes to SOC accumulation for these croplands, owing to the contained fine particles (Sun et al. 2015) and organic matter (Zhu et al. 2012). The same mechanism was also confirmed by Dong et al. (2018), showing that long-term irrigation with the Yellow River water increased soil fine particles and organic C in croplands located in the middle reaches of the Yellow River. When taken together with previous works, our results indicate the promotion of agricultural activities on SOC accumulation in floodplains.

Similar to various natural ecosystems, the SOC contents were highest in the surface layer for this study. Moreover, the topsoil exhibited a significantly greater SOC accumulation

Fig. 2 Soil organic carbon (SOC), soil inorganic carbon (SIC), and soil total carbon (STC) concentrations at different soil depths across the reclamation chronosequence. Data are means and error bars are SD (*n* = 3). Note: Y0, natural floodplains free of reclamation; Y13, Y24, and Y33 represent croplands reclaimed for 13, 24, and 33 years, respectively

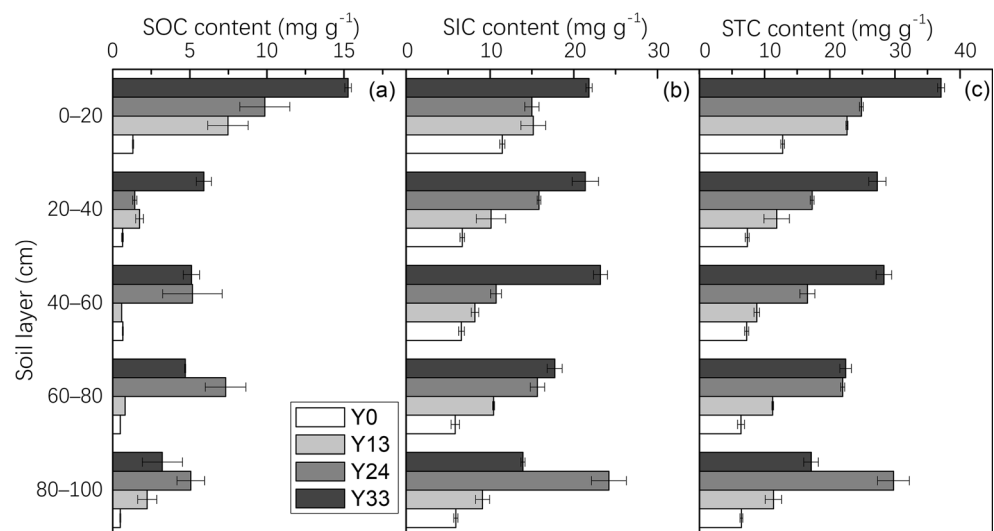


Table 3 Results of multiple stepwise regressions for soil organic carbon (SOC), soil inorganic carbon (SIC), and soil total carbon (STC)

	Step	Factors entered	<i>F</i>	<i>P</i>	<i>R</i> ²
SOC	1	Proportion of silt	53.9	< 0.001	0.473
	2	Proportion of silt, reclamation duration	21.3	< 0.001	0.506
SIC	1	Proportion of silt	195	< 0.001	0.766
	2	Proportion of silt, reclamation duration	160	< 0.001	0.843
STC	1	Proportion of silt	214	< 0.001	0.783
	2	Proportion of silt, reclamation duration	179	< 0.001	0.858

In the analyses, the proportion of sand and pH were excluded from the model because of the tight correlation ($r > 0.800$) with the proportion of silt and the reclamation duration, respectively

rate than deeper soil layers after reclamation, presumably due to accumulation of crop residue in the topsoil (Novara et al. 2015). Such results agree with our second hypothesis and suggest a crucial role of the plow layer on SOC storage. However, the Y24 croplands were found to accumulate a large amount of organic C in deep soils, i.e., the 60–100 cm layer, where the SOC contents were significantly higher than in the 20–40 cm layer. Such phenomenon could be primarily attributed to the high proportion of silt in this layer, presumably induced by a high variability in alluvial plains. Because of leaching, large amounts of organic compounds would infiltrate into the deep soils and be absorbed by these fine soil particles, resulting in SOC accumulation (Kindler et al. 2011; Kaiser and Kalbitz 2012). In another typical fluvial plain, namely, the Yellow River Delta, Li et al. (2014) also found SOC accumulation phenomenon in deep soils where there were also high proportions of fine soil particles. Taken together, the silt-rich deep soils may not be a consequence of reclamation, which could cause an overestimation of the SOC

stock in deep soils of Y24 croplands. However, the crucial role of fine soil particles in SOC accumulation was further confirmed.

4.2 Changes of SIC with reclamation duration

Like SOC, the SIC often also plays an important role in terrestrial C budget (Batjes 1996; Shi et al. 2017; Zhang et al. 2019). Our present study provides more supporting evidence for our first hypothesis, i.e., SIC stock greatly increased along the reclamation chronosequence. Moreover, SIC stock even presented a greater increase relative to SOC stock, 182.8 versus 90.2 Mg ha⁻¹, after 33 years of reclamation. The increased SIC stock may be related to the following mechanisms. First, agricultural activities result in a rise of CO₂ concentration in soil columns due to a facilitated microbial mineralization after reclamation (Wang et al. 2014), thus leading to increased HCO₃⁻ concentrations, which is beneficial to SIC precipitation (Guo et al. 2016; Shi et al. 2017; You et al. 2020). Moreover, the increase in SIC stock could be partly explained by the increased silt fractions with reclamation duration, because improved soil texture contributes to accumulating SIC not only by decreasing the CO₂ exchange between the atmosphere and soil but also by reducing SIC leaching (Gaines and Gaines 1994; Kindler et al. 2011). Furthermore, long-term irrigation with the water from the Yellow River is also noteworthy, as it contains high concentrations of Ca²⁺ (45 ~ 51 mg L⁻¹) and Mg²⁺ (22 ~ 26 mg L⁻¹) and thus is well known to have a positive effect on SIC precipitation (Guo et al. 2016).

In the North China Plain, the average amount of SIC in the 0–100 cm layer was 165 Mg C ha⁻¹ in croplands (Shi et al. 2017), which is comparable to that in the Y13 croplands but far lower than both Y24 and Y33 croplands. Such results imply a high inorganic C accumulation potential of croplands reclaimed from natural floodplains. In the lower reaches of the Yellow River, more than 70% of riparian floodplains have been reclaimed, mostly after the construction of Xiaolangdi Dam in 1999 (Zhang 2018). This suggests that for decades and even to this day, these croplands have been playing a vital

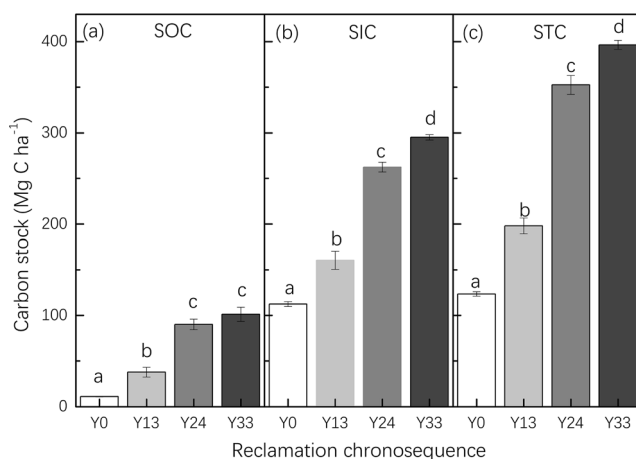


Fig. 3 Stocks of soil organic carbon (SOC), soil inorganic carbon (SIC), and soil total carbon (STC) at 0–100 cm depth across the reclamation chronosequence. Different lowercase letters indicate significant differences among reclamation duration treatments ($P < 0.05$). Data are means and error bars are SD ($n = 3$). Note: Y0, natural floodplains free of reclamation; Y13, Y24, and Y33 represent croplands reclaimed for 13, 24, and 33 years, respectively

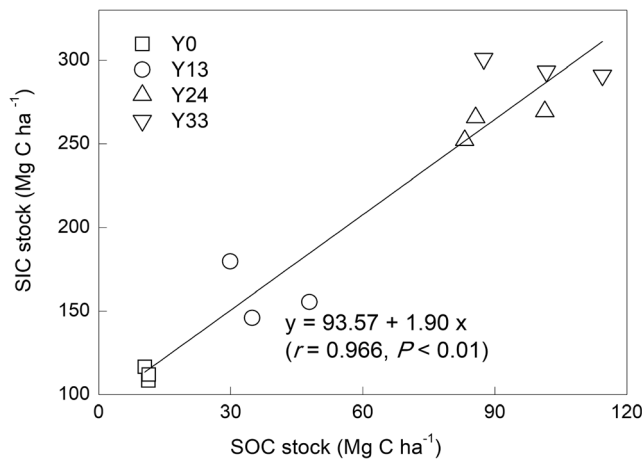


Fig. 4 Simple linear relationship between the soil inorganic carbon (SIC) stocks and the soil organic carbon (SOC) stocks at 0–100 cm depth

C sink role by accumulating SIC. Nonetheless, pH was found to decrease with the reclamation duration, which may be partly due to the addition of nitrogen fertilization (Raza et al. 2020) as well as the CO₂ emission during organic C mineralization (Andrews and Schlesinger 2001). Soil acidification is believed to interfere with SIC storage in soils (Raza et al. 2020), which may slow the increase rate of SIC stock after a long-term reclamation. However, the issue of soil acidification is not the primary focus of this study.

In soil profiles, SIC contents were higher in the topsoil of natural floodplains, with an obvious decreasing trend with soil depth. However, such a trend gradually weakened with reclamation duration, which is inconsistent with our second hypothesis. Similar to our results, previous studies suggested that long-term reclamation may cause SIC redistribution

throughout the soil profile (Guo et al. 2016). For instance, the SIC content showed a slightly increasing trend with soil depth in the cropland of the upper Yellow River Delta (Guo et al. 2016). In addition to leaching owing to irrigation (Gaines and Gaines 1994; You et al. 2020), the accumulated Ca²⁺ and Mg²⁺ in deep soils also favor SIC accumulation (Shi et al. 2017). Moreover, the SIC loss caused by the lower pH in topsoil was also a potential reason (You et al. 2020). Considering that deep soil C has a long turnover time, the increased SIC proportion in deep soil with increased reclamation duration is beneficial to long-term C sequestration.

4.3 Soil stocks compared with other areas

In this study, the STC stocks increased from 123 Mg C ha⁻¹ to 396 Mg C ha⁻¹ after 33 years of reclamation. The stock was lower relative to that in the Yanqi Basin of northwest China (512 Mg C ha⁻¹, Wang et al. 2015a), mainly due to a lower increase in SIC stock. The reasoning behind this may lie in the differences of climate conditions, soil types, and reclamation duration (Guo et al. 2016). Nonetheless, the STC stock in our study area was still at a higher level compared to that in most previous studies (Table 4) due to a significant increase of both SIC and SOC after reclamation. Based on the comparative analysis, our findings confirm the contribution of reclamation to C accumulation in riparian floodplains.

Based on comparison with previous studies, we also realized that the croplands reclaimed for > 40 years usually have a lower C stock relative to the croplands (13 ~ 33 a) investigated in this study. Of course, the differences in crop species, tillage methods, beginning soil conditions, and climate inevitability account for such phenomenon. Additionally, C loss resulting

Table 4 The stocks of soil organic carbon (SOC), soil inorganic carbon (SIC), and soil total carbon (STC) in cropping lands at 0–100 cm depth

Location	Soil classification	Reclamation duration	SIC (Mg C ha ⁻¹)	SOC (Mg C ha ⁻¹)	STC (Mg C ha ⁻¹)	Reference
35° 24'–36° 48' N, 102° 54'–105° 00' E	Calcaric Regosol	> 50 a	208	60	268	Zhang et al. 2015
36° 38'–38° 09' N, 114° 27'–117° 28' E	Calcaric Cambisol and Fluvo-aquic	> 50 a	165	75	240	Shi et al. 2017
36° 50'–37° 45' N, 117° 20'–117° 10' E	Fluvo-aquic	> 50 a	169	57	226	Guo et al. 2016
36° 52' N, 115° 100' E	Fluvic Cambisol	40 a	112	66	178	Bughio et al. 2016
42° 10'–41° 55' N, 86° 20'–86° 33' E	Haplic Calcisol	40 ~ 60 a	420	92	512	Wang et al. 2015a
44° 44' N, 123° 44' E	Salic Solonetz	24 a	179	92	260	Yu et al. 2014
46° 87'–47° 98' N, 124° 53'–125° 16' E	Haplic Fluvisol	–	170	98	268	You et al. 2020
34° 53' N–34° 57' N, 114° 7' E–114° 10' E	Fluvo-aquic	33 a	295	101	396	This study

from soil tillage may be another potential mechanism behind such phenomenon. After a long-term reclamation, the soil C stock will gradually reach a balance between C capture and C loss (Zhang et al. 2019). Moreover, the increasing farming intensity, as well as the resulting soil acidification due to long-term farming, has the potential to accelerate C loss, eventually leading to a decline of soil C stock (Kindler et al. 2011; Zhang et al. 2019). Unfortunately, we failed to provide supporting evidence for such an assumption in this study. The follow-up research on the current croplands can help reveal soil C stock dynamics after long-term reclamations, as well as the potential mechanisms.

4.4 Limitations of the study

Space-for-time substitution is an important and often necessary tool for investigating soil development, and the ideal chronosequence is defined as a sequence with similar starting conditions and under the influence of constant or ineffectively varying climatic and biotic factors (Walker et al. 2010; Huang et al. 2015). To minimize the effects of factors beyond the reclamation chronosequence, we chose plots with similar starting soil characteristics (and relatively consistent management practices for the croplands) in this study following a consultation with the agriculture department and local farmers. As a result, the effects of reclamation on soil C pools were vividly presented, especially in the 0–20 cm layer (i.e., the plow layer), and even the 20–40 cm layer, where both SOC and SIC increased substantially along the reclamation chronosequence. Nevertheless, the high spatial variability generally arising in alluvial plains is still an interference to our study. Specifically, the high silt proportion at 60–100 cm soil depth of the Y24 treatment is an inexplicable issue, which may lead to an overestimation of soil C stock in this layer and a misrepresentation of vertical pattern. For the space-for-time substitution study on flood plains, the comparability of starting conditions among plots is indeed difficult to achieve. To avoid erroneous inferences about the observed results, a pre-survey about lithologic discontinuity, in addition to inquiring native people, is necessary for chronosequence studies (Schaeztl 1998; Chen and Zhang 2011; Huang et al. 2015). Alternatively, another investigation on these chosen plots 5 to 10 years later can help compensate the shortcomings of our current study.

In this study, the 80–100 cm soil layer was found to still contain high contents of organic and inorganic C, which should mainly result from high leaching in soil profiles rich in coarse particles. Such phenomenon indicates that the results regarding soil C stock within 100 cm depth underestimates the positive effect of reclamation on

soil C accumulation, and further studies are necessary to pay attention to determine the C stock in deeper soils (> 100 cm).

5 Conclusions

In riparian floodplains located in the lower reaches of the Yellow River, soil C contents always varied greatly in the soil profile, and the topsoil generally contain higher SIC and SOC contents. Moreover, both SIC and SOC stocks showed an increasing trend with reclamation duration, with the mean increase rate of 2.73 Mg C ha⁻¹ and 5.54 Mg C ha⁻¹, respectively. Specifically, the SOC content increased more in the topsoil along the reclamation chronosequence, but the SIC content often had a higher increase rate at deeper depths. Based on a multiple regression, the contents of SOC, SIC, and STC were positively related to the proportion of silt. Our findings suggest that the reclamation of riparian floodplains plays an important role in C accumulation and highlight the importance of soil inorganic C in C budget, and the plow layer is crucially important in C accumulation. Moreover, soil C accumulation is closely related to soil texture, which changes continuously along the reclamation chronosequence, and is often governed by spatial heterogeneity of riparian floodplains.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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