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When river meets ocean: distribution and conversion of suspended organic particles in a Sundarbans mangrove river-estuary system, Bangladesh

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Abstract

Global carbon cycle has received extensive attention, among which the river-estuary system is one of the important links connecting the carbon cycle between land and ocean. In this paper, the distribution and control factors of particulate organic carbon (POC) were studied by using the data of organic carbon contents and its carbon isotopic composition ($\delta^{13}C$) in the mainstream and estuary of Passur River in the Sundarbans area, combined with the hydrological and biological data measured by CTD. The results show that POC content ranged from 0.263 mg/L to 9.292 mg/L, and the POC content in the river section (averaged 4.129 mg/L) was significantly higher than that in the estuary area (averaged 0.858 mg/L). Two distinct stages of POC transport from land to sea in the Sundarbans area were identified. The first stage occurred in the river section, where POC distribution was mainly controlled by the dynamic process of runoff and the organic carbon was mainly terrestrial source. The second stage occurred during estuarine mixing, where the POC distribution was mainly controlled by the mixing process of seawater and freshwater. The source of POC was predominantly marine and exhibiting vertical differences. The surface and middle layers were primarily influenced by marine sources, while the bottom layer was jointly controlled by terrestrial and marine sources of organic carbon. These findings are of great significance for understanding the carbon cycle in such a large mangrove ecosystem like the Sundarbans mangrove.

Key words: suspended particles, particle organic carbon, Sundarbans mangrove, river-estuary system

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1 Introduction

More than 90% of the global marine organic carbon is buried in the continental margin, which plays an important role in the global carbon cycle (Hedges and Keil, 1995; Bianchi et al., 2018; Wang et al., 2018). Estuaries and coastal areas are the channels of material transported from land to ocean (Hedges et al.,1997; Gordon and Goñi, 2003; Lin et al., 2019). The amount of particulate matter transported to the ocean by rivers around the world is up to 1.8×10^{10} t per year, and the particulate organic carbon (POC) carried by rivers accounts for about half of the TOC transported by rivers (Milliman and Syvitski, 1992; Ludwig et al., 1996). Therefore, understanding the transport process of POC in the river-estuary system is an important part of global carbon cycle research, which is helpful to further explore the source and sink processes of organic carbon in marginal seas.

Estuaries are an important place for organic carbon transport and transformation, and most organic carbon is converted, deposited, and buried in estuaries (Alongi, 2014; Bouillon et al., 2008; Dittmar et al., 2006; Duarte et al., 2005; Jennerjahn and Ittekkot, 2002). Among them, the mangrove estuaries have played an irreplaceable place due to their unique ecosystems. Mangroves, along with salt marshes and seagrass, are known as “blue carbon” ecosystems, referring to the high rate at which these coastal ecosystems sequester and store carbon (Rahman et al., 2021; Lovelock and Duarte, 2019; Macreadie et al., 2019). Although mangroves cover only 0.1% of the world’s land area, they sequester more carbon per unit area than any other natural ecosystem (Atwood et al., 2017; Lovelock and Duarte, 2019; Duarte

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et al., 2005; Jennerjahn and Ittekkot, 2002). It is of great significance to study the organic carbon cycle in mangrove estuaries.

The Sundarbans mangrove, which has the world's largest continuous mangrove (Giri et al., 2011), is located in the Ganges-Brahmaputra River (with an annual sediment flux of approximately 1 × 10^9 t) Delta (Dietrich et al., 2020), leading this region to be one of the world's most important carbon transport corridors. Studies have shown that land-sea organic carbon flows can occur either actively by mobile consumers (Bouillon and Connolly, 2009) or passively by tidal, coastal and/or river emissions (Hyndes et al., 2014; Gillis et al., 2014). Therefore, in the Sundarbans area with a dense river network, the study of organic carbon transport and conversion process in the river-estuary system is particularly complex and important. Although a lot of progress has been made in organic carbon research in Sundarbans, most of the studies focus on organic carbon traceability, estimation of carbon storage and carbon transport flux and so on (Rahman et al., 2021; Abdullah et al., 2016; Das et al., 2020; Donato et al., 2011; Rahman et al., 2015; Khan and Amin, 2019). In Sundarbans, the variation of suspended particulate matter content is controlled by hydrodynamic conditions (Zou et al., 2022), which in turn significantly affects the distribution of POC. The composition of POC is regulated by the seasonal litter fall, river discharge and phytoplankton production (Ray and Shahraki, 2016). Low organic carbon contents and elemental ratios (TN/TOC) indicate intense mineralization and transformation of organic matter (OM) in the sediment (Ray et al., 2015). It is estimated that Sundarbans mangroves transport 0.58 Tg C as POC per annum into the ocean (Ray et al., 2018). The lack of studies on estuarine processes, especially the confluence of river and ocean systems (organic carbon content, occurrence state, control factors, and their transformation processes, etc), is not conducive to a comprehensive understanding of the carbon cycle processes in the region, and then restrict the government's environmental management and ecological evaluation of the region.

In this study, the POC content and distribution in the water column from the mainstream to the estuary of Passur River in the Sundarbans area were analyzed by combining the data of water salinity, turbidity, and Chlorophyll-*a* (hereafter Chl *a*). The influence mechanism of the content and distribution of POC and the source of POC are further explored. In addition, the dynamic conversion of POC in the river-estuary system is qualitatively described and compared with other estuary systems in the world.

2 Material and methods

2.1 *Study area and sample collection*

Sundarbans mangrove formed on the Ganges-Brahmaputra Delta. It is a tide-dominated mangrove surrounding hundreds of islands spread through India and Bangladesh (Ranjan et al., 2018). Sundarbans' mangrove forest covers an area of about 10 200 km^2, with numerous small rivers, waterways and streams (Ray et al., 2011; Ray and Shahraki, 2016). The hydrology of Sundarbans is controlled by the freshwater flows of the Ganges, Brahmaputra and Meghna River, with large seasonal variations (Rahman et al., 2021). The tidal current is a regular semi-diurnal tide, with high tides ranging from 1.5 m (neap tides) to 5 m (spring tides) (Rahman et al., 2021; Mukhopadhyay et al., 2006; Chatterjee et al., 2013).

The study area is situated at the low steam and mouth of the Passur River in the Sundarbans, Bangladesh (Fig. 1). In January 2018, two Sections (AB and CD) with total 40 stations and a 13-hours mooring station (Station M) were set up in the mainstream and estuary of Passur River. A Conductivity-Temperature-Depth system (CTD, SD204, SAIV AS, Norway) was performed at each station to record temperature, Chl *a*, salinity and turbidity. Three water samples were taken from the surface to the bottom of each station. The Section AB begins at the upper reaches of the river and follows the channel to the sea. The Section CD is placed in the area of the estuary and spans the estuary from east to west. The mooring Station M is located in Section CD, and the horizontal coordinate is 0 at 14:00 on January 26, 2018. The three-dimensional spatial positions of the above two sections are shown in Figure 2.

2.2 *Laboratory analysis*

First, the water sample was filtered through a all-glass-fiber Whatman GF/F membrane and dried at 40℃. Second, the glass membrane was decalcified with 1.2 mol/L HCl. The acidified membrane was washed six times with deionized water and dried at 60℃. Finally, the treated membrane were grounded into a powder and packed into a tin cup for testing. POC and δ^{13}C test equipment is the Element Analyzer-Stable Isotope Mass Spectrometer (Vario ISOPOTE CubeIsoprime, Elementar). All the experiments were completed in the Third Institute of Oceanology, Ministry of Natural Resources, China.

3 Result

3.1 *Distribution of salinity, Chl a and turbidity*

3.1.1 *Salinity and turbidity*

According to previous study results, salinity and turbidity have different characteristics in the river section, estuary section and mooring station, respectively (Fig. 2) (Zou et al., 2022). In the river part, the salinity is low (mostly less than 5). There is almost no change in the vertical direction and increases gradually in the seaward direction and increases significantly in the estuary (Fig. 2b-1). The turbidity fluctuates greatly in the vertical direction and increases with the increase of the depth and decreased significantly in the estuary (Fig. 2b-3). In the estuary part, the salinity is characterized by obvious stratification, low salinity in the upper and middle layers and high salinity in the bottom layer (Fig. 2). The high turbidity area is blocked in this section and the high and low turbidity area is distributed alternately (Fig. 2). In the mooring station, the salinity is relatively lower and the vertical mixing is stronger at low tide. At high tide, the salinity reaches the maximum value and stratification occurs (Fig. 2). On the contrary, the turbidity increases during low tide, then decrease after reaching the maximum and reaching the minimum at high tide (Fig. 2).

3.1.2 *Chl a*

The Chl *a* content ranged from 0.32 μg/L to 3.97 μg/L (averaged 1.37 μg/L), with an increased trend from the upper part of the river to the sea and reaching the maximum value in the estuary. In the river part, most of the Chl *a* is lower than 1 mg/L without vertical variation (Fig. 2b-2). In the estuary, the Chl *a* increased up to 2.5 mg/L, and the content in the bottom layer was higher than that in the middle and upper layers (Fig. 2c-2). At the mooring station, the Chl *a* performed a significant tidal variation with minimum value occurring at low tide and maximum value at high tide and a vertical trend of decreasing from the surface to bottom layers (Fig. 2d-2).

3.2 *Distribution and variation of POC and δ^{13}C*

The content of POC ranged from 0.263 mg/L to 9.292 mg/L

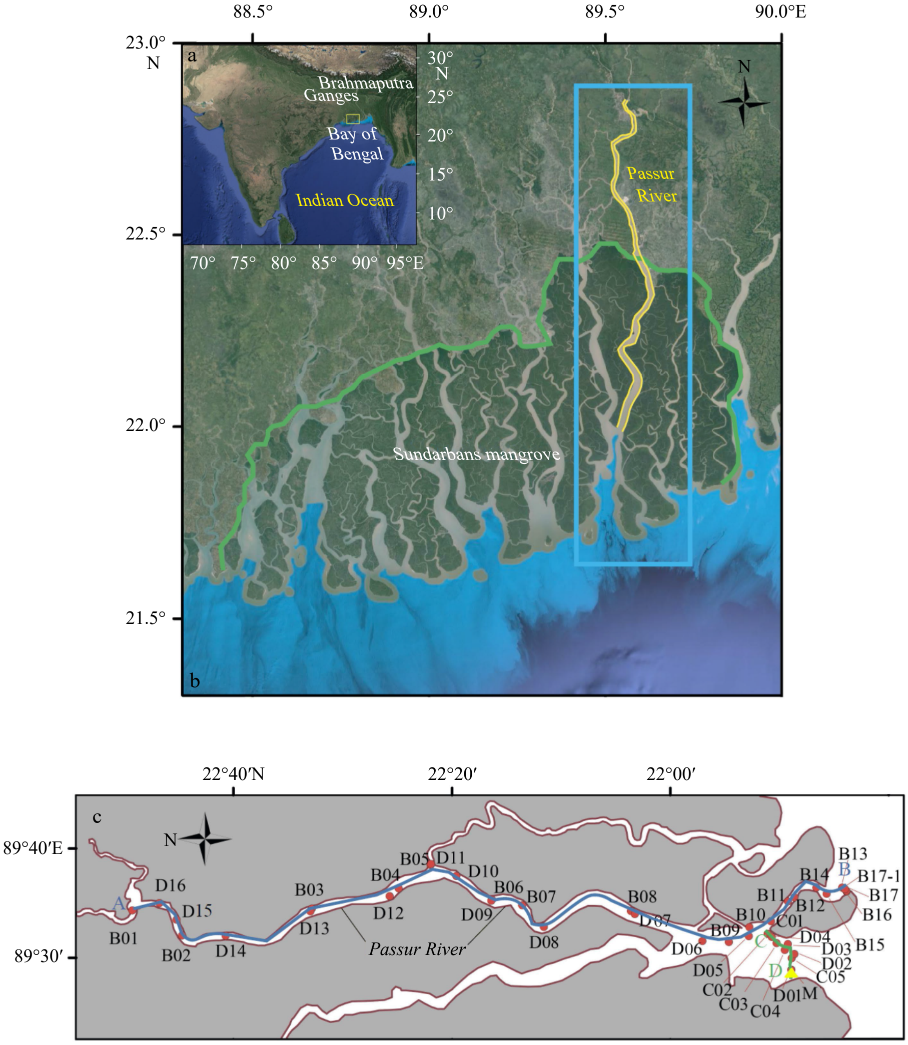

Fig. 1. Study area and station distribution map (modified from Zou et al., 2022). a. A large map indicating the location. b. A smaller map shows the Sundarbans range and the location of the Passur River. c. Specific sample distribution map. AB is river section and CD is estuary section. The red dot represents the sampling location of the section, and the yellow triangle represents the location of the mooring station.

(averaged 3.040 mg/L). Generally, the content of POC in the river section (averaged 4.129 mg/L) is higher than that in the estuary area (averaged 0.858 mg/L). The range of δ^{13}C values is relatively small (from –27.566‰ to –24.608‰ with an average of –26.443‰) and the δ^{13}C values lack regular distribution characteristics. The correlation analysis method was used to analyze the organic carbon and its isotope with temperature, salinity, turbidity and Chl *a*. The correlation coefficient results showed that the POC at Section AB, Section CD and continuous Station M had a strong positive correlation with the turbidity of water (Table 1), while the correlation between POC and other parameters was different in different regions. Specifically, POC in Section AB has a good negat-

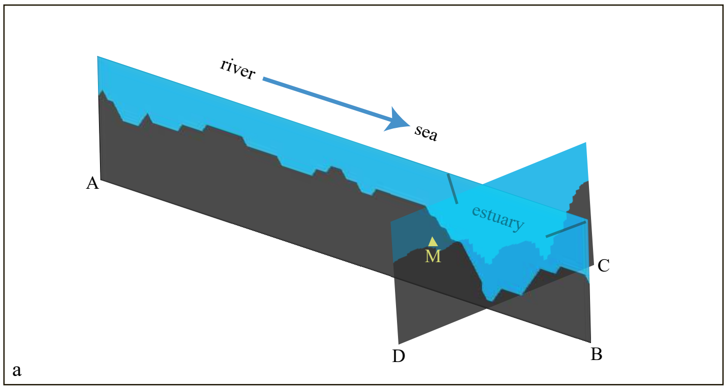

Fig. 2.

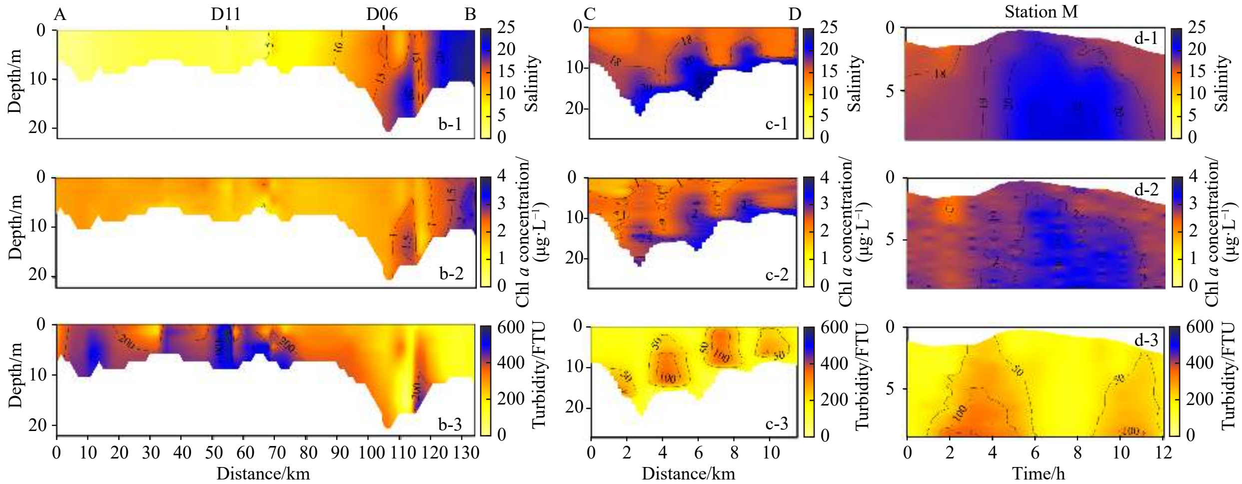

Fig. 2. Distribution of salinity (b-1, c-1, and d-1), chlorophyll *a* (b-2, c-2, and d-2) and turbidity (b-3, c-3, and d-3) in the Section AB (left panel), Section CD (middle panel) and mooring Station M (right panel). Figure a is a schematic diagram of the position of Sections AB and CD, and the mooring Station M (modified from Zou et al., 2022).

Table 1. Correlation coefficients of organic carbon and its isotope with environmental parameters

		Salinity	Temperature	Turbidity	Chl *a*
Section AB	$\delta^{13}C$	−0.156	−0.082	0.212	−0.139
	POC	−0.623**	−0.620**	0.791**	−0.503**
Section CD	$\delta^{13}C$	−0.217	−0.191	0.445*	−0.236
	POC	−0.314	−0.301	0.878**	−0.321
Station M	$\delta^{13}C$	−0.178	0.147	0.115	−0.278
	POC	0.127	−0.063	0.860**	0.252

Note: **, a significant association at the 0.01 level. *, a significant association at the 0.05 level.

ive correlation with salinity, temperature and Chl *a*, while there is no significant correlation between Section CD and continuous stations. This may be because the values of POC, temperature, salinity and Chl *a* in Section AB are significantly different in the river and estuary areas. So there is a false correlation in Section AB. The correlation between $\delta^{13}C$ and each parameter is not significant, because the variation of this value is small and it is affected by different material sources.

In order to more intuitively show the distribution of POC and its relationship with turbidity, the value points of POC were projected into the turbidity base map (Fig. 3). The results show that the POC content has a good correlation with water turbidity both in the river section and estuary area (Figs 3a–2, 3b–2, 3c–2). There is no significant relationship between $\delta^{13}C$ and water turbidity in the river section and estuary area. However, the distribution of $\delta^{13}C$ has certain tidal fluctuation characteristics in the mooring station and there is some certain inverse correlation between its distribution and turbidity distribution in the mooring station Figs 3a–1, 3b–1, 3c–1).

4 Discussion

4.1 *Transport process of POC in river-estuary system*

The source of POC in the river-estuary system can be divided into exogenous and autogenous sources (Abril et al., 2002; Meybeck, 1982). Exogenous POC mainly came from soil erosion, terrestrial plants and human activities, while autogenous POC is mainly produced by plankton in aquatic ecosystems (Lu et al., 2022). There are two distinct stages of POC in the process of river transport to the sea, namely the river transport process and the estuarine mixing process. In the riverine stage, the vertical mixing is intense due to shallow depth and strong hydrodynamic, resulting in high turbidity and POC. However, high turbidity limits the growth of phytoplankton due to lower transmittance of light, resulting in lower Chl *a* content (Chen et al., 2017). Thus, these riverine POC may be not autogenous sources but mainly come from an exogenous source. In the estuary, the variation of water depth and the location of the mixing interface are the keys to controlling the concentration of suspended particulate matter (Zou et al., 2022). At this time, subsidence occurs in estuary areas due to sediment carried by rivers. The light transmittance in-

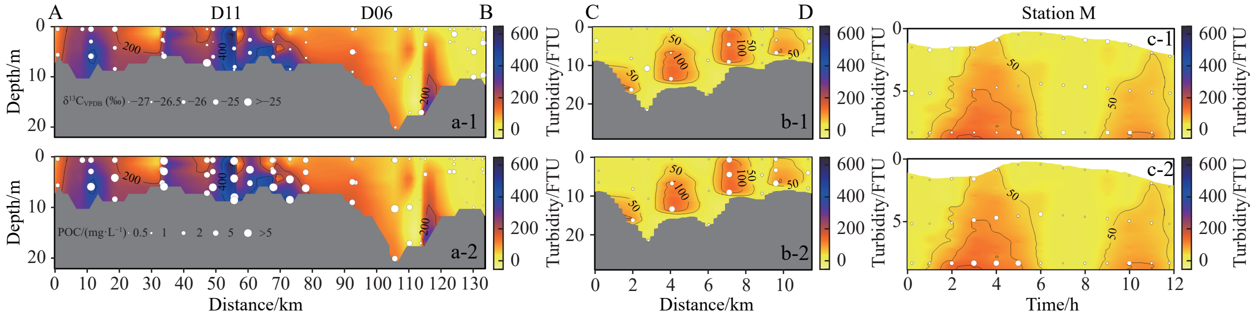

Fig. 3. Distribution of $\delta^{13}C$ (a-1, b-1, and c-1), POC (a-2, b-2, and c-2) in the Section AB (left panel), Section CD (middle panel) and mooring Station M (right panel).

creases, leading to a significant increase in Chl *a* content, and the contribution of autogenous POC gradually increases. In particular, an increase of δ^{13}C can be seen at the high tide level, which is closely related to the contribution of plankton.

Although the POC content in the Passur River and its estuary were significantly correlated with the turbidity, the variation of the turbidity in the river and estuary process was dominated by different factors (Chai et al., 2017; Zhao et al., 2013; Li et al., 2019). To further analyze the difference between the Passur River and its estuary, salinity 15 was used as the boundary between the river and the estuary. The distribution of POC content in the Passur River and its estuary both showed a significant positive correlation with suspended particulate concentration (SSC, which was obtained by filtration membrane weighing) (Fig. 4a). The content of POC in the river section is higher than that in the estuary, which has a significant tidal cycle, and has a negative correlation with salinity and a positive correlation with turbidity (Fig. 5a). The results show that the distribution of POC in the river area is mainly controlled by hydrodynamics, while the distribution of POC in the estuary area is affected by transgression. P_{POC} refers to the mass proportion of POC to the suspended particulate matter, which can be used to characterize the fluctuation of the source of POC. The stable value of P_{POC} indicates a single source, while the large value fluctuation indicates different sources (Zhai et al., 2005; Hong, 2005). The P_{POC} of the river part is relatively stable (ranging from 0.278 to 4.574 with an average of 1.723) with variable SSC (Fig. 4b), indicating a stable external input of riverine POC. However, the P_{POC} of the estuary (ranged from 0.225 to 10.989 with an average of 3.025) varied significantly with low SSC (<0.04 g/L), but remained stable when SSC > 0.04 g/L (Fig. 4b), indicating a complex source of POC. In addition, the P_{POC} has the characteristics of the tidal cycle fluctuation, which is positively correlated with salinity and negatively correlated with turbidity (Fig. 5b), also indicating a variation source during tidal cycles. The content of Chl *a* in the estuary is low, but with the increase of salinity, the content of Chl *a* in the estuary increases significantly (Fig. 4c), which indicates an increased contribution of authigenic POC. Therefore, the distribution of POC in the river part is mainly controlled by runoff dynamics. The source of POC is single and mainly exogenous. The distribution of POC in the estuary part is controlled by the estuarine mixing process and the source of POC varies significantly.

To further analyze the fluctuation characteristics of organic carbon sources in the context of river-ocean interactions,

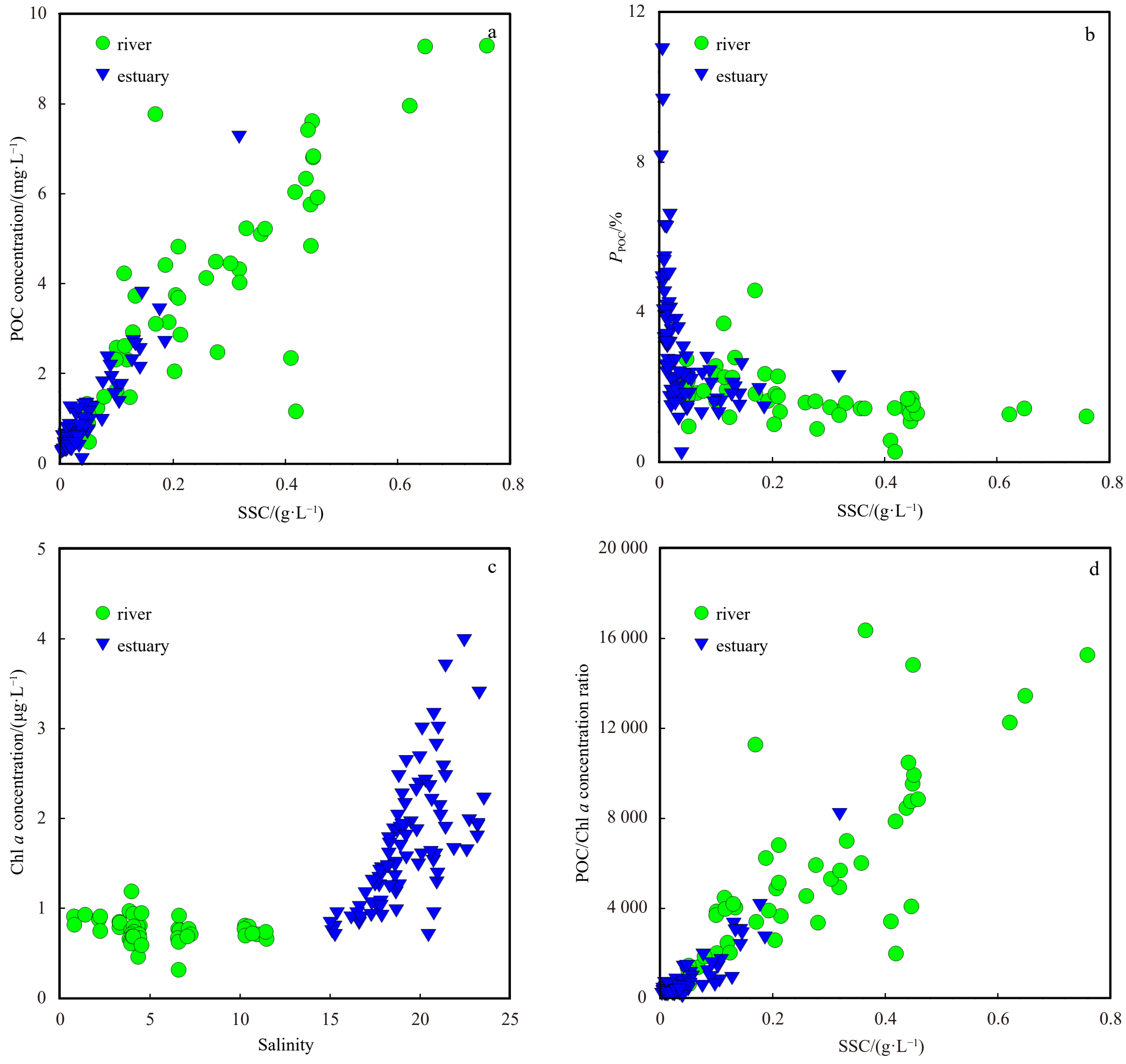

Fig. 4.

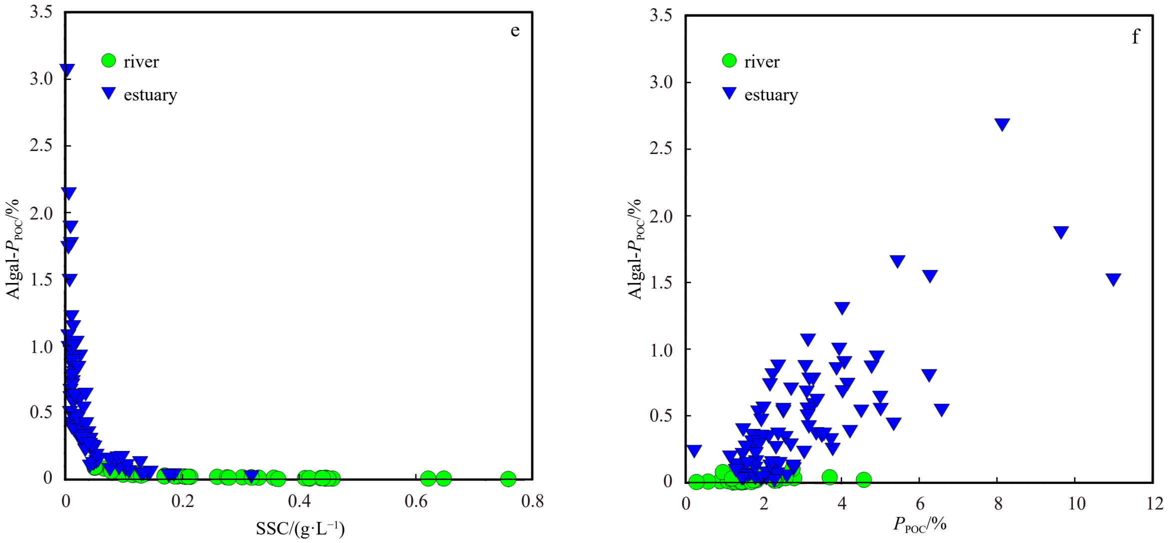

Fig. 4. Regression analysis between different parameters (POC concentration, P_{POC}, SSC, Chl *a* concentration, salinity, POC/Chl *a* concentration ratio, algal-P_{POC}). The data of mooring station is considered estuarine data.

Fig. 5. The POC (a) and P_{POC} (b) in surface, middle, and bottom layers of water column, respectively. In the abscissa, blue and orange represent the station of Section AB and Section CD, green represents the time of mooring station, respectively.

POC/Chl *a* concentration ratio and algal-$P_{\rm POC}$ were calculated using the existing data to analyze the changes of POC sources. POC/Chl *a* concentration ratio (characterization of exogenous POC contribution) and algal-$P_{\rm POC}$ (characterize the autogenetic POC contribution, algal-$P_{\rm POC}$ = Chl *a* concentration × 60/SSC) are an indicator of the source of POC (Herman and Heip,1999; Abril et al., 2002). POC/Chl *a* concentration ratio increased with the increase of SSC (Fig. 4d), indicating that the contribution of exogenous POC increases with SSC in the Passur River and its estuary. Algal-$P_{\rm POC}$ has a good negative exponential relationship with SSC (Fig. 4f). The results of algal-$P_{\rm POC}$ indicate that the contribution of autogenetic POC to the river section with high SSC is small (Fig. 4e). The contribution of autogenetic POC increased significantly in the estuary section with low SSC (Fig. 4e). This is consistent with the result shown by $P_{\rm POC}$. In the Passur River and its estuary, the POC/Chl *a* concentration ratio (contribution of exogenous POC) decreased significantly from river to estuary, with a vertical increase from surface to bottom (Fig. 6a), which also showed an obvious fluctuation during tidal variation and is consistent with turbidity. The algal-$P_{\rm POC}$ (contribution of autogenetic POC) increased significantly from river to estuary, with a vertical decrease from surface to bottom (Fig. 6b). The algal-$P_{\rm POC}$ is a significant positive correlation with salinity (Fig. 5b), and a certain positive correlation with the change of $P_{\rm POC}$ (Fig. 4f). The above results indicate that the POC source in the river section is mainly non-living organic carbon, and the living organic carbon is very few. The estuary section is a dynamic mixing process, which is controlled by the relative strength of the river and the current, and has significant tidal cycle characteristics. In conclusion, the source of POC is stable in the river transport stage, which mainly comes from exogenous inputs and is closely related to sediment re-suspension caused by hydrodynamics. In the mixing stage of estuary, the contribution of autogenous organic carbon increased significantly and was controlled by the degree of river-ocean mixing.

In terms of changes within the tidal cycle, the changes of different levels in the mooring station indicate that POC/Chl *a* concentration ratio and algal-$P_{\rm POC}$ have opposite fluctuation charac-

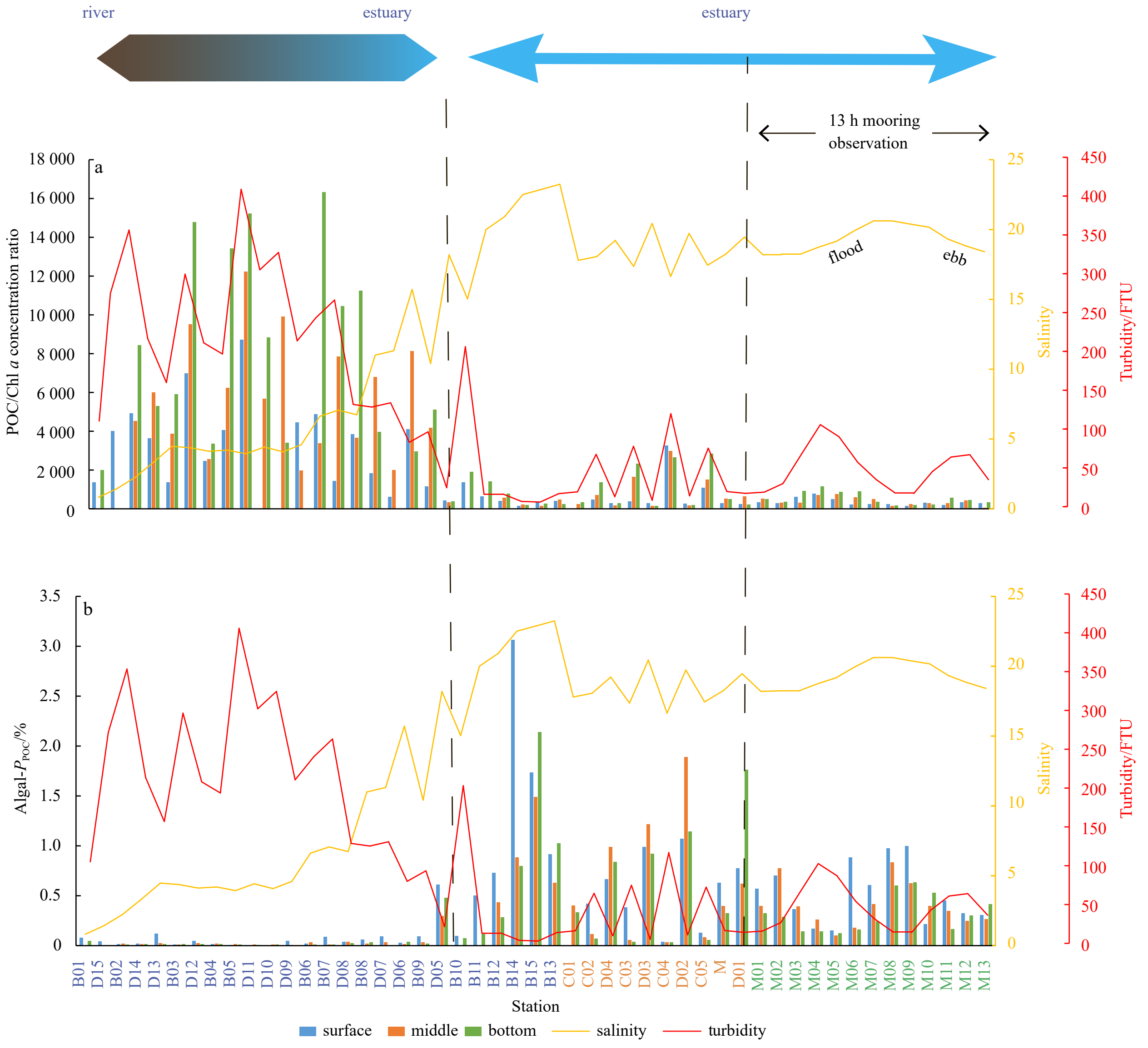

Fig. 6. The POC/Chl *a* concentration ratio (a) and algal-$P_{\rm POC}$ (b) in surface, middle, and bottom layers of water column, respectively. In the abscissa, blue and orange represent the station of Section AB and Section CD, green number represents the time of mooring station, respectively.

teristics (Fig. 6). The high value of algal-P_{POC} (autogenetic POC) appeared during tidal slack with weaker hydrodynamic due to high Chl *a* concentration induced by lower turbidity (Figs 6a and b). In contrast, the high value of POC/Chl *a* concentration ratio (exogenous POC) appeared during the flood and ebb tides with strong hydrodynamic and higher turbidity (Figs 6a and b), and the organic carbon mainly comes from the bed sediment re-suspension (Ray and Shahraki, 2016). In this process, P_{POC} is mainly controlled by the relative contribution of the two organic carbon sources. The P_{POC} in the surface and middle layers both showed an obvious tidal cycle fluctuation characteristic and the changing trend is consistent with the algal-P_{POC}, whereas the bottom layer was more stable and had no obvious fluctuations (Fig. 7). It is worth noting that the estuary of the Passur River has residual seawater at the bottom due to the special seabed topography (trench) (Fig. 2c), resulting in significant water stratification in the estuary area. This results in limited conversion of the underlying organic carbon sources during the tidal cycle. Therefore, in the estuary section, the POC in the surface and middle layers mainly come from autogenetic POC, while the bottom layer is controlled by both living and non-living organic carbons, with a stable source of organic carbon

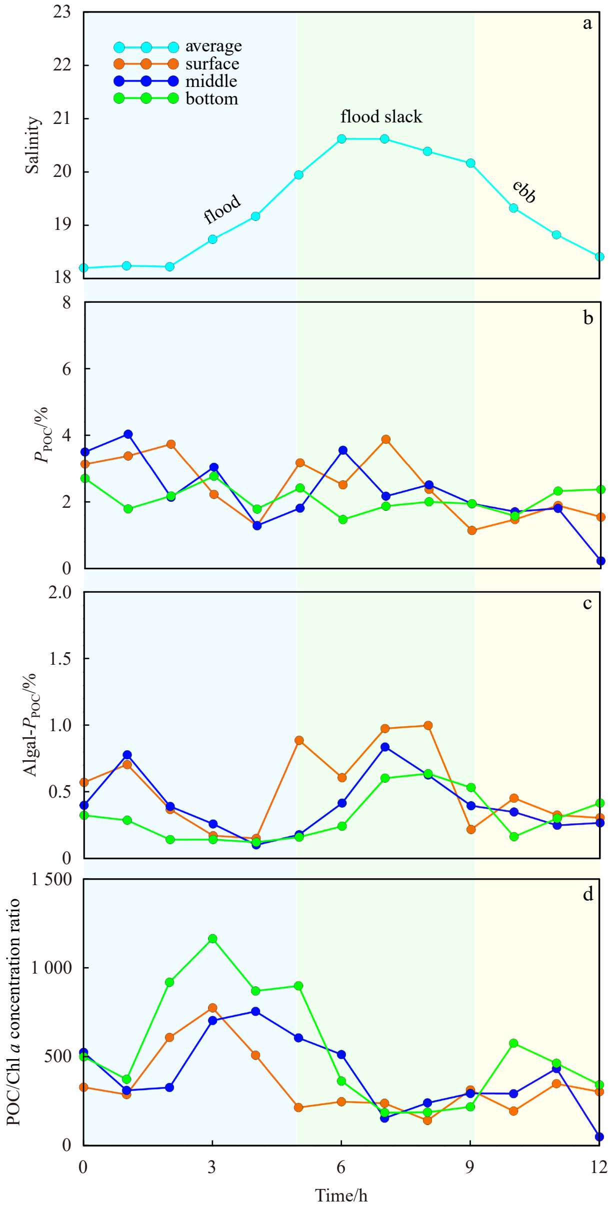

Fig. 7. Changes in salinity (a), P_{POC} (b), Algal-P_{POC} (c), and POC/Chl *a* concentration ratio (d), during the tidal cycle.

4.2 *Implications of land-sea interaction on the conversion of POC*

The study of POC in the Sundarbans area not only provides a more comprehensive understanding of the transport process of POC in the area but also helps to understand the influence of river-ocean interaction on the distribution of POC and its conversion process. In Sundbans, the distribution and conversion of POC from river to ocean are controlled by the relative intensity of river and ocean and there are two different processes. One is the process of river transport when the riverine hydrodynamic dominates and the influence of tidal current is relatively weak (Zou et al., 2022). At this stage, the content of POC is high, and its distribution is mainly controlled by sediment resuspension caused by runoff dynamics (Fig. 3a). Therefore, the organic carbon source is mainly exogenous POC and is highly correlated with turbidity in river section (Fig. 8). The other is the estuarine mixing process, in which the tidal current is strong. The runoff is relatively weak and the ocean is dominant (Zou et al., 2022). At this stage, the distribution of POC is mainly controlled by the mixing process of seawater and freshwater. The contribution of autogenetic POC increased significantly and was highly correlated with salinity, while the content of exogenous POC decreased significantly (Figs 6 and 8). Terrestrial organic carbon and marine organic carbon fluctuated during the tidal cycle (Fig. 6). It has significant tidal cycle fluctuation characteristics. There are vertical differences, the surface and middle layers are controlled by marine sources, while the bottom layer is controlled by both terrestrial and marine sources (Fig. 7). The organic carbon from the two sources underwent a series of physical and chemical reactions at the mixing interface of brackish water and finally settled mainly in the estuarine turbidity maximum zone (ETM) of the river mouth (Viers et al., 2009; Zeng et al., 2019; Yuan et al., 2012; Liu et al., 2020). During the process of river-ocean mixing, the intensity of runoff and tidal current are complementary to each other, which dynamically controls the organic carbon conversion process in Sundarbans area (Fig. 8). When the runoff is strong and the tidal current is weak, the contribution of terrigenous organic carbon is significant, whereas the contribution of marine organic carbon is large.

Although the distribution of estuarine organic carbon in other regions is inconsistent with the results of this study, the core mechanism remains consistent. For example, large river estuaries such as the Huanghe River, the Changjiang River and the Mississippi River have higher runoff and sediment transport, but the tidal current has minimal effect. Consequently, the source of organic carbon is mainly from terrestrial POC input (Zhang et al., 2007; Lu et al., 2022; Trefry et al., 1994). Moreover, the sources of organic carbon in the same estuary also differ greatly during estuary mixing due to variable relative intensity of runoff and tidal current in different seasons (Meybeck, 1982; Lu et al., 2022; Pang et al., 2021; Zhang et al., 2019). Therefore, the relative intensities of runoff and tidal current control the sources of organic carbon in the estuarine area. This is the core of the difference of terrestrial and marine organic carbon distribution and source conversion in different estuarine types around the world.

As the junction of material and energy transfer from the terrestrial to the marine ecosystem, estuaries are very important for the study of the origin, transport and conversion of organic carbon (Harrison et al., 2005; Zhang et al., 2007). According to statistics, the total amount of organic carbon transported from the

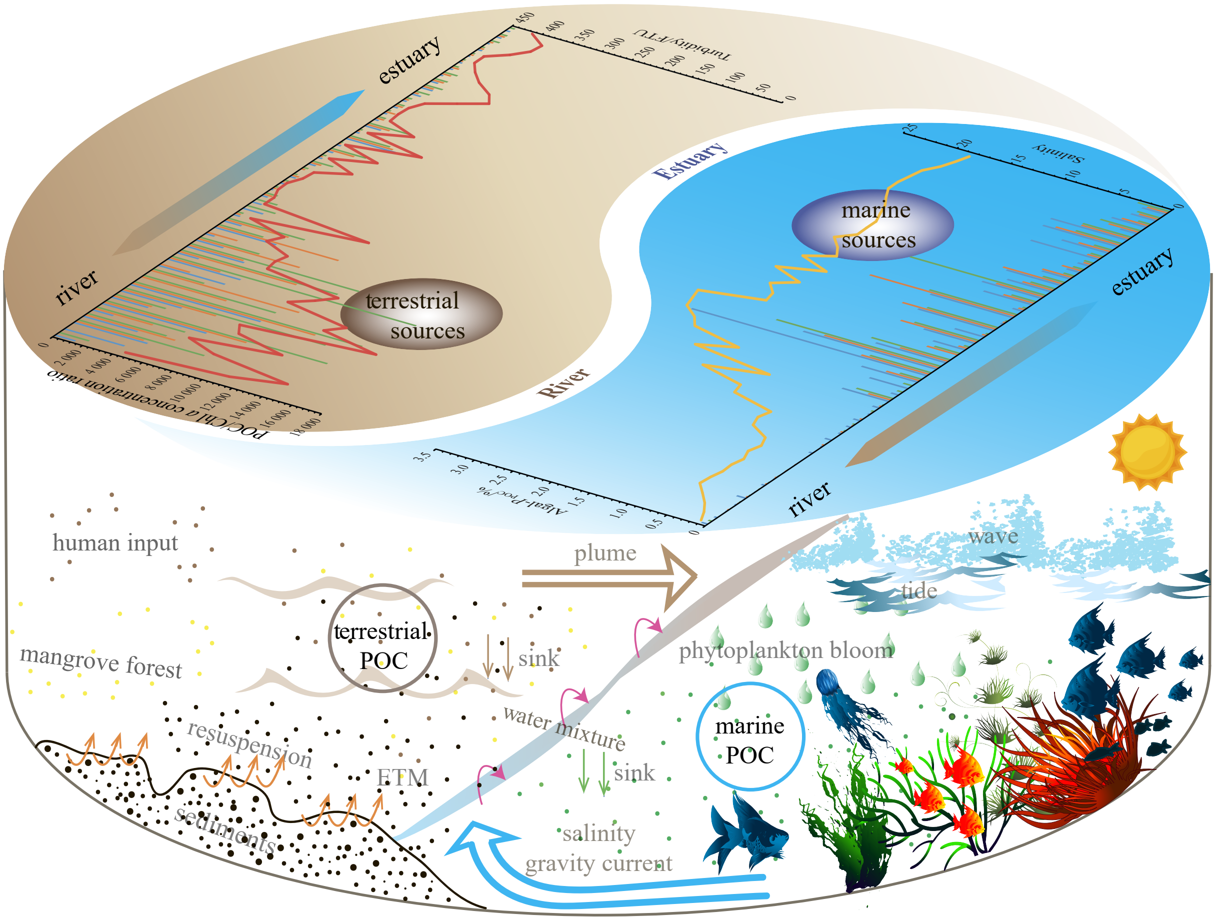

Fig. 8. The picture shows the river-ocean mixing process of the POC and the change of POC source during the process. The brown arrows indicate the direction in which runoff is moving, the blue arrows indicate the direction in which highly saline water is moving. Yellow and purple arrows indicate re-suspension and brackish water mixing, respectively. ETM: estuarine turbidity maximum zone.

world's major rivers to the offshore through estuaries is about 0.4 Gt/a, of which the POC is about 0.15 Gt/a (Hedges et al., 1997). POC experiences deposition and re-suspension, adsorption and resolution, biological absorption and release processes in the estuarine area, relatively. In these processes, POC is frequently transferred and converted in different phases, and finally mainly settled in the ETM. Thus, a large amount of terrestrial organic carbon was buried in the estuaries due to the high carbon sink effect and deposition rate (Bianchi et al., 2018; Wang et al., 2018). However, some studies show that the total burial of organic carbon in estuaries is much lower than the flux of river transport, indicating that a certain number of organic carbon may undergo obvious mineralization and biodegradation in estuaries. In addition, the results of this study show that the river-ocean mixing process in estuarine area can lead to dynamic transformation of organic carbon sources and significant vertical differences. Therefore, the behavior of organic carbon under the influence of ocean-river interaction is an extremely complex dynamic conversion process, which has a great impact on the transport and sedimentation of terrigenous organic carbon to the ocean. Consequently, it is important to understand the dynamic transformation process of organic carbon in the estuary during the tidal cycle for the study of transport, burial and cycle of organic carbon on the marginal seas.

5 Conclusions

Based on the POC data of the Passur River and its estuary in the Sundarbans area and the salinity, turbidity and Chl *a* data measured by CTD, the content and distribution of POC in suspended particulate matter in this area are discussed. The study analyzes the transport process and source of POC in the river-estuarine system and highlights the importance of the river-estuary system in understanding the terrestrial and marine organic carbon cycle. The results indicate that the content of POC is significantly higher in the river section than in the estuary section. The distribution of POC is mainly controlled by the dynamic process of runoff in the river section and controlled by the mixing process of saltwater and freshwater in the estuary section. In the river section, the source of POC is mainly terrigenous input, and the contribution of exogenous POC is much greater than that of autogenetic POC. In the estuary section, the main source of POC is the marine origin, and the contribution of autogenetic POC is increased. In the vertical direction, sea-derived organic carbon is dominant in the surface and middle layers, while terrestrial and sea-derived organic carbon co-controls in the bottom layer. The source of organic carbon in estuarine areas is controlled by the relative intensity of rivers and oceans interaction. The study highlights the significance of understanding the dynamics of organic carbon in the estuarine area during the tidal cycle for studying the terrestrial and marine organic carbon cycle.

This study improves the understanding of organic carbon transport and transformation process in the river-estuary system in this region and is of great significance for the study of the estuarine carbon cycle in the world. The study on the dynamic conversion process of POC in the estuary during the tidal cycle is of great significance for clarifying the fate of organic carbon in the estuary. Future research should be focused on quantitatively analyzing the relative contributions of organic carbon from different sources over a tidal cycle.

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References

Abdullah A N M, Stacey N, Garnett S T, et al. 2016. Economic dependence on mangrove forest resources for livelihoods in the Sundarbans, Bangladesh. Forest Policy and Economics, 64: 15–24, doi: 10.1016/j.forpol.2015.12.009

Abril G, Nogueira M, Etcheber H, et al. 2002. Behaviour of organic carbon in nine contrasting European estuaries. Estuarine, Coastal and Shelf Science, 54(2): 241–262

Alongi D M. 2014. Carbon cycling and storage in mangrove forests. Annual Review of Marine Science, 6: 195–219, doi: 10.1146/annurev-marine-010213-135020

Atwood T B, Connolly R M, Almahasheer H, et al. 2017. Global patterns in mangrove soil carbon stocks and losses. Nature Climate Change, 7(7): 523–528, doi: 10.1038/nclimate3326

Bianchi T S, Cui Xingqian, Blair N E, et al. 2018. Centers of organic carbon burial and oxidation at the land-ocean interface. Organic Geochemistry, 115: 138–155, doi: 10.1016/j.orggeochem.2017.09.008

Bouillon S, Borges A V, Castañeda-Moya E, et al. 2008. Mangrove production and carbon sinks: a revision of global budget estimates. Global Biogeochemical Cycles, 22(2): GB2013

Bouillon S, Connolly R M. 2009. Carbon exchange among tropical coastal ecosystems. In: Nagelkerken E, ed. Ecological Connectivity among Tropical Coastal Ecosystems. Dordrecht: Springer, 45–70

Chai Minwei, Li Ruili, Zan Qijie. 2017. Effects of mangrove plants on heavy metal risk in sediment based on SEM-AVS analysis. Regional Studies in Marine Science, 13: 12–18, doi: 10.1016/j.rsma.2017.03.008

Chatterjee M, Shankar D, Sen G K, et al. 2013. Tidal variations in the Sundarbans Estuarine System, India. Journal of Earth System Science, 122(4): 899–933, doi: 10.1007/s12040-013-0314-y

Chen Dongxing, He Lei, Liu Fenfen, et al. 2017. Effects of typhoon events on chlorophyll and carbon fixation in different regions of the East China Sea. Estuarine, Coastal and Shelf Science, 194: 229–239

Das S, Ganguly D, Chakraborty S, et al. 2020. The first report of Glomalin from the Sundarban Mangrove Biosphere Reserve, India, a long-term sediment carbon storage. Regional Studies in Marine Science, 39: 101398, doi: 10.1016/j.rsma.2020.101398

Dietrich M, Best K B, Raff J L, et al. 2020. A first-order geochemical budget for suspended sediment discharge to the Bay of Bengal from the Ganges-Brahmaputra River system. Science of the Total Environment, 726: 138667, doi: 10.1016/j.scitotenv.2020.138667

Dittmar T, Hertkorn N, Kattner G, et al. 2006. Mangroves, a major source of dissolved organic carbon to the oceans. Global Biogeochemical Cycles, 20(1): B1012

Donato D C, Kauffman J B, Murdiyarso D, et al. 2011. Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience, 4(5): 293–297, doi: 10.1038/ngeo1123

Duarte C M, Middelburg J J, Caraco N. 2005. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences, 2(1): 1–8, doi: 10.5194/bg-2-1-2005

Gillis L G, Ziegler A D, Van Oevelen D, et al. 2014. Tiny is mighty: Seagrass beds have a large role in the export of organic material in the tropical coastal zone. PLoS One, 9(11): e111847, doi: 10.1371/journal.pone.0111847

Giri C, Ochieng E, Tieszen L L, et al. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecology and Biogeography, 20(1): 154–159, doi: 10.1111/j.1466-8238.2010.00584.x

Gordon E S, Goñi M A. 2003. Sources and distribution of terrigenous organic matter delivered by the Atchafalaya River to sediments in the northern Gulf of Mexico. Geochimica et Cosmochimica Acta, 67(13): 2359–2375, doi: 10.1016/S0016-7037(02)01412-6

Harrison J A, Caraco N, Seitzinger S P. 2005. Global patterns and sources of dissolved organic matter export to the coastal zone: results from a spatially explicit, global model. Global Biogeochemical Cycles, 19(4): BS404

Hedges J I, Keil R G. 1995. Sedimentary organic matter preservation: an assessment and speculative synthesis. Marine Chemistry, 49(2–3): 81–115, doi: 10.1016/0304-4203(95)00008-F

Hedges J I, Keil R G, Benner R. 1997. What happens to terrestrial organic matter in the ocean?. Organic Geochemistry, 27(5–6): 195–212, doi: 10.1016/S0146-6380(97)00066-1

Herman P M J, Heip C H R. 1999. Biogeochemistry of the maximum turbidity zone of estuaries (MATURE): some conclusions. Journal of Marine Systems, 22(2–3): 89–104, doi: 10.1016/S0924-7963(99)00034-2

Hyndes G A, Nagelkerken I, Mcleod R J, et al. 2014. Mechanisms and ecological role of carbon transfer within coastal seascapes. Biological Reviews, 89(1): 232–254, doi: 10.1111/brv.12055

Jennerjahn T C, Ittekkot V. 2002. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. Naturwissenschaften, 89(1): 23–30, doi: 10.1007/s00114-001-0283-x

Khan M, Amin M. 2019. Macro nutrient status of Sundarbans forest soils in southern region of Bangladesh. Bangladesh Journal of Scientific and Industrial Research, 54(1): 67–72, doi: 10.3329/bjsir.v54i1.40732

Li Huan, Chai Liyuan, Yang Zhihui, et al. 2019. Seasonal and spatial contamination statuses and ecological risk of sediment cores highly contaminated by heavy metals and metalloids in the Xiangjiang River. Environmental Geochemistry and Health, 41(3): 1617–1633, doi: 10.1007/s10653-019-00245-2

Lin Yunpeng, Li Yunhai, Zheng Binxin, et al. 2019. Evolution of sedimentary organic matter in a small river estuary after the typhoon process: A case study of Quanzhou Bay. Science of the Total Environment, 686: 290–300, doi: 10.1016/j.scitotenv.2019.05.452

Liu Shengfa, Wu Bin, Seddique A A, et al. 2020. Distribution, sources and chemical screening-level assessment of toxic metals in the northern Bay of Bengal, Bangladesh. Marine Pollution Bulletin, 150: 110676, doi: 10.1016/j.marpolbul.2019.110676

Lovelock C E, Duarte C M. 2019. Dimensions of Blue Carbon and emerging perspectives. Biology Letters, 15(3): 20180781, doi: 10.1098/rsbl.2018.0781

Lu Taian, Wang Houjie, Wu Xiao, et al. 2022. Transport of particulate organic carbon in the lower Yellow River (Huanghe) as modulated by dam operation. Global and Planetary Change, 217: 103948, doi: 10.1016/j.gloplacha.2022.103948

Ludwig W, Probst J L, Kempe S. 1996. Predicting the oceanic input of organic carbon by continental erosion. Global Biogeochemical Cycles, 10(1): 23–41, doi: 10.1029/95GB02925

Macreadie P I, Anton A, Raven J A, et al. 2019. The future of Blue Carbon science. Nature Communications, 10: 3998, doi: 10.1038/s41467-019-11693-w

Meybeck M. 1982. Carbon, nitrogen, and phosphorus transport by world rivers. American Journal of Science, 282(4): 401–450, doi: 10.2475/ajs.282.4.401

Milliman J D, Syvitski J P M. 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. The Journal of Geology, 100(5): 525–544, doi: 10.1086/629606

Mukhopadhyay S K, Biswas H, De T K, et al. 2006. Fluxes of nutrients from the tropical River Hooghly at the land–ocean boundary of Sundarbans, NE Coast of Bay of Bengal, India. Journal of Marine Systems, 62(1–2): 9–21, doi: 10.1016/j.jmarsys.2006.03.004

Pang Yu, Wang Kai, Sun Yongge, et al. 2021. Linking the unique molecular complexity of dissolved organic matter to flood period in the Yangtze River mainstream. Science of the Total Environment, 764: 142803, doi: 10.1016/j.scitotenv.2020.142803

Rahman M S, Donoghue D N M, Bracken L J. 2021. Is soil organic carbon underestimated in the largest mangrove forest ecosystems? Evidence from the Bangladesh sundarbans. Catena, 200: 105159, doi: 10.1016/j.catena.2021.105159

Rahman M M, Khan N I, Hoque A K F, et al. 2015. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones. Wetlands Ecology and Management, 23(2): 269–283, doi: 10.1007/s11273-014-9379-x

Ranjan P, Ramanathan A L, Kumar A, et al. 2018. Trace metal distribution, assessment and enrichment in the surface sediments of Sundarban mangrove ecosystem in India and Bangladesh. Marine Pollution Bulletin, 127: 541–547, doi: 10.1016/j.marpolbul.2017.11.047

Ray R, Baum A, Rixen T, et al. 2018. Exportation of dissolved (inorganic and organic) and particulate carbon from mangroves and its implication to the carbon budget in the Indian Sundarbans. Science of the Total Environment, 621: 535–547, doi: 10.1016/j.scitotenv.2017.11.225

Ray R, Ganguly D, Chowdhury C, et al. 2011. Carbon sequestration and annual increase of carbon stock in a mangrove forest. Atmospheric Environment, 45(28): 5016–5024, doi: 10.1016/j.atmosenv.2011.04.074

Ray R, Rixen T, Baum A, et al. 2015. Distribution, sources and biogeochemistry of organic matter in a mangrove dominated estuarine system (Indian Sundarbans) during the pre-monsoon. Estuarine, Coastal and Shelf Science, 167: 404–413

Ray R, Shahraki M. 2016. Multiple sources driving the organic matter dynamics in two contrasting tropical mangroves. Science of the Total Environment, 571: 218–227, doi: 10.1016/j.scitotenv.2016.07.157

Trefry J H, Metz S, Nelsen T A, et al. 1994. Transport of particulate organic carbon by the Mississippi River and its fate in the Gulf of Mexico. Estuaries, 17(4): 839–849, doi: 10.2307/1352752

Viers J, Dupré B, Gaillardet J. 2009. Chemical composition of suspended sediments in World Rivers: New insights from a new database. Science of the Total Environment, 407(2): 853–868, doi: 10.1016/j.scitotenv.2008.09.053

Wang Chuanyuan, Lv Yingchun, Li Yuanwei. 2018. Riverine input of organic carbon and nitrogen in water-sediment system from the Yellow River estuary reach to the coastal zone of Bohai Sea, China. Continental Shelf Research, 157: 1–9, doi: 10.1016/j.csr.2018.02.004

Yuan Huamao, Song Jinming, Li Xuegang, et al. 2012. Distribution and contamination of heavy metals in surface sediments of the South Yellow Sea. Marine Pollution Bulletin, 64(10): 2151–2159, doi: 10.1016/j.marpolbul.2012.07.040

Zeng Jie, Han Guilin, Wu Qixin, et al. 2019. Heavy metals in suspended particulate matter of the Zhujiang River, southwest China: contents, sources, and health risks. International Journal of Environmental Research and Public Health, 16(10): 1843, doi: 10.3390/ijerph16101843

Zhai Weidong, Dai Minhan, Cai Weijun, et al. 2005. The partial pressure of carbon dioxide and air–sea fluxes in the northern South China Sea in spring, summer and autumn. Marine Chemistry, 96(1–2): 87–97, doi: 10.1016/j.marchem.2004.12.002

Zhang Yifan, Li Dewang, Wang Kui, et al. 2019. Contribution of biological effects to the carbon sources/sinks and the trophic status of the ecosystem in the Changjiang (Yangtze) River estuary plume in summer as indicated by net ecosystem production variations. Water, 11(6): 1264, doi: 10.3390/w11061264

Zhang J, Wu Y, Jennerjahn T C, et al. 2007. Distribution of organic matter in the Changjiang (Yangtze River) Estuary and their stable carbon and nitrogen isotopic ratios: implications for source discrimination and sedimentary dynamics. Marine Chemistry, 106(1–2): 111–126, doi: 10.1016/j.marchem.2007.02.003

Zhao Shou, Feng Chenghong, Wang Dongxin, et al. 2013. Salinity increases the mobility of Cd, Cu, Mn, and Pb in the sediments of Yangtze Estuary: relative role of sediments' properties and metal speciation. Chemosphere, 91(7): 977–984, doi: 10.1016/j.chemosphere.2013.02.001

Zou Xiaochun, Li Yunhai, Wang Liang, et al. 2022. Distribution and assessment of heavy metals in suspended particles in the Sundarban mangrove river, Bangladesh. Marine Pollution Bulletin, 181: 113856, doi: 10.1016/j.marpolbul.2022.113856