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Shifts in riverine POC sources reduce terrestrial OC burial in the subaqueous Changjiang Delta

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Abstract. Global riverine particulate organic carbon (POC) fluxes have declined worldwide due to dam-induced reductions in sediment load. However, how the composition of riverine POC has evolved in response to declining sediment supply, and how such shifts influence OC burial in subaqueous deltaic systems remain unclear. Here, we collected suspended particulate matter (SPM) from the Changjiang Estuary during the summer and winter of 2025 to analyze N/C ratios and δ13C values. These data were integrated with a four-decade (1980–2021) dataset comprising POC proxies (N/C, δ13C, and Δ14C) for SPM in the estuary and surface sediments from the subaqueous Changjiang Delta. Our results reveal a temporal increase in N/C ratios and a decrease in δ13C values in riverine SPM. Based on a Bayesian end-member mixing model, we attribute these trends to an increasing proportion of POC derived from freshwater algae and a decreasing proportion of POC originating from soil/bedrock erosion. This temporal increment in river-delivered labile algae POC drove a 1.5-fold decrease in OC preservation efficiency in subaqueous Changjiang Delta from 15.1% (before 2003) to 10.7% (after 2003), resulting in a more pronounced reduction in deltaic OC burial. Consequently, the amount of OC retained in sediments decreased by approximately 50%, from 0.68 × 105 t/month in 2001 to an average of 0.34 × 105 t/month during the flood seasons of 2011–2020. Our findings emphasize that the shifts in riverine OC sources, not merely the decline in total OC flux, may exert great effects on OC burial in deltaic systems globally.

1 Introduction

Rivers deliver annually a large amount of (480 Mt/yr) terrestrial organic carbon (OC) into the ocean, and thus plays a key role in land-ocean carbon cycling and further climate change (Galy et al., 2015; Regnier et al., 2022; Liu et al., 2024). Particulate OC (POC), generally identified as organic particles with size larger than 0.7 μm, is an important component of riverine OC, accounting for approximately 180 Mt C budgets input into the ocean each year (Liu et al., 2024). In recent decades, however, the riverine sediment loads have decreased sharply worldwide due to anthropogenic activities including river damming, land

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use change and water and soil conservation policies (Dethier et al., 2022), which exerts a substantial influence on riverine POC budgets and the broader global OC cycles.

Delta and its adjacent inner shelf, constituting < 10% of the entire ocean area, but contributing > 90% to the overall OC preservation in oceans globally, act a disproportional hotspot in oceanic OC burial (Hedges and Keil, 1995; Muller-Karger et al., 2005; Hage et al., 2022). As the channels connecting terrestrial and marine realms, sediments in these regions are subjected to complex marine hydrodynamic settings during seaward transport, resulting in OC exchange between sediment-water interface and ultimately OC burial (Blair and Aller, 2012; Bauer et al., 2013). Given that a substantial fraction of riverine POC is ultimately deposited in deltaic sediments, the marked decline in POC flux would be expected to have profound implications for OC burial in these coastal depocenters. In two largest rivers of China, the Changjiang River and Yellow River, the POC fluxes decreased evidently from 13.4 and 7.7 Tg/yr in 1950s to 2.9 and 0.4 Tg/yr in 2016, respectively (Liu et al., 2020). In mainstem of the Red River in Vietnam, the POC fluxes decreased evidently from 0.68 Tg/yr in 1960s to 0.05 Tg/yr in 2016 (Le et al., 2018), as the clearly temporal decline of sediment loads in the river (Dang et al., 2010).

Riverine POC originates from multiple sources that exhibit distinct degrees of lability under varying physicochemical conditions (Hilton et al., 2024). For instance, petrogenic OC, primarily supplied by bedrock and soil erosion in the upstream watershed, is relatively stable during riverine transport due to its strong organo-mineral protection. Nevertheless, this stability can be disrupted in estuarine environments, where intense shear stress destabilizes organo-mineral associations and enhances degradation (Sun et al., 2022; Sun et al., 2024). In contrast, algal-derived OC, mainly produced by aquatic plankton, is highly labile and readily decomposed in the water column through biological processes owing to its enrichment in proteins, carbohydrates, and lipids with high bioavailability (Wang et al., 2024). Vascular plant–derived POC, dominated by debris from C3 plants in the watershed, is generally resistant to degradation during downstream transport; as a result, it can be conveyed over long distances and ultimately deposited and preserved within proximal deltaic sediments (Rathburn et al., 2017; Sun et al., 2021). These source-specific POC components respond sensitively to variations in sediment flux, and their relative contributions exert a critical influence on OC transport and burial along the river–estuary–shelf continuum. Given the substantial shifts in riverine sediment budgets, as well as the consequent changes in both the magnitude and composition of POC delivery, the fluxes of OC burial in deltaic areas may change profoundly and necessitates a systematic re-evaluation.

The Changjiang River offers an ideal natural laboratory to address this knowledge gap. Due to the construction of upstream dams since 1980s, the Changjiang River had experienced sustained reduction in sediment load over time (Fig. 1f). Sediments delivered by the river are predominantly deposited in subaqueous Changjiang Delta, while this depocenter has experienced extensive seabed erosion in response to the reduced fluvial sediment supply (Luan et al., 2016). Previous work has shown that POC burial in the subaqueous delta has decreased markedly, primarily driven by the sharp reductions in transport flux and deposition rate of OC-bearing sediments (Zhao et al., 2021a). However, how terrestrial POC components shift in response to declining sediment supply and their impact on deltaic OC burial have not yet been clearly elucidated. By integrating a multi-decadal dataset of OC characteristics (C/N, $\delta^{13}C$ and $\Delta^{14}C$) from suspended sediments in Changjiang Estuary and surface sediments in subaqueous Changjiang Delta with a Bayesian end-member mixing model, our study attempts to clarify: (i)

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temporal changes of different sources terrestrial OC input into the ocean; and (ii) how these variations affect OC burial in subaqueous Changjiang Delta.

2 Material and methods

2.1 Study area

Changjiang River, with a length of 6300 km and a watershed area of 1.8×10^6 km^2, is the largest river in East Asia (Fig. S1). Prior to the construction of dams, the river annually delivered approximately 472 Mt of sediment and 900 km^3 of freshwater to the East China Sea (Zhao et al., 2021a). These fluxes were predominantly concentrated during the flood season (June–October), accounting for over 70% of the annual water discharge and more than 87% of the sediment load, in contrast to the dry season (November–May) (CWRC, 1953–2022). Historically, the estimated OC budgets export to the estuary ranged from 0.86 to 13 Mt yr^{-1}, of which approximate 50% was POC (Milliman et al., 1985; Wang et al., 2012). However, the sediment flux and its related POC flux declined continuously since about 1981 due to sediment retention by upstream dam operation (Fig. 1f). Two sharp reductions of sediment flux were observed in 1981 and 2003, respectively, corresponding to the commissioning year of Gezhouba Dam and Three Gorges Dam that constructed in main stream of the Changjiang River (Fig. S1; Table S1). Given the limited dataset prior to the operation of the Gezhouba Dam in 1980, the commissioning of the Three Gorges Dam (2003) was used as a temporal breakpoint to examine changes in the characteristics of river-delivered POC and deltaic OC associated with the sharp reduction in sediment flux.

More than 90% of the riverine sediments deposited in subaqueous Changjiang Delta are derived from the Changjiang River; in comparison, the contributions other rivers, including Yellow River, Qiantang River and Taiwanese rivers, are relatively small that can be basically ignored (Liu et al., 2007; Van der Voort et al., 2018). Because of the accumulation of a large amount of POC, the subaqueous Changjiang Delta was generally considered as a critical area for OC sink (Zhao et al., 2021a; Shi et al., 2024; Ran and Wang, 2025). Under the strong hydrodynamic interactions among river discharge, tides, and coastal currents (e.g., the Zhejiang–Fujian and Yellow Sea Coastal Currents), sediments with distinct grain size deposited in different nearshore regions of the Changjiang Estuary. Based on the characteristics of these accumulated sediments, the subaqueous Changjiang Delta can be subdivided into four sedimentary units (Chen et al., 1991): the Delta front, the Prodelta, the transition zone from delta to continental shelf (Delta-Shelf), and the continental shelf (Shelf) (Fig. 1a).

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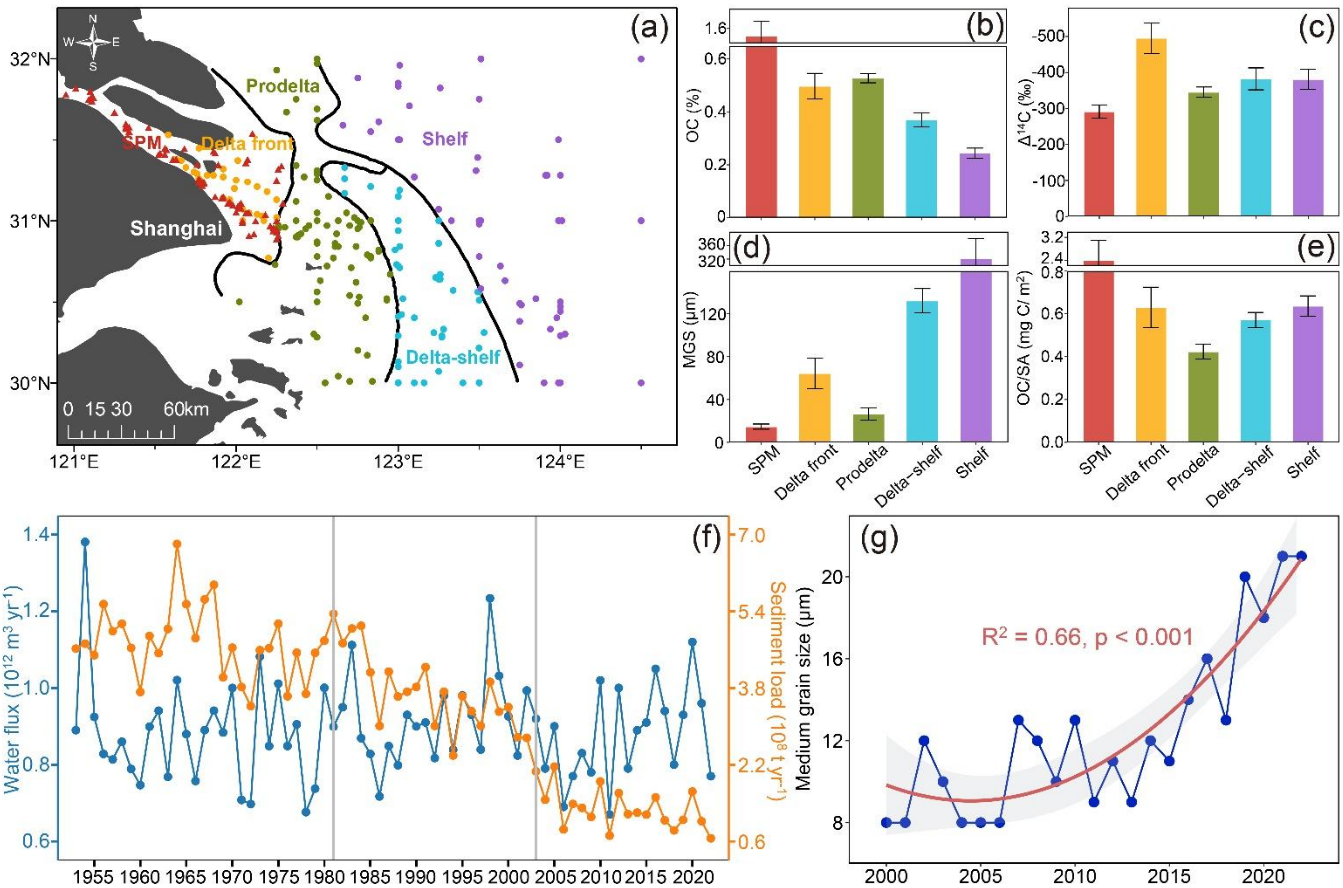

Figure 1 Sampling sites of suspended particulate matters (SPM) and surface sediment in Changjiang Estuary and its adjacent areas (a). Characteristics of sediment in riverine SPM and delatic sediments, including organic carbon (OC) content (b), $\Delta^{14}C$ (c), medium grain size (MGS) (d) and ratios between OC content and specific surface area (OC/SA) (e). Variations of annual mean water flux and sediment load of the Changjiang River from 1953 to 2022 (f). Changes of annual MGS of the sedimet delivered by the Changjiang River from 2000 to 2022 (g). Four sedimentary units (Delta front, Prodelta, Delta-shelf and Shelf) of the subaqueous Changjiang Delta in panel (a) are classified according to Chen et al. (1991) and delineated by black lines. Data of riverine water flux, sediment load and MGS in Datong Gauge Station are applied to represent characteristics of water and sediment input into the East China Sea, which are obtained from annual China River Sediment Bulletin (CWRC, 1953–2022).

2.2 Samples collection and analysis

The suspended particulate matter (SPM) samples from the Changjiang Estuary were collected during winter (March) and summer (July) cruises in 2025 aboard R/V Runjiang I. At each sampling site, surface seawater was collected using a Seabird® SBE 55 water sampler and subsequently filtered through pre-combusted (450 °C, 5 h) 0.7 µm glass fiber membranes (47 mm diameter, Whatman GF/F) and pre-weighed 0.7 µm acetate cellulose membranes, respectively. To determine the OC characteristics (C/N, $\delta^{13}C$), the particle-laden glass fiber membranes were acidified with 4 mol/L HCl for 24 h to remove inorganic carbon completely (Leithold et al., 2013) prior to analysis using an Elemental Analyzer (Elementar Analysen Systeme GmbH, Germany) and an Isotope-Ratio Mass Spectrometer (IRMS, IsoPrime100, UK). Total suspended matter (TSM) concentrations were obtained gravimetrically by calculating the weight difference of the acetate cellulose membranes before and after freeze-drying.

2.3 Data compilation

A dataset of OC-related parameters (N/C molar ratio, $\delta^{13}C$ and $\Delta^{14}C$) and sediment characteristics (medium grain size (MGS); specific surface area (SA)) in SPM in Changjiang Estuary and surface sediments in subaqueous Changjiang Delta from 1980 to 2021 was compiled. The dataset was comprehensively incorporated the available sources (data was shared or can be extracted from figures and tables) from published articles. To represent a purely terrestrial OC source, the SPM data was refined by selecting surface samples with salinity levels of sampling sites below approximately 20 (Yao et al., 2024). In total, 301 individual data samples were incorporated in the dataset, including 64 SPM and 237 surface sediments (Fig. 1a). Dataset of annual water and sediment flux from 1953 to 2022, the monthly water and sediment flux (June and July) from 2001 to 2020, as well as the MGS of the SPM from 2000 to 2022 was obtained from the Hydrological Statistical Yearbook of the Ministry of Water Resources of the People's Republic of China (CWRC, 1953–2022) based on the continuous observation in Datong gauging station (30°6′N, 117°7′E). Details of the data processing are presented in the Supplementary Material.

2.4 Sources of OC in SPM and surface sediment

The Bayesian end-member mixing model, implemented in R Studio (version 4.2.3) based on the "*rjags*" package, was run with 10^7 iterations, using a burn-in of 10,000 steps, and a data thinning of 100 according to (Andersson et al., 2015). By using N/C molar ratio and $\delta^{13}C$ values, the relative contributions of three sources of POC in SPM were separated, targeting petrogenic ($f_{Petrogenic}$), C3 plant (f_{Plant}) and algae sources (f_{Algae}), based on the following formulas:

$$(f_{Petrogenic} \times N/C_{Petrogenic}) + (f_{Plant} \times N/C_{Plant}) + (f_{Algae} \times N/C_{Algae}) = N/C \quad (1)$$

$$(f_{Petrogenic} \times \delta^{13}C_{Petrogenic}) + (f_{Plant} \times \delta^{13}C_{Plant}) + (f_{Algae} \times \delta^{13}C_{Algae}) = \delta^{13}C \quad (2)$$

$$f_{Petrogenic} + f_{Plant} + f_{Algae} = 1 \quad (3)$$

where f represents the proportion of a specific terrestrial source of POC in SPM. Selection of end-member values is presented in Table S2.

Because of the nonnegligible marine OC generated in nearshore regions off the Changjiang Estuary, the sedimentary OC in surface sediment in subaqueous Changjiang Delta is divided into terrestrial and marine sources according to the following formulas:

$$(f_{Terrestrial} \times \delta^{13}C_{Terrestrial}) + (f_{Marine} \times \delta^{13}C_{Marine}) = \delta^{13}C \quad (4)$$

$$f_{Terrestrial} + f_{Marine} = 1 \quad (5)$$

where f represents the proportion of OC source, and the end-member values of $\delta^{13}C$ are -25.6‰ and -20.0‰ for terrestrial and marine source, respectively (Chen et al., 2021).

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2.5 OC burial efficiency and OC preservation efficiency

The OC burial efficiency in surface sediments in subaqueous Changjiang Delta was estimated according to Keil et al. (1997) through the following formula:

$$OC\ burial\ efficiency\ (\%) = \frac{OC\ loading_{\ Surface\ sediment}}{OC\ loading_{\ SPM}} \times 100\% \tag{6}$$

where the *OC loading* $_{Surface\ sediment}$ represents the loading of terrestrial OC (OC/SA× terrestrial OC proportion) in surface sediment, and the *OC loading* $_{SPM}$ denotes the OC/SA in SPM.

Besides the calculation of OC burial efficiency, we also estimated the preservation of terrestrial OC during sediment transport by comparing differences between the terrestrial OC content in surface sediments and riverine SPM in terms of Blair and Aller (2012). To distinguish this metric from burial efficiency, it is defined as preservation efficiency in our study. The preservation efficiencies of terrestrial OC in different sedimentary units of the subaqueous Changjiang Delta are calculated through the following formula:

$$OC\ preservation\ efficiency\ (\%) = \frac{OC_{\ Surface\ sediment}}{OC_{\ SPM}} \times 100\% \tag{7}$$

where the *OC* $_{Surface\ sediment}$ represents the content of terrestrial OC in surface sediment, and the *OC* $_{SPM}$ denotes the OC content in SPM.

Based on the assessed OC burial and preservation efficiencies at different sampling sites, we calculated the overall OC burial and preservation efficiencies across the entire subaqueous Changjiang Delta. Using the estimated OC preservation efficiency, we further quantified the net preservation flux of terrestrial OC delivered by the Changjiang River. Details of the data calculations are provided in the Supplementary Material.

2.6 Statistical analyses

Regression analysis, conducting by R Studio (version 4.2.3), is utilized to estimate the temporal trend of hydrological and sediment characteristics, OC-related parameters (N/C, δ^{13}C), proportion of different sources of terrestrial POC in SPM, as well as riverine POC flux and amounts of OC preserved in subaqueous Changjiang Delta. Relationships between C/N and δ^{13}C were exhibited to identify different sources of OC in SPM and surface sediments. Kriging interpolation, by using ArcMap 10.8, was applied to present horizontal patterns of OC preservation efficiency in subaqueous Changjiang Delta. Factors controlling OC loss and retention during sediment transport are proved by establishing relationships between OC loading (OC/SA), OC characteristics (C/N, δ^{13}C and Δ^{14}C) and sediment parameters (MGS, SA) in SPM and surface sediment through scatter plot and linear regression analysis.

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3 Results

3.1 Temporal shifts in riverine SPM and spatial heterogeneity in deltaic sediments

Since 2000, the grain size of SPM delivered to the East China Sea has progressively ($p < 0.001$) coarsened (Fig. 1g), indicating that anthropogenic activities, particularly dam construction such as Three Gorges Dam in 2003 (Table S1), have exerted a substantial influence on the characteristics of river-delivered materials. The operation of the Three Gorges Dam has also altered the composition of riverine POC, as reflected by C/N ratios and $\delta^{13}C$ signatures that capture a clear transition in POC sources, from mainly petrogenic to algal OC over time (Fig. S2).

In addition, marked spatial heterogeneity in OC-related indices and sediment characteristics was observed across the four sedimentary units (Fig.1). OC content was substantially higher in nearshore zones than in offshore areas (Fig. 1b), consistent with the fining trend in sediment grain size shoreward (Fig. 1d). While when considering OC loading (OC/SA), the values were comparable across three sedimentary units, except for notably lower levels in the Prodelta (Fig. 1e). For $\Delta^{14}C$, the lowest value was recorded in Delta front, whereas the other units exhibited little differences (Fig. 1c).

3.2 Temporal variations of OC characteristics in SPM

The N/C molar ratio in surface SPM collected within Changjiang Estuary increased significantly ($p < 0.001$) from 1980 to 2025, with the value rise approximately 2.5-fold from 0.07 in 1980 to 0.17 in 2025 (Fig. 2a). In comparison, the $\delta^{13}C$ values decreased evidently ($p < 0.01$) during the same period (Fig. 2c), with the value ranged between -23.5‰ to -28.0‰ (Table S3). Between flood and dry seasons, the N/C and $\delta^{13}C$ exhibited limited differences ($p > 0.05$) (Fig. 2b, d).

Based on the Bayesian End-member Mixing model, the riverine POC in SPM were separated into three terrestrial sources (algae, petrogenic and C3 plant). Temporally, the proportion of algae OC increased significantly ($p < 0.01$), rising approximately 2.6-fold from 16% in 1980 to 42% in 2025. In contrast, the proportion of petrogenic OC showed a marked decline ($p < 0.01$), decreasing roughly 2.3-fold from 63% in 1980 to 27% in 2025 (Fig. 2e). The contribution of C3 plant OC exhibited limited temporal variation ($p > 0.05$), ranging between 22% and 35% over the study period (Fig. 2e).

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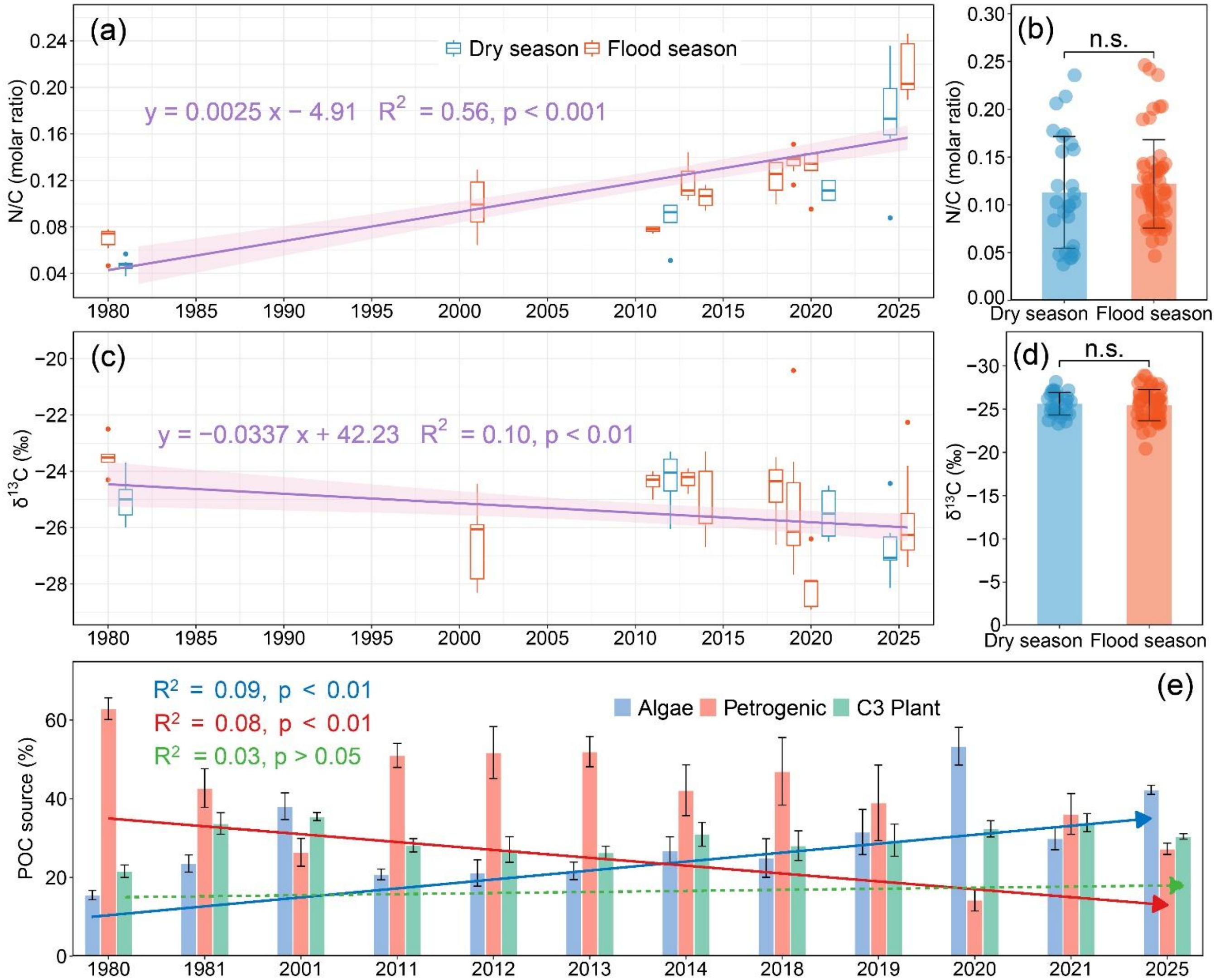

Figure 2 Temporal variations of N/C molar ratios (a) and $\delta^{13}C$ values (c) in suspended particulate matter (SPM) collected in surface water in Changjiang Estuary from 1980 to 2025, and the differences of N/C ratios (b) and $\delta^{13}C$ values (d) between dry and flood seasons. Temporal trends of proportions of particulate organic carbon (POC) derived from different terrestrial sources (algae, petrogenic and C3 plant sources) estimated through a Bayesian End-member Mixing approach (e). Solid lines represent significant ($p < 0.05$) linear associations, and the light purple areas around the line indicate 95% confidence interval. The n.s. indicates insignificant ($p > 0.05$) differences.

3.3 Changes of OC characteristics in surface sediment

In Delta front, the values of $\delta^{13}C$ and C/N in surface sediment were increased and decreased over time, respectively. Surface sediments collected after 2003 exhibit $\delta^{13}C$ and C/N values that predominantly plot within the petrogenic domain, aligning along a mixing line between marine and riverine OC end-members. In contrast, samples collected prior to 2003 display that the $\delta^{13}C$ and C/N fall outside the fields defined for either petrogenic or freshwater algal sources, lying outside of a simple

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mixing between two end-members of marine and riverine OC (Fig. 3a). In the Prodelta, the $\delta^{13}C$ and C/N ratios in surface sediments exhibited minor temporal variability. A slight depletion in $\delta^{13}C$ was observed in pre-2003 samples compared to those after 2003. Most data points plot within the petrogenic domain and align along a mixing line between marine and riverine OC end-members (Fig. 3b). By comparison, the values of $\delta^{13}C$ and C/N in both Delta-shelf and Shelf displayed limited temporal change. They are consistently closer to the marine OC end-member ($\delta^{13}C$ = -20.5‰, C/N = 7) and only partially overlap with the petrogenic component, falling within a mixing zone of marine and riverine OC (Fig. 3c, d).

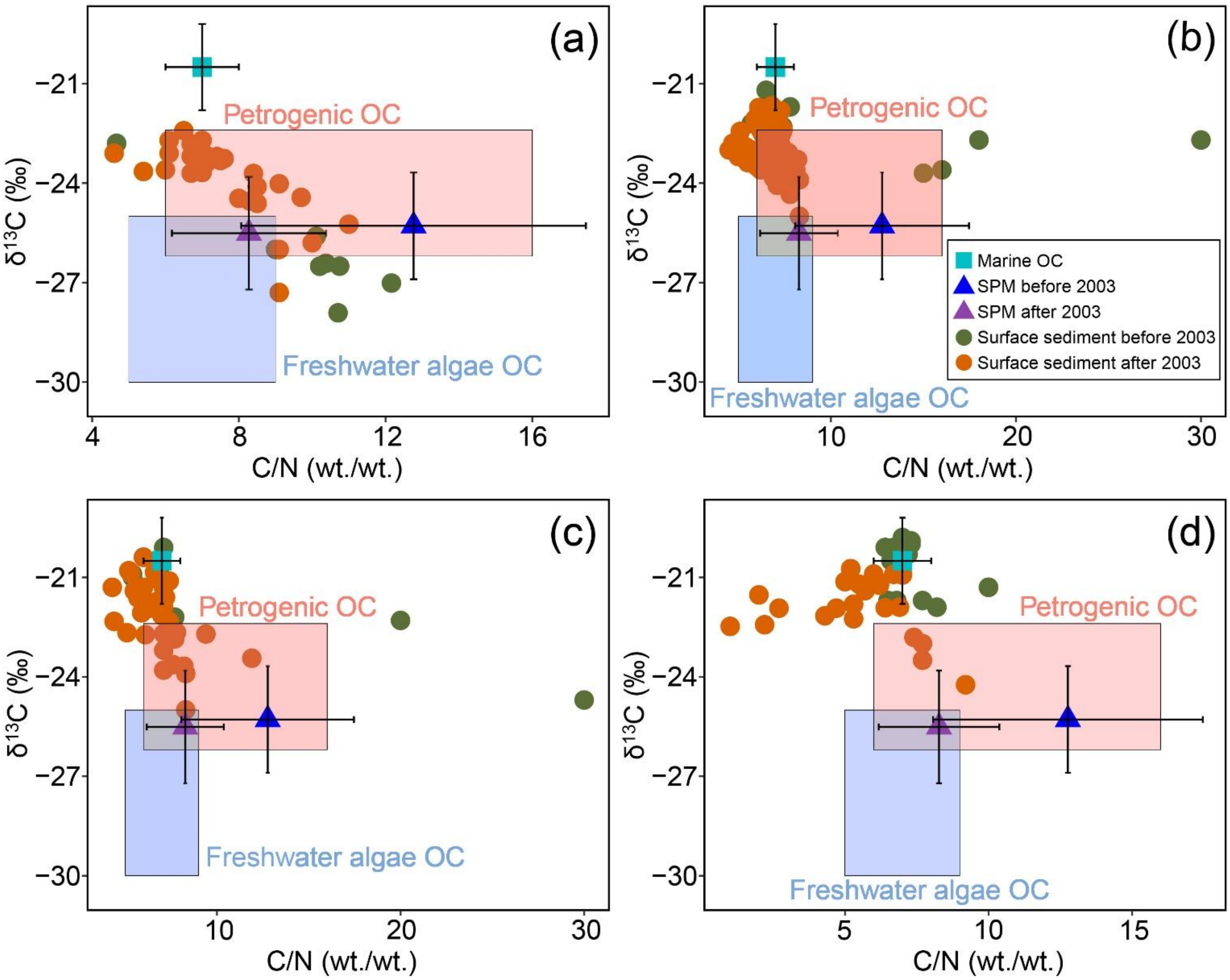

Figure 3 Relationships between $\delta^{13}C$ and C/N in surface sediments in Delta front (a), Prodelta (b), Delta-shelf (c) and Shelf (d) prior to and after 2003. Light red and blue areas represent ranges of $\delta^{13}C$ and C/N corresponding to terrestrial organic carbon (OC) derived from petrogenic and freshwater algae OC sources, respectively, in terms of Lamb et al. (2006) and Menges et al. (2020). The marine OC end-member of $\delta^{13}C$ is from -19.2‰ to -21.8‰ and of C/N is 6–8 (Xing et al., 2011; Bao et al., 2018).

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3.4 OC burial efficiency and OC preservation efficiency

Terrestrial OC burial efficiency in subaqueous Changjiang Delta is 12.6%, with the range from 2.3 to 43.3% (Fig. S4). Higher OC burial efficiencies were observed in Delta front (21.3%), which were significantly higher ($p < 0.05$) than that in Prodelta (9.8%), Delta-shelf (9.6%) and Shelf (9.7%) (Fig. S4a). The OC burial efficiency is positively and closely ($p < 0.001$) related to OC preservation efficiency (Fig. S4b). The OC preservation efficiency is 11.2%, with the range from 0.4 to 39.2% (Fig. 4a). Higher OC preservation efficiencies were detected in Delta front (16.8%) and Prodelta (15.7%) regions when compared with Delta-shelf (7.5%) and Shelf (4.7%) (Fig. 4b).

Temporally, the OC preservation efficiency decreased by approximately 1.5-fold, from 15.1% before 2003 to 10.7% after 2003 (Fig. 4c). During flood seasons, based on these estimated preservation efficiencies, the amounts of OC preserved in sediments decreased by about 50%, from 0.68×10^5 t/month in 2001 to an average of 0.34×10^5 t/month during 2011 to 2020 ($R^2 = 0.27$, $p < 0.01$). Similarly, the riverine OC flux decreased by approximately 49%, from 4.5×10^5 t/month in 2001 to an average of 2.3×10^5 t/month ($R^2 = 0.28$, $p < 0.01$) (Fig. 4d).

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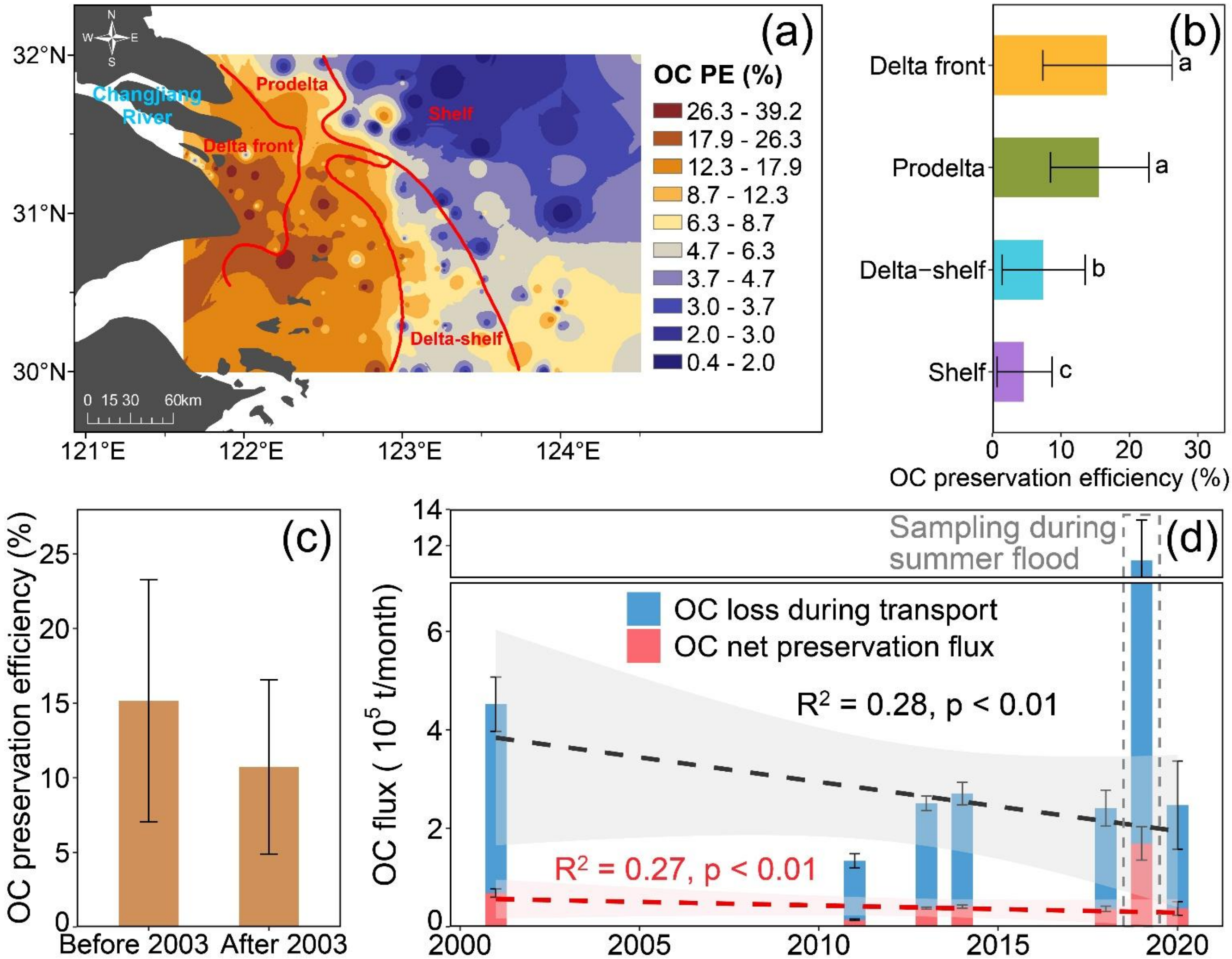

Figure 4 Distribution of organic carbon (OC) preservation efficiencies in subaqueous Changjiang Delta, PE: preservation efficiency (%) (a), and OC preservation efficiency in different sedimentary units (b). Comparison of OC preservation efficiency before and after 2003 (c). Temporal trends of the amount of OC preserved (red dashed line) in deltaic sediments and riverine OC flux (black dashed line) from 2001 to 2020, and the blue bars reflect OC loss (difference between amount of OC preservation and riverine OC flux) during sediment seaward transport (d). Different lowercase letters in panel (b) denote statistically significant differences ($p < 0.05$) among sedimentary units. In panel (d), the high value in 2019 (gray dashed circles) primarily induced by extreme summer flood (Sun et al., 2021) was excluded from trend analysis. The dashed lines indicate linear relationships, and the light gray and red areas around the line represent 95% confidence interval.

4 Discussions

4.1 Temporal changes of riverine POC sources in Changjiang Estuary

Since the construction and operation of dams in the upper reaches of the Changjiang River beginning in 1980, the characteristics of terrestrial POC transported to the East China Sea have changed markedly, with N/C molar ratios increasing

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significantly ($p < 0.001$) and $\delta^{13}C$ values decreasing significantly ($p < 0.01$) over time (Fig. 2a, c). These shifts resulted in temporally elevated proportion of POC derived from freshwater algae and declined proportion of POC originated from watershed bedrock/soil erosion (Fig. 2e). Despite previous studies had revealed the increased proportion of freshwater algae source OC induced from the Three Gorges Dam impoundment after 2003 (Wang et al., 2021; Lyu et al., 2023; Wang et al., 2024; Ke et al., 2025), we proposed that this shift may initial since the 1980s when the sediment load begin to decrease under the operation of Gezhouba Dam in mainstem of the Changjiang River (Fig. 1f; Fig. S1; Table S1). Note the higher N/C molar ratio (0.099) in 2001 that was approximately 1.5-fold than 0.068 in 1980 (Fig. 2a), which reflected that the proportion of algae OC increased from 16% in 1980 to 38% in 2001, and the proportion of petrogenic OC decreased from 63% in 1980 to 26% in 2001 (Fig. 2e). These results capture, for the first time, the temporal variations in the relative contributions of different terrestrial sources of POC input into the East China Sea, highlighting the substantial influence of anthropogenic disturbances on the composition of river-borne terrestrial POC.

Despite the scarcity of studies examining the impacts of river damming on the temporal variations of individual terrestrial OC sources along the river–ocean continuum, our findings are broadly consistent with previous studies conducted within the Changjiang River Basin. The impoundment of Three Gorges Reservoir in 2003 significantly raised the proportion of riverine primary productivity-derived POC in downstream of the Changjiang River, resulting in higher fluxes of these labile POC components entering into East China Sea (Lyu et al., 2023). Wang et al. (2024) had also revealed that the proportion of autochthonous OC, originating from aquatic primary productivity, increased markedly from the Three Gorges Reservoir to estuary in the mainstem of the Changjiang River. Changes of contributions of different POC sources in Changjiang River were also comparable with other large rivers worldwide that experienced intensified anthropogenic activities. In the Mississippi, Colorado, Rio Grande, and Columbia Rivers, four major waterways in the United States, the construction of several dams has led to marked reductions in sediment loads. This alteration has, in turn, resulted in a notable increase in the relative contribution of plankton-derived POC in downstream waters relative to upstream areas (Kendall et al., 2001). In Yellow River, before and after the water-sediment regulation by Xiaolangdi Reservoir, the proportion of terrestrial POC derived from soils increased significantly from 56.4% to 82.0%, and the proportion of plant-originated POC declined from 43.6% to 18% (Lv et al., 2022). These findings indicate that the relative contributions of terrestrial POC sources were driven primarily by the riverine sediment budget. A reduction in sediment load prompted a shift in the dominant OC component from petrogenic OC (derived from bedrock/soil erosion) to OC from aquatic productivity (Dai et al., 2016). This interpretation is consistent with our observation that total suspended matter concentration was positively correlated with petrogenic OC but negatively correlated with algae OC (Fig. S5). Two interpretations may be involved in this alteration. On the one hand, a large amount of riverine sediment in upstream of the Changjiang River, primarily derived from montane bedrock weathering and soil erosion, were intercepted in reservoirs after dam construction (Li et al., 2015; Lambert et al., 2017). Therefore, the proportion of OC derived from aquatic biomass in downstream sections increased because of less mixing of petrogenic OC. On the other hand, the declined sediment load in downstream of the Changjiang River, by increasing light transparency into the water column, indirectly enhanced aquatic productivity and thus higher proportion of algae-originated OC (Robertson et al., 1993; Huettel et al., 2014).

We observed insignificant differences ($p > 0.05$) in N/C ratios or $\delta^{13}C$ values between dry and flood seasons (Fig. 2b, d), while this pattern may be derived from long-term averaging of our dataset. During a monthly monitoring conducted from September 2009 to August 2010 at Xuliujing Station (a Hydrological Gauging Station in lower Changjiang River), the N/C ratios were higher in flood season (0.099; 0.090–0.116) relative to dry season (0.086; 0.073–0.098), and the $\delta^{13}C$ values were comparable between seasons (Gao et al., 2012). Similarly, Ming et al. (2023) reported that from November 2016 to June 2019 at Xuliujing Station, the N/C ratio in the flood season (0.112 ± 0.015) was clearly higher than in the dry season (0.093 ± 0.013), whereas $\delta^{13}C$ values showed little seasonal variation. By comparison, across multiple sites in the lower reaches of the Changjiang River, Mao et al. (2011) found similar N/C molar ratios between the flood (0.109) and dry (0.118) seasons, with slightly lower $\delta^{13}C$ values in flood season (-25.4‰ to -24.1‰) than dry season (-25.4‰ to -21.6‰). These contrasting findings across seasons and locations reveal pronounced temporal and spatial variability in the terrestrial sources of POC, underscoring the critical role of the estuary–ocean continuum in regulating the composition of river-delivered POC. Such variability may, in turn, exert an important influence on OC burial in subaqueous deltas, thereby highlighting the need for sustained, high-temporal-resolution monitoring.

4.2 Patterns of OC burial in subaqueous Changjiang Delta

Burial efficiency of terrestrial OC in subaqueous Changjiang Delta is 12.6% estimated in our study (Fig. S4a). This indicates a large proportion of OC in sediment is reworked into seawater rather than prolonged preservation, which was primarily attributed to the desorption and decomposition of POC during sediment seaward transport (Sun et al., 2021; Sun et al., 2024). The burial efficiency of terrestrial OC (12.6%) in subaqueous Changjiang Delta is similar with Zhao et al. (2021b), who revealed that the OC burial efficiency was 16% in East China Sea. Spatially, the OC burial efficiency exhibits marked heterogeneity in different sedimentary units, with higher values observed in proximal delta relative to offshore regions (Fig. S4a). This is in a good line with Wu et al. (2013), who reported that the burial efficiency of organic matter was higher in inner shelf sediment (24.7% versus 21.3% in Delta front in our study) and lower in outer shelf sediment (10.7% versus 9.8% in Prodelta, 9.6% in Delta-shelf and 9.7% in Shelf in our study). However, these estimated burial efficiencies were markedly lower than individual burial efficiency of petrogenic OC (33–94%) (Sun et al., 2022). This suggests the petrogenic OC being comparatively resistant to degradation during sediment offshore transport, implying heterogeneous losses among different terrestrial POC sources. Our results also denoted that the higher OC contents were observed in surface sediments in Prodelta, which are primarily corresponding to petrogenic OC components in terms of C/N and $\delta^{13}C$ end-member values (Fig. S6). These patterns underscore the need to account for source-specific behaviors when evaluating POC delivery.

Beyond assessing OC burial efficiency via OC loadings in riverine SPM and deltaic sediments, the ratio of terrestrial OC contents between SPM and surface sediments was also employed as a quantified metric (Blair and Aller, 2012). This method can capture the preservation of terrestrial OC in solid phase from suspended sediment to deposition, which is well-suited for analyzing extensive published datasets of OC, given that the dataset of OC loadings is normally limited. In our study, we calculated this metric and termed it “OC preservation efficiency” to distinguish from “burial efficiency” (Section 2.5). We found that the OC preservation efficiency is similar to the burial efficiency of terrestrial OC, yielding values of 11.2%. Moreover, the OC preservation efficiency is tightly linked to the OC burial efficiency ($p < 0.001$) (Fig. S4b), denoting that preservation efficiency serves as an alternative proxy for the degree of riverine POC retention/loss. However, the estimated OC preservation efficiency (11.2%) in subaqueous Changjiang Delta is notably lower than approximately 28% estimated in Blair and Aller (2012). This can be ascribed to that our study accounts for distinct sedimentary units, rather than treating the marginal system as an entity. We observed higher OC preservation efficiency in proximal deltaic areas compared with offshore regions, with burial efficiencies reaching 25–40% in the Delta front and Prodelta, where sediments are predominantly fine grained (Fig. 1d; Fig. 4a). Sediment grain size is closely linked to OC retention capacity, as fine-grained sediments generally exhibit higher OC loading due to their greater specific surface area associated with constituent minerals (e.g., quartz, feldspar, calcite, and phyllosilicates) (Bao et al., 2019; Sun et al., 2022; Sun et al., 2024). These results highlight the critical role of sediment characteristics, sorted by hydrodynamic processes across different sedimentary units, in controlling OC sequestration in deltaic sediments.

Advanced from spatial pattern of OC preservation efficiency in subaqueous Changjiang Delta, we furtherly investigated its temporal changes. We found that the OC preservation efficiency decreased visibly from 15.1% prior to 2003 to average 10.7% after 2003 (Fig. 4c). This implied that the river-delivered POC after 2003 is more prone to decompose during sediment transport, primarily due to the increased proportion of freshwater algae OC over time (Fig. 2a; Fig. S2). The algae OC components, generally derived from aquatic primary productivity, was composed of algae cells, debris and aggregates, enriching in proteins, carbohydrates (e.g., polysaccharides) and lipids (Henderson et al., 2008; Villacorte et al., 2015). These components are easily degraded and assimilated through biological processes (Guo et al., 2025). Temporally decreased terrestrial proportion of OC in the Delta front, from 91.8% before 2003 to 64.9% after 2003 (Fig. S7), also verified that a larger amount of riverine POC was decomposed prior to burial, consistent with the deviation of OC characteristics from typical algal-derived organic matter components (Fig. 3a). In addition, the temporal decline in OC preservation efficiency in the subaqueous Changjiang Delta was primarily driven by decreases in preservation efficiency in the Delta front (from 21.7% to 16.5%) and Prodelta (from 21.6% to 14.9%) between the pre-2003 and post-2003 periods. This suggests that, in nearshore regions of the Changjiang Estuary, high OC loading-fine grain sediment (mainly petrogenic OC) was constantly washed away into distal regions, with less replenishment through reduced sediment load. Given the decreased riverine petrogenic OC input and coarser sediment grain size (Fig. 1g; Fig. 2e), we inferred that the OC preservation efficiency in proximal delta will continue to decline in the future. Riverine POC flux declined significantly ($p < 0.01$) by 49% from 0.45 Mt/month in July 2001 before the Three Gorges Dam construction to averaged 0.23 Mt/month in flood seasons from 2011 to 2020 as expected with the temporal reduction of sediment load (Fig. 1g; Fig. 4d). This was consistent with Wang et al. (2022), who revealed a POC flux of 0.21 Mt/month in flood season from 2013–2014 and 2018–2019. By considering OC preservation efficiency in different periods, we furtherly denoted a visible decrease ($p < 0.01$) in amounts of OC preserved in sediments by 50%, from 0.068 Mt/month in 2001 to averaged 0.034 Mt/month in flood season from 2011 to 2020 (Fig. 4d). This decline likely reflects the preferential degradation of algal POC during seaward transport, as indicated by deviations in end-member values (C/N, $\delta^{13}C$) between surface

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sediments and SPM (Fig. 3a; Fig. S2). It is further supported by the low proportion of terrestrial OC preserved in proximal deltaic deposits, particularly in the delta front of the subaqueous Changjiang Delta (Fig. S7a). Future studies should account for temporal variations in contributions from different terrestrial sources of riverine POC when evaluating deltaic OC burial in other large estuarine systems.

4.3 Loss of labile POC during sediment transport

Despite previous investigations had found that river damming predominantly changed contributions of different sources for POC (Kendall et al., 2001; Pradhan et al., 2014; Bianchi et al., 2015; Ulseth and Hall Jr., 2015; Lv et al., 2022; Lyu et al., 2023; Wang et al., 2024; Hu et al., 2025; Ke et al., 2025), to best our knowledge, limited studies explored influence of this alteration on terrestrial OC burial in marginal seas. By compiling a dataset of riverine POC characteristics in the Changjiang Estuary since 1980, prior to dam constructions in the upper mainstem (Gezhouba Dam and Three Gorges Dam) (Table S1), we unveiled that the proportion of labile POC (derived from freshwater algae) input into East China Sea increased continuously over time (Fig. 2e), and thus decreased OC preservation efficiency and less OC retention in deltaic sediments. Globally, riverine sediment fluxes have declined sharply over time due to intensified anthropogenic activities such as dam constructions (Dethier et al., 2022). These reductions in sediment loads not only diminish OC burial in marginal seas by directly lowering riverine POC fluxes, but may also enhance OC degradation during seaward transport by improving the relative contributions of labile OC fractions. To clarify the loss of labile OC along its offshore transport, we analyze contrasts in OC-related metrics between SPM and surface sediments.

Specific surface area (SA), which is generally higher in fine-grained sediments, is considered a key factor controlling OC retention capacity (Bergamaschi et al., 1997; Bock and Mayer, 2000; Yang et al., 2015). Our results also found that the SA was closely associated to MGS in both SPM and surface sediment in Changjiang Estuary (Fig. 5a), whereas it exhibited opposite relationships with OC content and $\Delta^{14}C$ between SPM and surface sediment (Fig. 5b, c). The SA of surface sediments was positively correlated with both OC content and $\Delta^{14}C$, suggesting that mineral protection plays a primary role in the initial stabilization of OC. However, this influence weakens progressively offshore (from the Delta Front to the Shelf), likely due to repeated cycles of sediment resuspension and deposition under dynamic estuarine conditions, which ultimately promote the loss and aging of sedimentary OC (Sun et al., 2021). In contrast, the OC content in SPM decreased with increasing SA and aging of OC, suggesting a clear mixing between petrogenic OC (older and carbon-poor) and algal OC (younger and carbon-rich). Unfortunately, the lack of $\Delta^{14}C$ measurements in SPM across different years limits our ability to furtherly prove the temporal shift in dominant sources of terrestrial OC. Vanish of these younger, OC-enriched components in surface sediments indicates the preferential decomposition of labile algal OC prior to deposition. Over time, the increasing proportion of freshwater algal OC in SPM further enhances the lability of OC derived from these easily degradable biospheric POC (Zhao et al., 2023), ultimately resulting in reduced OC burial in the subaqueous Changjiang Delta.

Ratios of OC to SA (OC/SA) in sediments, reflecting OC loading in per unit surface area of sediment (mg C/m^2), were assessed to represent potential remineralization of OC during sediment transport and OC burial (Bouchez et al., 2014; Sun GCA 2021).

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Typical OC/SA ratios in marginal sediments ranged from 0.5 to 1 mg C/m^2 (Mayer, 1994; Hedges and Keil, 1995; Blair and Aller, 2012; Bianchi et al., 2018). This range was comparable with our results (0.23–1.33) in surface sediments in subaqueous Changjiang Delta, while it was markedly lower than OC/SA in SPM (2.4 ± 0.7) collected in inner Changjiang Estuary (Fig. 1e). Given that the protection effect to OC commonly derived from the mineral composition in sediments, similar mineralogies would be expected to result in comparable OC loadings. Although the clay mineral assemblages are comparable between riverine SPM and surface sediments (Sun et al., 2022), the markedly higher OC loading in SPM suggests that a larger fraction of OC is unprotected by minerals and thus more susceptible to loss. To trace the burial of OC in different sedimentary units, we established the relationships between OC/SA and C/N, $\delta^{13}C$ and $\Delta^{14}C$. We found that the $\delta^{13}C$ exhibited weak relationship ($p > 0.05$) with OC/SA (Fig. 5e), while the C/N and $\Delta^{14}C$ were positively and negatively associated ($p < 0.05$) to OC/SA, respectively (Fig. 5d, f). The aged OC, characterized by lower SA and OC content but higher C/N ratios (> 8), was predominantly deposited in the proximal subaqueous delta and identified as coarse C_3 plant debris originating from the river basin (Zhu et al., 2013; Sun et al., 2021). In contrast, younger OC displayed higher SA and OC content with lower C/N ratios (< 8) and was primarily found in the distal delta, comprising lithogenic detritus from watershed bedrock erosion and inputs from marine primary production (Fig. 3). Despite these differences, identified characteristic of freshwater algal OC (C/N, $\delta^{13}C$ and $\Delta^{14}C$) (Fig. 3; Fig. 5f), were largely absent in deltaic sediments, implying that this OC component undergoes preferential loss prior to burial during seaward transport.

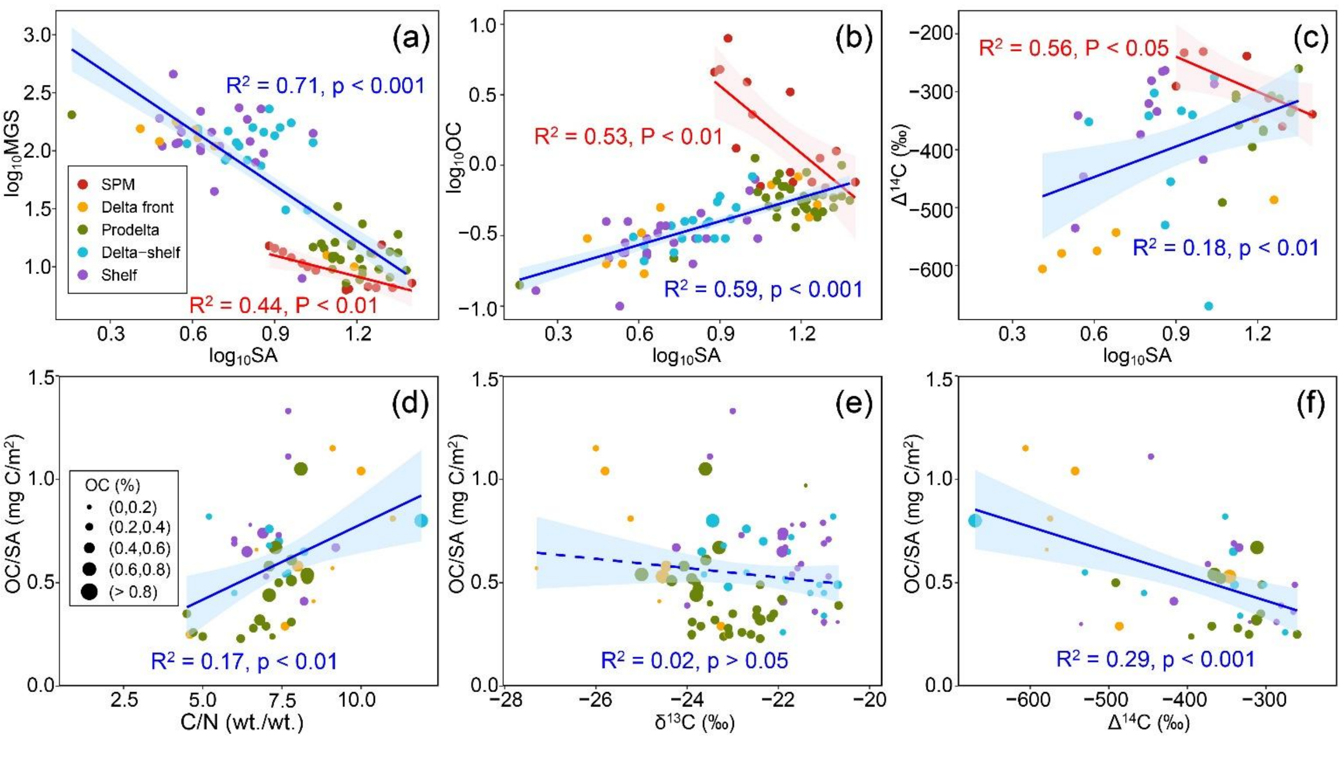

Figure 5 Factors controlling organic carbon (OC) contents and loadings in suspended particulate matter (SPM) of the Changjiang Estuary and surface sediments in subaqueous Changjiang Delta. Relationships between specific surface area (SA) and medium grain

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size (MGS) in SPM and surface sediments (a). Relationships between SA and OC content in SPM and surface sediments (b). Relationships between the OC/SA and C/N in SPM and surface sediments (c). Relationships between the OC/SA and C/N (d), $\delta^{13}C$ (e), $\Delta^{14}C$ (f), respectively, in surface sediments. The solid and dashed lines indicate statistically significant ($p < 0.05$) and insignificant ($p > 0.05$) relationships, respectively, and the light blue and red areas around the line represent 95% confidence interval.

5 Conclusions

This study reveals that the decline in sediment load of the Changjiang River since 1980 has led to a temporal increased N/C molar ratio and decreased $\delta^{13}C$ values of POC delivered to the East China Sea. These changes reflect a decreasing proportion of POC derived from soil/bedrock erosion and a growing contribution of POC originating from freshwater primary production, suggesting enhanced degradation of labile algal OC during seaward sediment transport and consequently reduced OC burial in the subaqueous delta. The reduction of terrestrial OC burial mainly occurs in the proximal deltaic sediments, where the OC preservation efficiency in the Delta front dropping notably from 21.7% to 16.5% following the impoundment of the Three Gorges Dam in 2003. This trend is further evidenced by the pronounced decline in terrestrial OC components and the improving dominance of petrogenic OC in Delta front sediments. As a result, the OC preservation efficiency across the entire subaqueous Changjiang Delta decreased by approximately 1.5-fold, from 15.1% before 2003 to 10.7% afterward. Consequently, the amount of OC preserved in sediments declined approximately by 50%, from 0.68×10^5 t/month in 2001 to an average of 0.34×10^5 t/month during 2011–2020. Our study demonstrates that, in the context of intense anthropogenic disturbance, assessing deltaic OC burial requires consideration not only in the decline of terrestrial POC flux caused by basin dam constructions, but also shifts in POC sources, since the stability of POC varies markedly among its different components, thereby altering the efficiency of OC burial in the delta.

Data availability

Data will be available from the corresponding authors upon reasonable request.

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

Jiyuan Jin: Designation of this study, Data compilation & processing, Methodology & Software, Writing original draft preparation, Writing-review & editing. Ya Ping Wang: Project administration, Supervision, Writing-review & editing. Hui Sheng: Project administration. Bixuan Tang: Investigation. Wei Feng: Writing-review & editing. Lanyue Liu: Investigation. Rui Liu: Investigation.

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Competing interests

The authors declare that they do not have any competing interests that could have appeared to influence the work reported in this paper.

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