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# Low organic carbon storage of sediment due to frequent river course changes in Yellow River Delta

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ABSTRACT

Coastal alluvial plains in river deltas can store significant carbon by burying upland sediments and former topsoil. The Yellow River Delta, shaped by continuous upstream sediment deposition and shifting river courses, offers a unique case to study this. We collected five 2 m soil cores along a sediment sequence reflecting 80 years of deposition and river course changes. Our analysis of soil organic carbon (SOC) stocks and sources revealed that older river courses hold less SOC than newer ones. SOC was generally low, except near the surface. Upstream-derived organic carbon contributed more to SOC stocks than local vegetation, especially in younger sediments. All sediments showed high inorganic carbon and alkaline conditions, pointing to loess-derived subsoils from the uplands as the primary sediment source. These subsoils, low in organic carbon and weathering, indicate rapid erosion and a degraded terrestrial carbon cycle upstream. Although deltaic settings could protect deposited carbon, our findings highlight the limited increase in SOC due to the input of C-depleted materials. Therefore, soil conservation is critical not only in the delta but also in its erosion-prone upland sources.

## 1. Introduction

To address the challenges of global climate change, China has articulated its "double carbon" objectives, which include reaching peak carbon emissions by 2030 and attaining carbon neutrality by 2060 (Lim et al., 2007; Wang et al., 2021). These commitments highlight the critical need to preserve existing carbon (C) stocks, enhance C sequestration efforts, and remarkably reduce current emissions. Rivers play a vital role in regulating C turnover over various time scales by exporting large fluxes of C from upstream deposited sources ($C_{depo}$) from the continent towards the ocean, often with larger depositions of C-enriched sediments in coastal deltas (Yu et al., 2019; Li et al., 2021). Across all ecosystems, a particular focus lies on coastal wetlands, which play a vital role in C storage and sequestration (Ouyang and Lee, 2020; Poulter et al., 2021; Li et al., 2022). Coastal wetland sediments can store large amounts of C, thereby limiting C losses that occur through erosion in upland areas and greenhouse gas emissions (Van Oost et al., 2007; Doetterl et al., 2015; Wang et al., 2017) and contributing to the mitigation of global warming (Mcleod et al., 2011). The global average long-term C sequestration per unit area in coastal wetlands, ranging from 22 to 25 Mg C ha$^{-1}$ century$^{-1}$, is significantly higher compared to, for example, terrestrial forests (ranging from 0.7 Mg C ha$^{-1}$ century$^{-1}$ to 13.1 Mg C ha$^{-1}$ century$^{-1}$). This is partly due to their high efficiency in trapping organic matter during tidal inundation (Mcleod et al., 2011). Therefore, vegetation types and sediment loads are key factors influencing the provenance and preservation of C in these ecosystems. However, organic C sequestration processes in these environments are complex and influenced by multiple variables that affect soil organic carbon (SOC) storage in sediments. For example, the source of upstream deposited sediment may be C-enriched (from the upstream top

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sediment) or C-depleted (from the upstream bottom sediment) compared with the average SOC, affecting the resulting sediment C stock. Similarly, the rate of sediment deposition affects the preservation of in-situ topsoil SOC because rapid sedimentation can diminish the long-term carbon sequestration potential of coastal wetland soils by limiting their capacity for carbon enrichment (Fennessy et al., 2019). Therefore, the migration of the river course through coastal wetlands alters several factors such as river discharge, sediment deposition rates as well as local physical and chemical environments ( Nienhuis et al., 2020) that can affect SOC preservation as well as its spatial distribution ( Zhao et al., 2019).

Previous studies focused on the sediments of relatively stable floodplains, such as the Mississippi River course (Dodla et al., 2012; Schoolmaster et al., 2022). However, there has been limited research on rapidly evolving floodplains. The Yellow River Delta is an ideal region for studying the effects of rapid sediment deposition and river course changes on SOC depth profiles and stocks. It has long been known for its enormous sediment transport capacity, conveying billions of tons of sediment each year (Yang and Ji, 2011), which are eroded in its upland areas, mainly due to agricultural land expansion and the consequent topsoil degradation and mobilization (Wohlfart et al., 2016). Since 1855, the Yellow River has frequently changed its course due to natural or anthropogenic breaches (Zhao et al., 2015). Between 1889 and 2002, 11 changes in the main river course were observed (Ganti et al., 2014). Under the circumstance of such frequent changes in river flow paths, the upstream deposited sediment carries a large quantity of organic matter, resulting in notable changes in the SOC stock ($SOC_{Stock}$) within the delta. Down to a sediment depth of 0.3 m from the surface, the entire Yellow River Delta is estimated to contain approximately 3.55 million tons of C (Yu et al., 2012). But both its spatial distribution and C stocks in subsoil show marked uncertainty. In a typical annual cropping system, varying rates and degrees of erosion in the upland areas can lead to the deposition of not only C-enriched topsoil, but also C-depleted subsoil. This is because sediment erosion occurs at a faster rate than the replenishment of soil carbon through plant inputs (Doetterl et al., 2016; Berhe and Torn, 2017; Harden et al., 2018; Van Oost and Six, 2023).

Here, we assess the relationships between upstream sediments deposited during the 20th century along the main river courses of the Yellow River in its delta and the resulting $SOC_{Stock}$ and their sources (upstream deposited vs. in-situ produced). The main questions behind our work are (i) whether the Yellow River Delta is an efficient and numerous $SOC_{Stock}$, (ii) to identify potential changes in $SOC_{Stock}$ over time and (iii) to identify the main sources of SOC found in the sediments of the delta. We hypothesize that i) the C storage in the Yellow River Delta is lower than other global mature wetland because it is a new delta and avulse frequently receiving eroded soil in abundance. In addition, ii) $SOC_{Stock}$ of older river courses should be smaller than those in younger courses in the Yellow River Delta, since the newly upstream deposited SOC is less degraded and has been deposited faster than in former times contributing to the protection of SOC through burial. Furthermore, iii) SOC sources of the Yellow River Delta include upstream transported and deposited fresh particulate organic matter, as well as local C from in-situ vegetation. Due to the high sediment input and sparse vegetation in the Yellow River Delta, its main C source should be the upstream C from eroded soil. By understanding the complex interactions influencing SOC in the sedimentary environment of the Yellow River Delta, our findings can provide insights to effectively identify, manage, and conserve coastal environments.

## 2. Materials and methods

### 2.1. Study area

The study was conducted in the Yellow River Delta in northern China (37°20′-38°15′N, 118°0′-119°20′E), which predominantly formed through sediment deposition in the 20th century ( Fig. 1), following accelerated sediment deposition that began in the mid-19th century. The study area experiences a typical warm temperate continental monsoon

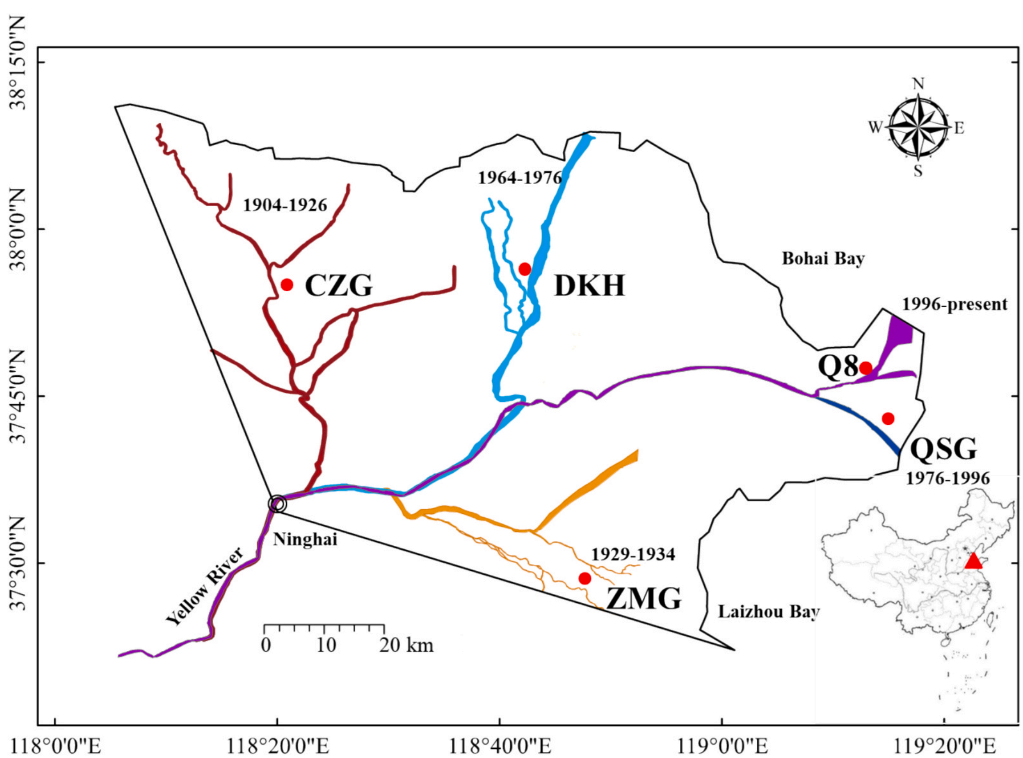


**Fig. 1.** The study area is located in the Yellow River Delate, China. This map was adapted from Zhao et al. (2015) with the changes of the main course courses of the Yellow River in its Delta marked and dated. Red points indicate sampling sites of sediment cores used in this study (Named after abbreviations of the historic main course and its current equivalent, Q8).

climate, with an annual average temperature of 12–13 °C and an annual average precipitation of 530–630 mm (Cui et al., 2011). The sediment median grain size ranges from 15 to 35 μm, with silt dominating the area (Wu et al., 2017). The Yellow River Delta resembles a typical fan-shape in which the river has altered its course numerous times within this area, both naturally and artificially. Among the five most important former main courses of the river are named: Chezigou (CZG) from 1904 to 1926, Zhimaigou (ZMG) from 1929 to 1934, Diaokouhe (DKH) from 1964 to 1976, Qingshuigou (QSG) from 1976 to 1996, and Qing8 (Q8) course from 1996 to the present (Zhao et al., 2015).

### 2.2. Field sampling and laboratory analysis

To determine the sediment properties along different Yellow River courses, five sediment cores (in the proximity of each of the former and current main courses named above) were drilled to a depth of 2 m using a 9.2 cm diameter drilling system with stamping machine and stainless steel tube (Li et al., 2025). Sampling sites were selected according to proximity to the rivers, good preservation without intense human activities and landuse changes, the evidence was provided by Fig. S4 and Table S1. Soil samples in each core were collected at 20 cm depth intervals, with 2 cm of soil taken from each interval for measurement, and there was no mixing of the samples from different depths. The samples were weighed while still wet after removing visible plant roots and stones. Subsequently, all sediment samples were dried in an oven at 60 °C. The dry bulk density was calculated by dividing dry weight by sample volume. After grinding, texture and particle size of every 0.2 m were analyzed using a laser particle size analyzer (LA960, Horiba Ltd., Japan) and classified into three categories: clay (≤2 μm), silt (2 μm ≤63 μm), and sand (>63 μm). pH of the sediment–water mixture (1:5 mass-to-volume ratio) was measured using a pH meter (HI 8424, Hanna Instruments Ltd., America) (Tandon, 2013) (reported in Table S1, also including SOC content ($SOC_{Content}$), soil inorganic carbon (SIC) content, total nitrogen (TN), dry bulk density, and sediment texture). Prior to measuring $SOC_{Content}$), dried samples were treated with 10 % HCl and then rinsed with deionized water to remove interference from SIC. SOC and TN contents were determined using an elemental analyzer (VARIO EL III, Elementar Analysensysteme GmbH Ltd., Germany) for three times replicate measurements, and the SOC/TN ratio (C/N) was calculated. For later C source identification, stable C isotope ratios ($\delta^{12}C$/ $\delta^{13}C$) were measured using an isotope mass spectrometer (FISHER 253PLUS, Thermo Fisher Scientific Ltd., Germany). To date the sediment age, an HPGe Gamma Spectrometer (Gamma-X, #) in State Key Laboratory of Earth Surface Processes and Resource Ecology of Beijing Normal University was adopted to measure $^{137}Cs$ and $^{210}Pb$ concentration for each analyzed depth increment (Lubis, 2006). HPGe Gamma Spectrometer enables precise measurement and discrimination of closely spaced gamma-ray energies. For common energy levels such as the 1.33 MeV emission from $^{60}Co$, the resolution typically ranges from 1.8 % to 2.0 %, ensuring accurate radiological analysis. In addition, the counting time was around 40,000 s. Specifically, the sampling intervals for sediment dating were standardized at 0.2 m, except for the top 0.2 m, where a 0.1 m interval was used to enhance the precision of $^{137}Cs$ dating. $^{137}Cs$ is used here as the independent time marker to make the dating more precise.

### 2.3. Data processing

#### 2.3.1. SOC quantity in sediment

To assess the C spatial distribution, we measured the sediment organic carbon content and sediment organic carbon density (Wang et al., 2004) as follows:

$$SOC_{Den} = SOC_{Content} \times DBD \times D \quad (1)$$

where, $SOC_{Den}$ represents the sediment organic carbon density in the sediment samples (kg C m$^{-2}$), $SOC_{Content}$ represents the content of soil organic carbon (g kg$^{-1}$), $DBD$ represents the dry bulk density (g cm$^{-3}$), $D$ represents the depth interval (m) of the subsamples. The $SOC_{Den}$ was used for the calculation of C storage. In addition, the $Sediment_{Stock}$ was calculated based on the dry bulk density.

#### 2.3.2. Carbon source assessment

To assess the carbon source (upstream transported and deposited fresh particulate organic matter ($C_{depo}$), and local and in-situ vegetation ($C_{insitu}$)), we used the carbon–nitrogen ratio (C/N), and stable C isotope signature of the samples to parameterize the C source identification model MixSIAR model (Stock and Semmens, 2016). The $\delta^{13}C$ and C/N of upstream transported and deposited fresh particulate organic matter and local and in-situ vegetation (*Phragmites australis* and *Suaeda salsa*) were obtained from datasets collected from the same species and geographical location as the study area and are presented in Tables S2–S3. In addition, we used $\delta^{13}C$ values and C/N ratio from the literature as end-member values to justify the sediment C source. Specifically, end-member values of $C_{depo}$ were obtained from the literature, with C/N (5.21 ± 0.17) and $\delta^{13}C$ (−24.77± 0.5) (Table S2). Correspondingly, the end-member of $C_{insitu}$ showed C/N (60.45 ± 9.23) and $\delta^{13}C$ (−27.76 ± 1.5) (Table S3).

MixSIAR is an open-source R software that provides a comprehensive analysis of the uncertainties in source proportions that contribute to an observed mixture of C sources in sediments. These uncertainties are derived from the prior distribution, ensuring a robust evaluation of source contributions. Notably, the prior discrimination assumption in MixSIAR was set to 0, as no prior information was available on the ratio of upstream deposited vs. in-situ buried C. The posterior probability density functions of the relative source contributions of $C_{depo}$, and $C_{insitu}$ of core sediment samples are shown in Figs. S5–S9. To increase the model accuracy, we set the iteration mode as "extreme" and all the runs were passed through the Gelman diagnostic to evaluate the convergence of multiple Markov Chain Monte Carlo chains as well as the Geweke diagnostic to assess the convergence of a single Markov Chain Monte Carlo chain by comparing the mean and variance of subsets of the chain. All the diagnostic values should be less than 1.05.

#### 2.3.3. Sediment dating

To determine sediment ages, we employed $^{137}Cs$ and $^{210}Pb$ dating for each sediment layer. $^{137}Cs$ is an anthropogenic radionuclide originating from atmospheric nuclear weapon tests and nuclear accidents, with its primary settling period globally observed from 1958 to 1968. Notably, the Chornobyl nuclear disaster in 1986 and the peak of global atmospheric nuclear testing in 1963 are pivotal for sediment dating due to the deposition of $^{137}Cs$ during these events (Wu et al., 2015; Zhou et al., 2020). In this study, $^{137}Cs$ were employed as an independent chronological marker for the sediments, which are shown in 1986 and 1963. Furthermore, our sediment dating technique mainly relies on $^{210}Pb$, which originates from the $^{238}U$ decay series. In this chain, $^{238}U$ decays to $^{226}Ra$, which is naturally present in sediments and rocks. The subsequent decay of $^{226}Ra$ produces $^{222}Rn$, a gaseous isotope that can escape into the atmosphere. Once released, $^{222}Rn$ further decays to form $^{210}Pb$, which returns to the Earth's surface with precipitation and is ultimately incorporated into sediments (Lim et al., 2007). In our study, the measurement of the radionuclide tracer $^{210}Pb$ in all samples is used to determine the age over the past century at annual to decadal timescales.

To assess the age of sediment in coastal area, we follow the research of Lubis (2006) using a model assuming a constant rate of supply for $^{210}Pb$ (CRS model) is employed (Olid et al., 2016). In this model, sediment age $t$ is assessed as follows:

$$t = \frac{1}{\lambda_{Pb}} \ln\left(\frac{C(0)}{C(Z)}\right) \quad (2)$$

where $C(0)$ (Bq kg$^{-1}$) is the total activity of $^{210}Pb$, $C(Z)$ (Bq kg$^{-1}$) is the specific activity of $^{210}Pb$ when the depth is $Z$ (m), and $\lambda_{Pb}$ is the decay constant (0.03114 yr$^{-1}$) of $^{210}Pb$. In addition, the sediment deposition rate was calculated by sediment depth divided by the sediment period (Wang et al., 2013).

To calculate the $SOC_{Stock}$ and sediment stock ($Sediment_{Stock}$), all sediments have then been structured and aggregated into depth-explicit 20 years increments.

### 2.4. Statistics analyses

All statistical analyses and collinearity diagnostics were conducted using IBM SPSS version 23 (Armonk, NY, USA). The MixSIAR analysis was calculated using R software version 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria). Statistical significance of differences between samples was assessed by one way analysis of variance (ANOVA) with the least significant difference (LSD) post hoc multiple tests at $p < 0.05$.

## 3. Results

### 3.1. Basic physiochemical properties across main river courses

Dry bulk density ranged from 0.8 to 1.6 g cm$^{-3}$, without significant variation across different river courses and soil depth ($p > 0.05$, Table S1). Soil texture was dominated by silt (Table S1). $SOC_{Content}$ ranged between 0.1 and 8.0 g kg$^{-1}$ soil with topsoil (0–0.2 m) exhibiting higher $SOC_{Content}$ compared to the subsoil (0.2–2.0 m) across all main river courses (Table S1). Similarly, SIC values ranged between 8.7 and 13.5 g kg$^{-1}$, and were approximately ten times higher than $SOC_{Content}$ across all main river courses (Table S1). Conversely, TN content (0.2 ± 0.1 g kg$^{-1}$) was about ten times lower than $SOC_{Content}$ (1.0 ± 1.0) (Table S1). The soil pH was relatively high (8.2 ± 0.4), indicating mostly alkaline conditions, without significant variation across soil depth and river courses (All values can be found inTable S1). For the sedimentary describtion, the cores predominantly move from silty clay to clayey silt from top to bottom, with rare localized strata of grayish-black material and irregular occurrences of silty sand in between.

### 3.2. Ages distribution of sediments across main river courses

Vertical profiles of excess $^{210}Pb$ and $^{137}Cs$ activities across five sediment cores in the Yellow River Delta were depicted in Fig. 2. $^{210}Pb$ values across all sediment samples ranged from 0 to 100 Bq kg$^{-1}$. Accordingly, $^{137}Cs$ ranged between 0 and 3 Bq kg$^{-1}$. Peaks of sediment deposition after 1963 (peak of weapon test $^{137}Cs$ deposition) and 1986 (Chornobyl incident) could be found in all sediment cores, but in some cores taken in younger main river courses (younger than 1964), only the 1986 peak was found. In general, cores taken in older courses (older than 1964) of the main course showed slower deposition (the dating indicating the year 1986 was found closer to the surface) than younger main courses (younger than 1964). Notably, across all sediment cores, the entire sediment body of the assessed upper 2 m of sediment was consistently younger than 1942 and, therefore, the deposition time of the collected sediments is less than 80 years (Fig. 2). Notably, our results from the neighboring DKH core dated to 1971 at a depth of 1.8 m, and Gong (2010) found that the core ZK5 dated to 1976 at a depth of 1.73 m. Our dating results were in agreement with Gong (2010)'s findings. To estimate the dating uncertainty, we adopted Monte Carlo Model, we set the simulation times as 1000, the range is $^{210}Pb$ average ± error. This result further strengthens the credibility of the dating (Fig. S2).

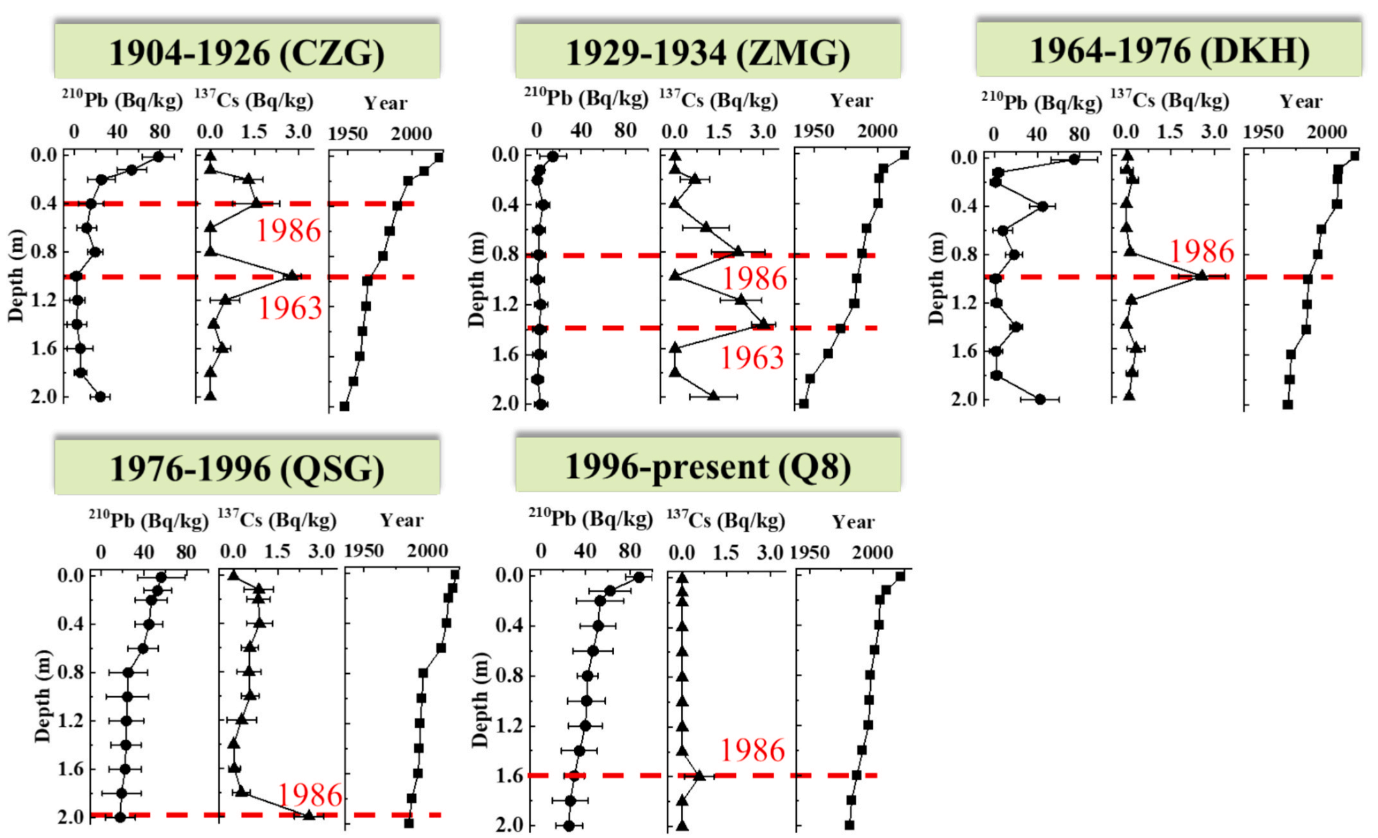


**Fig. 2.** $^{210}Pb$, $^{137}Cs$, and age change trends with increasing depth showing mean values with standard error bars. 1986 represents the Chornobyl incident, and 1963 represents the peak global atmospheric nuclear testing period. The period listed on top of each graph indicates the period in which the assessed course represented the river's main course in the delta.

### 3.3. Sediment and SOC stocks across main river courses

$Sediment_{Stock}$ to a depth of 2 m sediment varied between 2.3 ton $m^{-2}$ (core DKH) to 2.7 ton $m^{-2}$ (core Q8) in the past 80 years without significant differences ($p > 0.05$, Fig. 3). Sediment deposition was higher in the young river courses (core QSG and Q8). In contrast, sediment deposition was lower in the old river courses (core CZG, ZMG and DKH) over the last 36 years (Fig. 3). The younger cores (core DKH, QSG, Q8) had fast sediment deposition, thus only two or three periods were found in 2 m (Fig. 2). However, the old cores (core CZG, ZMG) had relatively slow sediment deposition, which showed four periods in 2 m (Fig. S2).

$SOC_{Stock}$ to a depth of 2 m sediment varied substantially across the investigated cores with a range of 2.2 kg C $m^{-2}$ $yr^{-1}$ (Core CZG) and 5.8 kg C $m^{-2}$ $yr^{-1}$ (Core QSG) (Fig. 3). The sediment core taken in the oldest river course (core CZG) had the lowest $SOC_{Stock}$ compared with other cores taken in younger main river courses (cores ZMG, DKH, QSG, Q8).

### 3.4. SOC sources for different river courses

The MixSIAR model application provided estimates for the relative ratio of SOC sources ($C_{depo}$ and $C_{insitu}$) (Fig. 4 and Fig. S3). In all except one (core ZMG in 2002–2022) of the investigated sediment packages, the ratio of upstream deposited to in-situ sequestered C was larger than one indicating a dominance of upstream deposited over in-situ C sources. The $C_{depo}/C_{insitu}$ ratio ranged from 0.8 ± 0.1 (core ZMG in 2002–2022) and 2.4 ± 0.1 (core QSG in 2002–2022. Due to high variation in the data, no significant trend with age of the nearby major river course could be observed. However, when analyzing the data for changes in C origin with the age of the sediment package, older sediments (1942–1962 & 1962–1982) tended to show ratios closer to 1, indicating a higher contribution of organic C from in-situ sources than in the younger sediment packages (1982–2002 & 2002–2022) where ratios indicated a higher contribution of organic C from upstream deposited sources. $SOC_{Content}$ of the different sediment packages ranged from 0.2 ± 0.1 g $kg^{-1}$ (core CZG, 1942–1962) to 2.8 ± 3.0 g $kg^{-1}$ (core Q8, 1982–2022).

## 4. Discussion

### 4.1. Age dependency of SOC stocks but no simple linear dependency of depth

In this study, we find evidence for substantial sediment deposition in all river courses being mobilized predominantly in the second half of the 20th century. Specifically, dating of the sediments at 2 m depth shows they are less than 80 years old (Fig. 2 and Fig. S4). Interestingly, following river course avulsion, sediment deposition rates in the abandoned course decrease significantly ($p < 0.05$, Fig. 2 and Fig. S4). Once the main course has changed, the majority of the sediment load is redirected to the newly formed main course, while the old course receives substantially reduced sediment input (Fig. 3). This redistribution of sediment flux results in a marked disparity in deposition rates between the new and old courses (Fig. S4). And over time, the sediment transport to the abandoned course further diminishes, leading to progressively lower deposition rates (Xue, 1993). Given that sediment input is closely associated with carbon input, this temporal decrease in sedimentation in the old course has implications for carbon sequestration in these fluvial environments (Ji et al., 2022).

The $SOC_{Stock}$ in the Yellow River Delta is comparatively low relative to other delta systems. Quantitative analysis reveals that the Yellow River Delta has a $SOC_{Content}$ of 1.9 ± 1.5g $kg^{-1}$ (Fig. 4 and Table S1), which is substantially lower than that observed in the Liaohe Delta (5.3 ± 0.1 g $kg^{-1}$) (Mao et al., 2018) and the Amazon Delta (6.0 ± 0.4 g $kg^{-1}$) (Sobrinho et al., 2021). This disparity can be partly explained by the fact that SIC predominates over SOC in the Yellow River Delta soil samples (Table S1). This is because the basin's geology provides a wealth of inorganic carbon (carbonates), while the few organic carbon sources are further reduced during transportation as a result of loss and decomposition (Guo et al., 2021). The high SIC values as well as alkaline pH across all investigated sediments (Table S1) and the lack of a pronounced depth pattern of SOC suggest the rapid deposition of source material that already comes with little amount of SOC and is only poorly weathered. Rapid upstream erosion must lead to a swift influx of sediment downstream, causing rapid accumulation along the river and in its delta (Cao et al., 2023). Our study corroborates former evidence that the majority of the sediment source in the Yellow River is the Loess Plateau (Table S1). The origin of the sediments is most likely eroded subsoils from the loess regions of the upland of Yellow river, which are known to

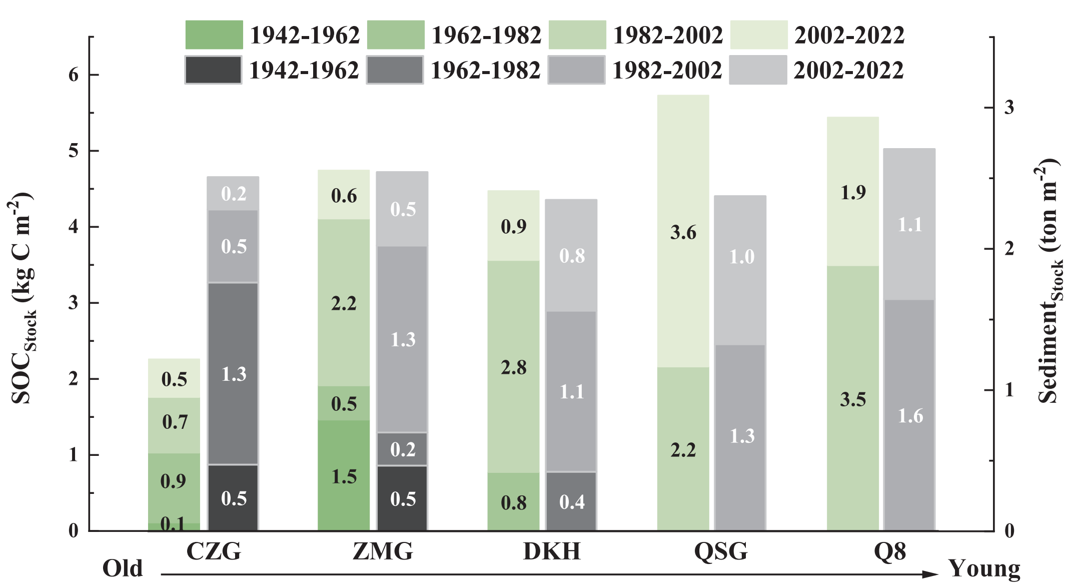


**Fig. 3.** SOCStocks (left bars, green) and SedimentStocks (right bars, grey) for the top 2 m of sediment near the investigated major river courses (from old to young river courses). The period listed on top of each graph indicates the age of the respective sediment package between 1942–2022, aggregated to intervals of 20 years.

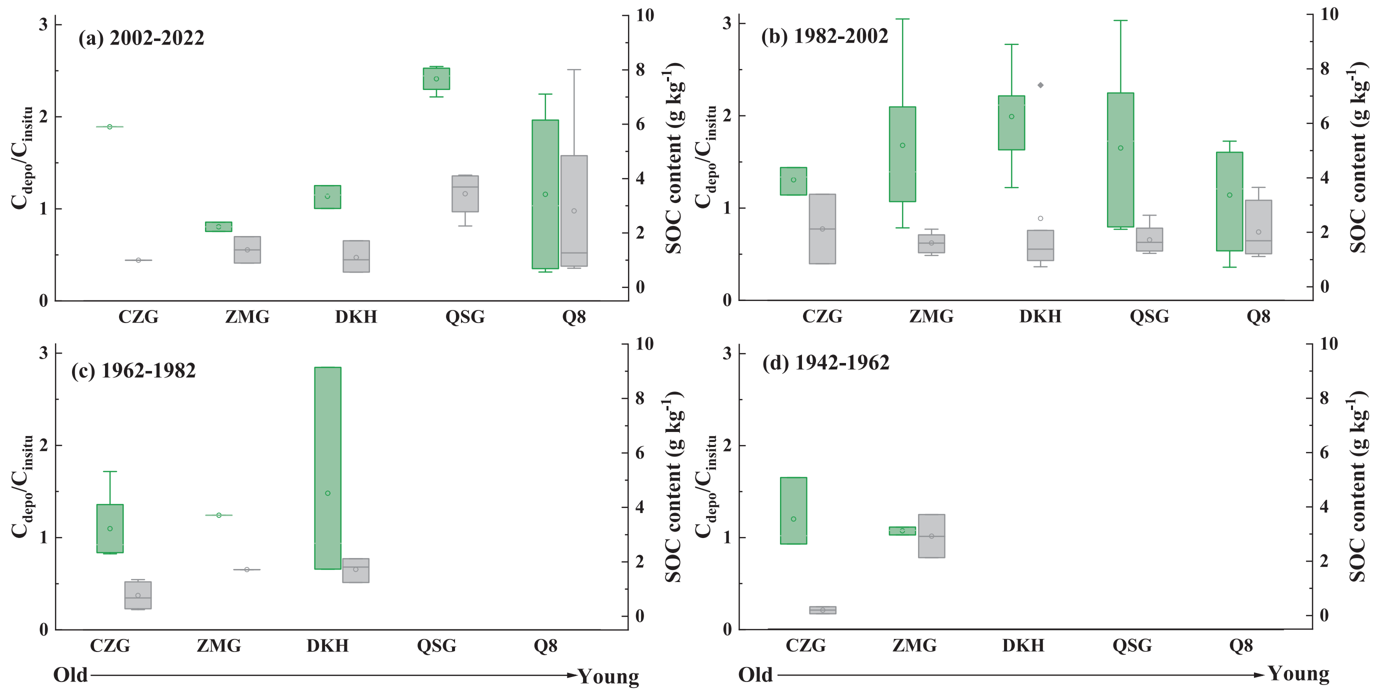


**Fig. 4.** Box-plots showing ratios between upstream deposited and in-situ C sources (left y-axis, green bars) and C concentration (right y-axis, blue bars) for age-defined sediment packages in the major river courses.

show heavy signs of erosion and soil degradation due to agricultural expansion in the 20th and 21st century and the increasing frequency of extreme weather events (Zhao et al., 2022). The Loess Plateau is characterized by its extensive deposits of carbonate-containing loess, predominantly composed of silt-sized particles (Cai, 2001). This fine-grained sedimentary material is highly susceptible to erosion and fluvial transport during precipitation events and subsequent water flow (Amit et al., 2014). The geochemical composition of the Loess Plateau also shows distinctive chemical properties in sediments from there, notably its mild alkalinity with elevated pH values (Table S1, Liu et al., 2013). The Yellow River Delta exhibits sedimentological characteristics that parallel those of its source region. The delta sediments are similarly dominated by silt-sized particles and demonstrate comparable alkaline properties (Table. S1). This geochemical continuity between the Loess Plateau and the Yellow River Delta reflects the low amount of alteration between sediment sources and its area of deposition, which is another indicator for the speed and extent of degradation and deposition dynamics in this geomorphologically highly active environment.

Interestingly, the oldest course which also shows the lowest recent deposition rates holds significantly less SOC than its younger counterparts ($p < 0.05$, Figs. 2 and 3). We interpret this as a sign of less erosion and sediment mobilization in upland areas while SOC decomposition can take place at the depositional sites while the burial of soil under newly upstream deposited sediment takes place. During the burial process, SOC is subjected to decomposition by the activities of microorganisms, fungi, and sediment animals, and oxidation–reduction reactions in sediment, which consume the organic carbon and release carbon dioxide into the atmosphere (Wade et al., 2020). Consequently, over extended burial periods, substantial decomposition of organic carbon occurs, leading to a reduced $SOC_{Stock}$ (Chaopricha and Marín-Spiotta, 2014). Furthermore, in a near neutral high-pH environment, the decomposition and mineralization of organic carbon at the surface are accelerated, primarily due to the increase in hydroxide ions, which triggers chemical reactions (such as hydrolysis and saponification) and the activity of microorganisms and enzymes adapted to alkaline conditions (Luo et al., 2011). Although high pH may inhibit some microorganisms, alkaliphilic microbes and enzymes can still effectively decompose organic matter in such environments (Mamo and Mattiasson, 2016). Notably, the ratio of in-situ to upstream deposited SOC is no different in the older courses compared to younger ones (Fig. 4). This indicates that microbial SOC decomposition as well as sediment deposition dynamics and river course changes are still disturbance enough to not allow for vegetation to grow abundantly and increase the amount of SOC from in-situ sources (Liu et al., 2018).

### 4.2. *The organic carbon source for different river courses*

SOC accumulation in delta ecosystems is primarily derived from two principal sources: allochthonous sediment deposition transported from upstream regions and autochthonous organic matter input from in-situ vegetation litterfall and root exudates (Boix-Fayos et al., 2015). In this study, we found that SOC from upstream deposition ($C_{depo}$) is the main source compared to SOC from in-situ burial ($C_{insitu}$) across all sediments and river courses (Figs. 4 and S5-S9). This contrasts with the C dynamics observed in areas like Yingluo Bay and Dongzhai Bay, where local mangrove vegetation dominates the C source, and the sediment load is much lower in the Yellow River Delta (Liu et al., 2016; Ding et al., 2022). Since 1950, the Yellow River Delta has exhibited an exceptionally high sediment load, averaging approximately $6.7 \times 10^8$ t yr$^{-1}$. This value significantly exceeds those reported for other major river deltas globally ($p < 0.05$). For instance, the Mekong River Delta and the Nile River Delta have reported sediment loads of $1.0 \times 10^8$ yr$^{-1}$ and $1.2 \times 10^8$ t yr$^{-1}$, respectively (Besset et al., 2019). Similarly, the Volta River Delta demonstrates a comparatively lower sediment load of $0.2 \times 10^8$ t yr$^{-1}$ (Li et al., 2021). These comparative data underscore the unique sedimentological characteristics of the Yellow River Delta, potentially influencing its downstream vegetation.

In terms of the local vegetation, the main vegetation in the Yellow River Delta includes *Suaeda salsa*, and *Phragmites australis* (Yu et al., 2019). The vegetation's root-shoot ratio and vertical root dispersion may influence the $SOC_{Content}$ and its vertical distribution. For example, *Phragmites australis* has relatively high $SOC_{Content}$ due to its well-developed root system, extending up to 1.0 m (Yu et al., 2014). But in the Yellow River Delta, the vegetation, including *Suaeda salsa* and

*Phragmites australis*, is sparse compared to other deltas such as the Liaohe River Delta (Huang et al., 2012; Cui et al., 2022). This suggests that the contribution of $C_{insitu}$ would be relatively low, even if deep rooting plants are present, making the contribution of $C_{depo}$ more critical (Figs. 4 and S5-S9). Additionally, compared to SOC derived from plant roots or litter, which is often labile particulate organic matter, the SOC bound within sediment, which is often stable mineral associated organic matter, is more effectively preserved and remains stable over a longer period (Burdige, 2007).

### 4.3. Implications for management

The alkaline condition of the delta soil environment has essential ecological implications, particularly in terms of vegetation adaptation. Loess Plateau and Yellow River Delta support halophytic plant communities, with notable examples including Salicornia and Reaumuria trigyna (Zhang et al., 2018). These species have evolved physiological mechanisms to thrive in high-pH, saline conditions, exemplifying the strong influence of substrate characteristics on local vegetation (Zhang et al., 2018; Chen et al., 2020).

In the context of global carbon emission reductions, $SOC_{Stock}$ in river delta environments is critically important and should receive widespread attention from government and stakeholders. However, in this study, our data indicates that the effective $SOC_{Stock}$ in the Yellow River Delta lags behind its potential capacity, as vegetation C inputs are low (Fig. 4) and the upstream deposited sediments are generally C-depleted compared with other deltas (Fig. 3). While the argument could be made that the delta sediments hold a substantial amount of inorganic C (Table S1), this does not contribute to active C sequestration as it is just a transfer of C from one subsoil environment to another. High SIC content and low $SOC_{Content}$ are instead an alarming sign for upland degradation with no additional C sequestration benefit in coastal wetlands. Being one of China's largest coastal wetland areas, the Yellow River Delta has therefore the potential to become an important C sink if (i) improved local management to promote the formation of dense vegetation cover for in-situ SOC sequestration is paired with (ii) better protection of upland areas to slow down erosion and allow for C enrichment in (eventually eroding) topsoil that gets upstream transported and deposited in the delta. This principle known as the dynamic replacement of eroded C (Van Oost & Six, 2023) is able to allow for sustainable agriculture at modest erosion rates to contribute to C sequestration as long as (i) areas of deposition are well protected against C decomposition and (ii) the source material for soil formation in upland is not depleted. The former requires the delta of the Yellow river to be managed as a water-logged wetland area with adapted vegetation, whereas the latter requires the conservation of the upstream Loess Plateau for maintaining and enhancing carbon sequestration in the associated mobilized soil before reaching the river delta system (Yu et al., 2020; Deng and Shangguan, 2021). Mitigating soil erosion in the Yellow River uplands is thus paramount, as C-depleted soils resulting from extensive erosion do not contribute extensively to downstream delta C storage (Fig. 3). Conversely, promoting soil stability in the Loess Plateau can yield multifaceted benefits. And can collectively contribute to the development of a more resilient and productive upstream ecosystem (Jiang et al., 2019). Furthermore, the retention of C in the Loess Plateau may indirectly benefit the delta by moderating the influx of nutrient-poor, mineral-dominated sediments (Ali Shah et al., 2021). This holistic approach to watershed management underscores the interconnectedness of upstream conservation efforts and downstream C dynamics, emphasizing the need for integrated strategies in optimizing carbon sequestration across the entire river-delta system (Zhao et al., 2022).

Lastly, to optimize the long-term carbon sequestration potential of river deltas as a strategy for mitigating global warming, it is crucial to maintain their stability and promote healthy coastal ecosystem growth. Given global warming, sufficient deltaic space must be preserved to adapt to sea level rise, prevent coastal congestion, and maintain the deltaic function as a C sink (Boix-Fayos et al., 2015; Pei et al., 2024). This approach aligns with recent research highlighting the importance of deltaic regions in global carbon cycling (Pei et al., 2024). Management strategies should prioritize minimizing frequent disturbances to these ecosystems, as such perturbations can induce enhanced sediment respiration and accelerate SOC consumption (Arriola et al., 2019; Jiao et al., 2020; Li et al., 2024). Preservation of delta stability may then not only contribute to sustained carbon sequestration but also provide a better scientific basis for the effective management of C pools in these dynamic coastal environments.

## 5. Conclusion

This study shows that soil organic carbon (SOC) dynamics in the Yellow River Delta are strongly influenced by upstream erosion and rapid sediment deposition. Supporting hypothesis (i), SOC stocks were low (2.2–5.8 kg C $m^{-2}$ $yr^{-1}$) compared with other wetlands, while soils were dominated by inorganic carbon (8.7–13.5 g $kg^{-1}$), reflecting inputs of C-depleted loess-derived sediments. In line with hypothesis (ii), younger river courses with faster sedimentation preserved more SOC than older courses, where slower accumulation led to lower stocks. Sediment dating confirmed that the upper 2 m was deposited within the past 80 years. Consistent with hypothesis (iii), isotope mixing indicated that most SOC originated from upstream deposition rather than in-situ vegetation, with deposited/in-situ ratios commonly $>1$. Overall, the delta functions as a sink for eroded upland carbon but has limited SOC accumulation capacity due to the dominance of C-depleted sediments. Integrated watershed management is needed to enhance both upland and deltaic carbon sequestration.

Despite the valuable insights provided by this study, several limitations should be acknowledged. The analysis was based on a limited number of soil cores, which may not fully capture the spatial variability of the Yellow River Delta, and the core length constrains the reconstruction of long-term carbon dynamics. Carbon source identification primarily differentiated between upstream-derived material and local vegetation, while finer contributions from aquatic biomass or anthropogenic inputs were not considered. Future research should expand spatial coverage, employ high-resolution dating techniques, and integrate isotopic and biomarker analyses to more accurately resolve carbon sources and deposition patterns. Moreover, linking upland erosion with deltaic carbon burial and assessing the effectiveness of soil conservation and wetland restoration measures will be essential to enhance carbon sequestration across the Yellow River Delta.

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**CRediT authorship contribution statement**

**Dongxue Li:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zhonghua Ning:** Writing – review & editing. **Kristof Van Oost:** Writing – review & editing. **Wasner Daniel:** Writing – review & editing. **Yi'na Li:** Investigation. **Baoshan Cui:** Writing – review & editing, Supervision, Conceptualization. **Sebastian Doetterl:** Writing – review & editing, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2025.109427.

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