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Inner-shelf mud belts as toggleable carbon-nitrogen sources and sinks in tide-dominated coastal systems

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24 **Abstract:** Estuaries mediate global land-ocean biogeochemical cycles, but few studies quantify
25 how shelf depocenters regulate estuarine carbon-nitrogen dynamics, limiting source-to-sink and
26 blue-carbon models. Here, we integrate bulk sedimentary organic carbon and nitrogen
27 abundances, stable isotopes, and a Bayesian mixing model across a fluvial-estuarine continuum
28 in southeastern China and the adjacent East China Sea inner-shelf mud belt. Our results reveal
29 a striking spatial bifurcation in organic matter provenance. Non-tidal reaches are dominated by
30 terrestrial signatures, primarily sewage and catchment-derived eroded soil (36.3% and 34.5%).
31 Conversely, tidally influenced reaches shift to a dual dominance of autochthonous marine inputs
32 (12.2%) and anthropogenic waste (25.7%), regulated by tidal hydrodynamic sorting, estuarine
33 mixing, and authigenic accretion. Crucially, inner-shelf mud sediments act as a major estuarine
34 end-member (28.6%), fundamentally reshaping the architecture of the estuarine carbon reservoir.
35 Mass-balance calculations indicate that tidal pumping drives a substantial landward flux of ~0.90
36 to 2.39 Mt C/yr from the shelf mud belt back into the estuarine reaches. Challenging the traditional
37 view that shelf sediments are passive carbon sinks, macro-tidal mud belts serve as active carbon
38 suppliers. This neglected backward carbon flux needs incorporating into coastal carbon budgets
39 for climate- and human-induced disturbance assessments.

41 **Introduction**

42 As critical land-ocean transition zones, estuaries and adjacent inner-shelf muddy
43 depocenters function as primary conduits and biogeochemical reactors that regulate material
44 fluxes across the land-ocean interface¹. Fluvial exports of terrigenous total organic carbon (TOC)
45 and nitrogen (TN) rarely exhibit conservative behavior during marine transit; instead, they are
46 non-conservatively intercepted within these high-energy zones². Driven by sharp salinity
47 gradients, tidal hydrodynamics, and microbial forcing, clay minerals efficiently scavenge both
48 allochthonous and autochthonous organic matter via flocculation-induced surface adsorption^{3,4}.
49 This process significantly prolongs particulate residence times and fosters intense localized
50 pathways, including mineral degradation, nitrification, and denitrification, while the prevalent
51 benthic anoxic-reducing framework facilitates long-term sedimentary burial. Accounting for these
52 localized transformations is imperative for accurate mass-balance flux budgeting and resolving
53 systematic discrepancies between upstream riverine gauging datasets and actual net marine
54 export.

55 In southeastern China, regional hydro-sedimentary dynamics are strongly regulated by the
56 East Asian Monsoon system^{5,6}. The East Asian Summer Monsoon transports fine sediments from
57 the Changjiang (Yangtze River) to its subaqueous delta; subsequently, approximately 32% of this
58 material is resuspended by winter storms and offshore upwelling^{7,8}. Driven by the East Asian
59 Winter Monsoon, the southward-flowing Zhe-Min Coastal Current redistributes these clastics
60 along the inner shelf, forming an ~800 km longshore mud belt (Fig. 1a)⁹⁻¹¹. While extensive
61 research has focused on the Holocene depositional evolution^{12,13}, sediment dynamics^{14,15}, and

62 steady-state elemental fluxes of this inner-shelf mud belt^{16,17}, its dynamic interaction with adjacent
63 coastal systems remains poorly constrained. Specifically, it remains unclear whether sedimentary
64 TOC and TN preserved in shelf muds can be remobilized and inversely subsidize tide-dominated
65 river-estuarine systems under the combined forcing of longshore currents and tidal
66 hydrodynamics. The quantitative mechanisms governing such bidirectional land–ocean material
67 exchange represent a major knowledge gap that currently limits accurate global estimates of
68 riverine and coastal organic matter fluxes.

69 To fill this critical gap, the present study focuses on the East China Sea inner-shelf mud belt
70 and a representative adjacent tide-dominated small mountainous river system (Fig. 1). We
71 systematically investigate the spatial patterns and compositional variability of particulate and
72 dissolved organic carbon and nitrogen throughout the tidal river continuum. By integrating stable
73 carbon and nitrogen isotope end-member tracing with multi-source mixing models, we constrain
74 the complex provenance, mixing processes, and transformation dynamics of organic matter
75 across the fluvial-estuarine-shelf continuum. This study ultimately clarifies the dual and context-
76 dependent function of inner-shelf mud belts as both sinks and sources of organic carbon and
77 nitrogen. The findings provide a mechanistic framework for improving the understanding of land-
78 ocean biogeochemical cycling in energetic small mountainous river systems and offer critical
79 constraints for calibrating global riverine organic matter budgets and earth system models.

80

81 Results

82 TOC, TN, C and N isotopic compositions

83 A strong linear covariance was observed between TOC and TN contents across all
84 sedimentary repositories, including the non-tidal main stem and tributaries of the Mulanxi, the
85 Changjiang Estuary, the inner shelf mud belt, and sediment core ZK5. This robust stoichiometric
86 coupling demonstrates that the sedimentary nitrogen pool is predominantly locked within the
87 organic matter matrix and is primarily hosted as organic nitrogen (Fig.2a). Concurrently, a
88 pronounced geochemical divergence was identified between sediment samples from the tidal and
89 non-tidal reaches of the Mulanxi, with bulk organic carbon and nitrogen parameters exhibiting
90 significant spatial heterogeneity across these two distinct hydro-geomorphic zones (Fig. 2b-e).

91 Sediments from the Mulanxi tidal reach are characterized by elevated elemental abundances
92 and distinct isotopic signatures, displaying mean TOC and TN contents of 0.74% and 0.09%,
93 respectively, alongside mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of -22.44‰ and 7.17‰. In contrast, the non-
94 tidal reach exhibits significantly depleted elemental baseline values (mean TOC=0.43%, TN=
95 0.03%) and a more depleted carbon isotope signature (mean $\delta^{13}\text{C}$ =-24.74‰), while maintaining
96 a comparable nitrogen isotope composition (mean $\delta^{15}\text{N}$ =7.28‰). Notably, the downcore sediment
97 matrix of core ZK5 closely mirrors the contemporary Mulanxi tidal reach, yielding similar average
98 values for TOC (0.40%), TN (0.07%), and $\delta^{13}\text{C}$ (-22.74‰). Meanwhile, the Changjiang Estuary
99 and adjacent inner shelf mud belt deposits display distinct regional signatures (Fig. 2b-e), with
100 mean TOC and TN contents of 0.48% and 0.06%, respectively, paired with a slightly enriched
101 mean $\delta^{13}\text{C}$ value of -22.06‰ and a markedly depleted mean $\delta^{15}\text{N}$ signature of 4.19‰ relative to

the Mulanxi fluvial-estuarine continuum.

Mineralogical characteristics

The bulk mineralogical composition of sediments from the Mulanxi River exhibits distinct spatial heterogeneity along the river catchment. Sediments in the tidal reach are predominated by clay minerals, with an average relative abundance of 66.54%, while quartz constitutes only 19.86% of the bulk mineral assemblage (Fig. 3a). In comparison, the non-tidal reach shows a substantial reduction in clay mineral content (average 43.92%) and a notable enrichment of quartz (average 40.26%). This pronounced mineralogical discrepancy arises from hydrodynamic sorting, indicating that sediments in the non-tidal reach are generally coarser-grained than those in the tidal reach. Furthermore, the clay mineral assemblages differ considerably between the two hydrological zones. The illite proportion within the clay fraction is significantly higher in the tidal reach (37.93%) than in the non-tidal reach (14.91%) (Fig. 3b).

Discussion and global implications

Superimposed human and tidal forcing across the fluvial-estuarine continuum

The lack of significant linear relationships between TOC, TN, organic carbon and nitrogen isotopes, and clay mineral abundances indicates that the grain-size effect on organic matter accumulation and its isotopic compositions is negligible (Fig. 4a-d). The combination of C/N elemental ratios and the $\delta^{13}\text{C}$ - $\delta^{15}\text{N}$ dual-isotope system effectively fingerprints the provenance of diverse organic matter pools, including terrestrial higher plants, soil organic matter, aquatic plankton, and anthropogenic wastewater across the river-coast continuum, thereby constraining

potential end-members for sedimentary organic carbon and nitrogen. Isotopic source tracking reveals that samples from the Changjiang Estuary, Inner shelf mud belt, tidal reach of Mulanxi, and core ZK5 cluster tightly within the marine particulate organic carbon and marine plankton end-member domains. Collectively characterized by low C/N ratios, $\delta^{13}\text{C}$ -enriched values, and $\delta^{15}\text{N}$ signatures of 3‰-6‰, these coastal samples demonstrate an overwhelming dominance of autochthonous marine planktonic sources (Fig. 4e). In contrast, samples from the non-tidal fluvial reaches of the Mulanxi display a distinct spatial gradient defined by elevated C/N ratios, significantly depleted $\delta^{13}\text{C}$ values, and progressively increasing $\delta^{15}\text{N}$. Specifically, isotopic signatures from upstream tributaries mirror those of C_3 terrestrial plants, soil organic matter, and freshwater dissolved organic carbon, reflecting substantial inputs from terrestrial higher plant debris and soil erosion. Downstream tidal samples, however, systematically converge toward the marine plankton end-member (Fig. 4f). Furthermore, the $\delta^{15}\text{N}$ values of most river basin samples fall squarely within the characteristic wastewater zone (7‰-9‰) (Fig. 4f). This spatial gradient from tributaries to the main stem and from upstream to downstream highlights a continuous attenuation of natural terrestrial organic matter inputs, alongside a concurrent increase in both marine autochthonous organic matter and domestic sewage loading.

Based on the outputs of the organic matter end-member mixing model, the spatial distribution of riverine organic matter sources exhibits pronounced heterogeneity between the tidal and non-tidal reaches. The non-tidal reaches are predominantly characterized by terrestrial organic matter signatures. Sewage and soil organic matter derived from catchment erosion represents the primary contributor, accounting for an average of 36.3% (95% credible interval (CI): 3.3%-69.5%)

144 and 34.5% (95% CI: 6.0%-58.5%), whereas terrestrial C₃ vascular plants (4.4%, 95% CI: 0.2%-
145 11.1%), and phytoplankton (24.8%, 95% CI: 1.7%-63.2%) serve merely as minor supplements.
146 Furthermore, the probability density distributions indicate that sediment samples from this reach
147 are prone to localized, elevated contributions from a single terrestrial end-member (Fig. 5a and
148 c). In sharp contrast, the tidal reach is jointly modulated by tidal hydrodynamic sorting, brackish-
149 freshwater mixing, and authigenic sedimentation on tidal flats. Here, the average contributions of
150 terrestrial soil decline to 22.1% (95% CI: 0.2%-55.4%) (Fig. 5c). The provenance system shifts to
151 a dual dominance of aquatic authigenic biogenic inputs and anthropogenic sewage, with
152 phytoplankton (12.2%, 95% CI: 0.1%-39.1%) and domestic sewage (25.7%, 95% CI: 1.6%-64.2%)
153 emerging as the primary estuarine organic matter sources (Fig. 5b). The inner-shelf mud belt
154 (28.6%, 95% CI: 1.8% to 73.7%), acting as an estuary-specific provenance end-member, further
155 complicates the estuarine organic matter pool and underscores the efficient transport of
156 catchment-derived terrestrial organic carbon and nitrogen toward the southeastern coastal
157 estuary. This spatial provenance differentiation is further corroborated by Sr-Nd isotope
158 systematics and clay mineral assemblages^{6,28}.

159 The end-member probability density curves confirm that the non-tidal reaches display
160 broader distributions of organic matter fractional contributions, with a high abundance of samples
161 exhibiting elevated end-member proportions. Conversely, the probability peaks for all end-
162 members within the tidal reach converge within low-contribution intervals. This trend reflects a
163 typical estuarine sedimentary facies characterized by thorough, multi-source mixing driven by
164 cyclic tidal perturbations. In summary, tidal action thoroughly reshapes the organic matter source

architecture of the river-estuary system by diluting terrestrial detrital inputs, promoting phytoplankton proliferation, trapping catchment-derived anthropogenic pollutants, and introducing tidal flat authigenic sediments (Fig. 5d). Consequently, it acts as the primary hydrodynamic driver regulating the source-to-sink dynamics of organic matter from the river basin to the marginal sea.

Dual source-sink dynamics of inner-shelf mud reservoirs

The East China Sea inner-shelf mud belt represents a persistent, long-lived depocenter for organic carbon burial across the East Asian continental margin; existing research has quantified its annual organic carbon sequestration flux of approximately 3.16 to 8.36 Mt C^{16,29}. Conventionally, this mud system has long been regarded as a permanent carbon sink that permanently locks away Changjiang-sourced organic matter. Nevertheless, coupled forcing from alongshore coastal currents and periodic tidal stirring can effectively remobilize buried organic carbon stored within shelf sediments, enabling tide-dominated small mountainous rivers to reprocess and draw this sequestered material landward. Such river-shelf interplay constructs a full cascading carbon loop spanning terrestrial particulate export from the large Changjiang River, carbon immobilization within shelf mud archives, and subsequent material recycling, upstream transport and secondary deposition within adjacent small river-estuary systems (Figs. 3 and 5d).

Combining published background burial rates of the mud belt with our Bayesian end-member apportionment results for shelf-derived organic carbon input into river waters, we quantify a substantial landward carbon flux of 0.90-2.39 Mt C yr⁻¹ flowing from shelf mud deposits into the Mulanxi Estuary each year. This empirical evidence fundamentally revises the traditional unidirectional sink paradigm for inner-shelf mud belts. Rather than operating solely as a passive

terminal repository for continental organic carbon, the mud belt functions as an active, renewable marine carbon pool that sustains the carbon budget of tide-controlled estuaries along southeast China. This bidirectional river-shelf carbon exchange adds a critical missing component to regional coastal carbon cycles and advances our understanding of dynamic source-sink transitions in global marginal sea systems.

Global implications

Globally, an estimated 165,000 km of river corridors are subject to tidal influence⁴¹, indicating that micro- to macro-tidal fluvial networks dominate Earth’s continental margin drainage systems. Across these widespread tidal-affected reaches, tidal hydrodynamics serve as a pivotal yet historically underappreciated driver of landward allochthonous organic carbon and nitrogen transport. This bidirectional back-flux and persistent tidal reworking substantially restructure organic matter composition and reservoir architecture at the critical land-ocean interface, challenging the conventional unidirectional “river-to-ocean” source-to-sink paradigm. Furthermore, tidal inundation modulates riparian soil nitrification and denitrification kinetics, while intensified estuarine mixing reshapes coastal nutrient stoichiometry, exacerbates inundation hazards, and amplifies saltwater intrusion threats to deltaic agroecosystems worldwide^{42,43}.

As the overarching hydrodynamic regulator of tide-dominated coastal systems, tidal forcing modulates organic carbon migration pathways, greenhouse gas efflux, and sediment carbon burial efficiency via coupled physical and biogeochemical processes—including current-induced sediment resuspension, episodic estuarine water mixing, tidal flat wetting-drying cycles, tidally mediated submarine groundwater discharge, and lateral material exchange through tidal creek

networks. Collectively, these tide-driven boundary processes constitute a fundamental missing mechanism in global land-ocean biogeochemical frameworks. Failure to explicitly resolve landward tidal carbon and nitrogen fluxes and high-frequency hydrodynamic reworking introduces systematic biases and substantial uncertainties in global riverine organic matter budget calculations. Therefore, integrating tidal reverse transport dynamics is indispensable for refining global source-to-sink models, constraining regional and planetary coastal carbon budgets, and improving future projections of blue carbon cycling under ongoing global climate change and anthropogenic coastal perturbation.

Conclusions

Focusing on a typical tide-dominated river in southeastern China and the adjacent inner shelf mud belt of the East China Sea, this study integrates bulk organic carbon and nitrogen elemental abundances, stable isotope geochemistry ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), and a MixSIAR Bayesian mixing model to quantify the spatial heterogeneity of organic matter sources within a tide-dominated fluvial-estuarine system. The results reveal a distinct dual source-sink function for the inner-shelf mud belt. Non-tidal reaches are predominantly characterized by terrestrial organic matter signatures, where sewage and catchment-derived eroded soil serve as the primary contributor (averaging of 36.3% and 34.5%, respectively), supplemented by minor inputs from terrestrial C_3 vegetation and phytoplankton. In contrast, tidally influenced reaches are jointly modulated by tidal hydrodynamic sorting, brackish-freshwater mixing, and authigenic tidal-flat sedimentation. Consequently, the average fractional contributions of terrestrial soil decline to 22.1%, as the

provenance system shifts to a dual dominance of autochthonous biogenic inputs (phytoplankton: 12.2%) and anthropogenic waste (domestic sewage: 25.7%). Inner-shelf mud sediments (28.6%) act as an estuary-specific end-member that further complicates the estuarine organic matter pool. Mass-balance calculations indicate that tidal forcing drives a substantial landward flux of roughly 0.90 to 2.39 Mt C/yr from the inner shelf mud belt back into the tidal river segments. Under combined coastal current and macro-tidal forcing, the inner-shelf mud belt functions as a dynamic marine carbon source rather than a static sink, actively sustaining carbon budgets in tide-dominated coastal rivers. Collectively, these findings highlight that tidal reverse transport and cross-boundary sediment reworking represent essential yet long-neglected processes. Explicit incorporation of this bidirectional river-shelf carbon exchange is critical to reduce systematic biases in global source-to-sink models and achieve more accurate quantification of global land-ocean carbon budgets.

Data availability

Research data are attached in the Supplementary Tables accompanying this paper.

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Author Contributions

Yalong Li collected samples and designed the research. Xiangtong Huang, Chao Li and SHouye Yang performed research. Zhongbo Wang contributed to the writing of the paper. All authors have read and agreed to the published version of the manuscript.

Competing Interest Statement

The authors declare that they have no competing interests.

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400

401 **Table**

Table 1 The end-member source values used in the MixSIAR modeling.

End-member	$\delta^{13}\text{C}/\text{‰}$	SD $\delta^{13}\text{C}/\text{‰}$	$\delta^{15}\text{N}/\text{‰}$	SD $\delta^{15}\text{N}/\text{‰}$	Concentration TOC/%	Concentration TN/%
C ₃ plant	-26.44	1.49	1.95	3.24	4.20	0.32
Soil organic	-23.48	1.42	2.80	2.08	0.90	0.09
Sweage	-25.10	2.41	7.31	5.50	2.10	0.22
Phytoplankon	-27.18	3.54	5.16	3.08	3.40	0.33
Inner mud belt	-22.32	0.92	4.19	0.73	0.48	0.06

Figure captions

Fig. 1 Study area and sampling design. (a) Location of the study area and sampling sites in southeastern China and the adjacent East China Sea. (b) Geological map of the Mulanxi catchment. (c) Distribution of sampling sites in the Mulanxi catchment. Abbreviations: YS, Yellow Sea; ECS, East China Sea; SCS, South China Sea; TS, Taiwan Strait; TWC, Taiwan Warm Current; ZMCC, Zhe-Min Coastal Current; OT, Okinawa Trough; KC, Kuroshio Current; EASM, East Asian Summer Monsoon; EAWM, East Asian Winter Monsoon.

Fig. 2 Relationship between TOC and TN (a). TOC (b), TN (c), $\delta^{13}\text{C}$ (d) and $\delta^{15}\text{N}$ (e) composition of Mulanxi, Changjiang estuary, Inner Shelf Mud Belt and ZK5. TR-M is the tidal reach of the Mulanxi, NTR-M is the non-tidal reach of the Mulanxi, T denotes tributaries, CJ-ISMB is the Changjiang estuary and inner shelf mud belt. Reference data for the Changjiang Estuary, adjacent inner shelf mud belt, and core ZK5 downcore records are compiled from Gao et al. (2008)¹⁸, Xu et al. (2017)¹⁹, Fan et al. (2025)²⁰ and Sun et al (2025)²¹.

Fig. 3 Mineralogical composition of Mulanxi sediment (a). Ternary plots of clay mineral source identification (b). Data of Changjiang were from Zhao et al. (2018)²². Data of inner shelf mud belt were from Zhang et al. (2022)²³.

Fig. 4 Cross-plots illustrating the geochemical relationships and provenance of sedimentary organic matter. Bivariate correlations between total clay mineral content and $\delta^{13}\text{C}$ (a), TOC (b), TN (c), and $\delta^{15}\text{N}$ (d). Provenance tracing and source discrimination of sedimentary organic matter are defined via $\delta^{13}\text{C}$ vs C/N (e) and $\delta^{13}\text{C}$ vs $\delta^{15}\text{N}$ (f). Data on source range were from Lamb et al. (2006)²⁴, Shao et al. (2019)²⁵, Xuan et al. (2020)²⁶, and Li et al. (2024)²⁷.

Fig.5 Schematic diagram illustrating the mixing pathways and biogeochemical transformation of organic carbon and nitrogen within a tide-dominated estuary (a). The proportion of each source end-member in the non-tidal reach (b) and tidal reach (c). The source data of C₃ plants were from Ma et al. (2012)³⁰, and Liu et al. (2005)³¹. Data on Phytoplankton were from Luo et al. (2016)³², Ogrinc et al. (2008)³³, and Vuorio et al. (2006)³⁴. Soil data were from Dou et al. (2016)³⁵, Li et al. (2020)³⁶, and Lu et al. (2013)³⁷. Data on sewage were from Liu et al. (2019)³⁸, Lu et al. (2016)³⁹, Shao et al. (2019)⁴⁰, and Wang et al. (2014)⁴¹. Data of the Changjiang estuary and inner shelf mud belt were from Fan et al. (2025)²⁰, Gao et al. (2008)¹⁸, Sun et al. (2025)²¹, and Xu et al. (2017)¹⁹. The end-member source values used in the MixSIAR modeling are provided in Table 1.

Materials and Methods

Geological background and materials

This study focuses on the Mulanxi in Fujian Province, an active small mountainous river system along the passive continental margin of southeastern China (Fig. 1a). The region experiences a subtropical monsoon climate characterized by a mean annual temperature of 17-22 °C and mean annual precipitation of 1400-2000 mm, with frequent perturbations from high-energy extreme weather events, including annual typhoons and flood episodes. The Mulanxi basin drains a rugged, forested upland landscape underlain primarily by Jurassic-Cretaceous igneous complexes, dominated by granitic lithologies (Fig. 1b). The main stem of the Mulanxi extends approximately 105 km, draining a catchment area of ~1732 km² with a maximum headwater elevation of ~1448 m and a mean annual fluvial sediment load of ~0.47 Mt/yr⁵. The lower reaches downstream of the historical Mulan Weir (constructed during the Song Dynasty, 1064 AD) are heavily influenced by semi-diurnal tidal hydrodynamics and intensive anthropogenic modifications (Fig. 1c). Long-term tidal gauge records indicate a highly energetic tidal regime with a mean tidal range of 7.1 m, driving a tidal reach that extends approximately 26 km upstream (<http://mds.nmdis.org.cn>).

Fluvial sediments were collected in October 2023 across 32 river channel and bank locations to characterize their geomorphological and geochemical signatures (Fig. 1c). Sample pretreatment and analytical geochemical procedures were conducted at the State Key Laboratory of Marine Geology, Tongji University. To contextualize these localized catchment signatures within the broader regional source-to-sink transport system, this dataset was integrated with 195

published data points from the Changjiang Estuary and its adjacent inner shelf mud belt, as well as downcore geochemical records from sediment core ZK5 retrieved from the Mulanxi estuary¹⁸⁻²¹.

C-N isotope analysis

Approximately 300 mg of the dried sample was transferred into a clean 50 mL centrifuge tube. Slowly, 1 N hydrochloric acid was added to a final volume of 40 mL, and the mixture was allowed to stand for at least 6 hours. The suspension was then centrifuged, and the hydrochloric acid supernatant was decanted. The sedimented sample was dispersed by adding distilled water and shaking thoroughly, followed by centrifugation to discard the supernatant. This rinsing process was repeated three times until the pH approached neutrality, after which the sample was dried.

The C and N isotopic compositions were analyzed using a stable isotope ratio mass spectrometer (GC-IRMS, Deltapuls XP), with an average analytical error of approximately 0.1‰ for $\delta^{13}\text{C}$ and 0.15‰ for $\delta^{15}\text{N}$. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data were normalized to the Acetanilide standard.

The calculation formulas of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ are:

$$\delta^{13}\text{C}(\text{‰}) = [(R_{\text{sample}} - R_{\text{standard}})/R_{\text{standard}}] \times 1000, R = {}^{13}\text{C}/{}^{12}\text{C} \quad (1)$$

$$\delta^{15}\text{N}(\text{‰}) = [(R_{\text{sample}} - R_{\text{standard}})/R_{\text{standard}}] \times 1000, R = {}^{15}\text{N}/{}^{14}\text{N} \quad (2)$$

where R_{sample} represents the isotopic ratio of the actual sample, while R_{standard} represents the isotopic ratio of the standard material. All of these measurements were finished at State Key Laboratory of Marine Geology, Tongji University.

XRD analysis

Bulk mineralogical compositions of 10 representative sediment samples from the Mulanxi

catchment were determined via X-ray diffraction (XRD). Analytical measurements were performed using a Bruker D8 ADVANCE diffractometer. Prior to analysis, aliquots of >0.2 g of oven-dried bulk sediment were pulverized in an agate mortar to a grain size of less than 200 mesh and mounted using the standard front-loading powder press method. The instruments operated under the following configurations: Cu-K α radiation source, an accelerating voltage of 40 kV, and a tube current of 40 mA. Diffractograms were acquired in step-scan mode over a 2 θ range of 3°-70°, with a step size of 0.02° and a counting time of 1 s/step. Major mineral phases were identified using Bruker DIFFRAC.EVA software linked to the Crystallography Open Database (COD). Semiquantitative relative abundances of the identified mineral components were subsequently determined via Rietveld refinement using Bruker TOPAS software.

MixSIAR mixing modeling

The Bayesian mixing model MixSIAR (version 3.1.0), implemented in R, was used to quantify the proportional contributions of organic matter from various sources to the sediment (Moore and Semmens, 2008). This model explicitly accounts for multiple sources of uncertainty, as expressed in Equation (5). The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for each potential source were obtained from published literature and used as input parameters. The median (50th percentile) of the output distribution represents the contribution of each organic matter source to the surface sediment. The source code is publicly available at <https://github.com/brianstock/MixSIAR>.

$$X_{ij} = \sum_{k=1}^k P_k (S_{jk} + C_{jk}) + \varepsilon_{jk} \quad (3)$$

$$S_{jk} \sim N(q_{jk}, \omega_{jk}^2)$$

$$C_{jk} \sim N(\lambda_{jk}, \tau_{jk}^2)$$

$$\varepsilon_{jk} \sim N(0, \sigma_j^2)$$

where X_{ij} is the i-isotope value j of the mixture; P_k is the proportional contribution of source k, which needs to be estimated using a Bayesian model; S_{jk} is the source value of isotope j; C_{jk} is the fractionation factor of isotope j on source k; ε_{jk} is the residual error, representing the unquantified additional variation between samples.

Fig. 1

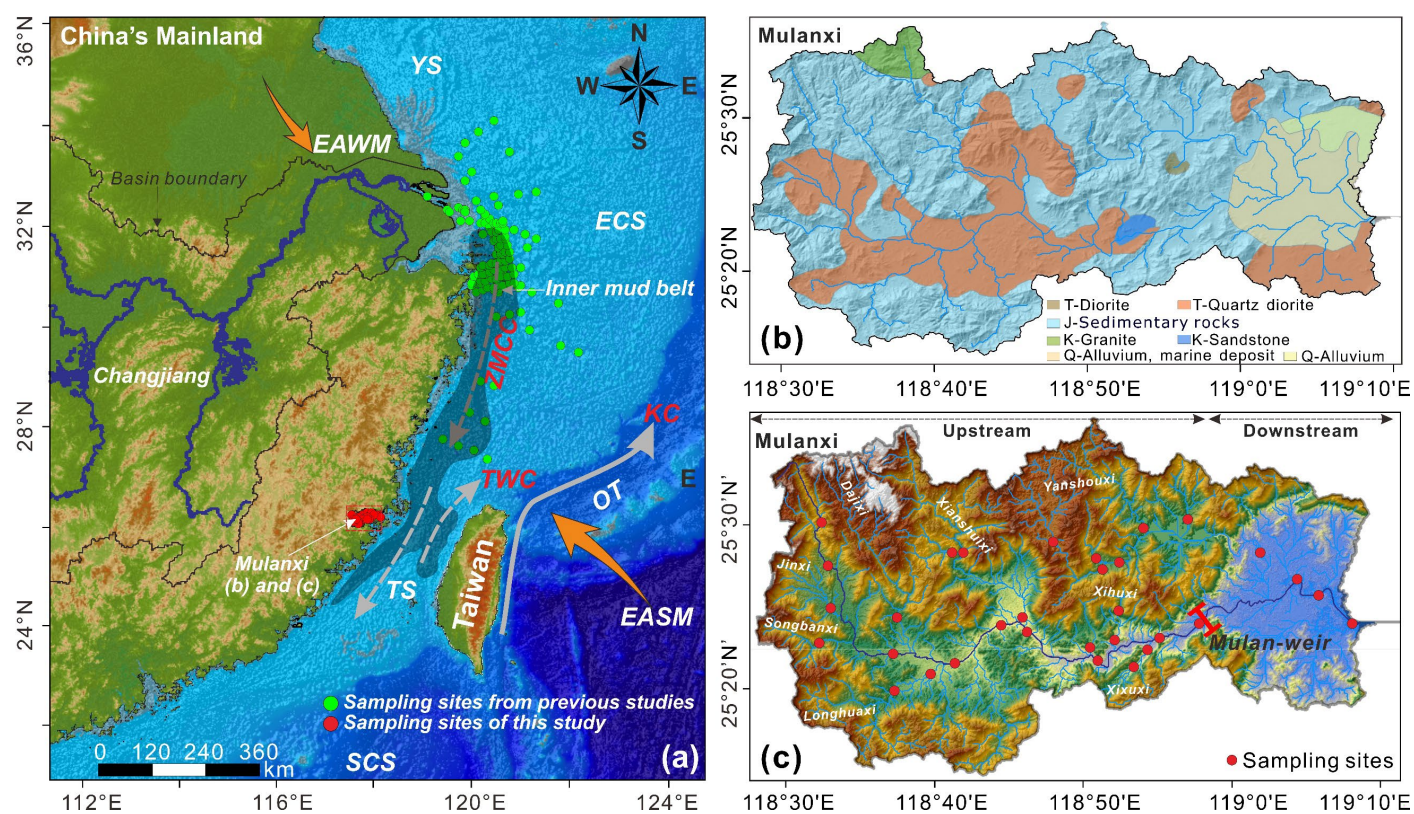


Fig. 2

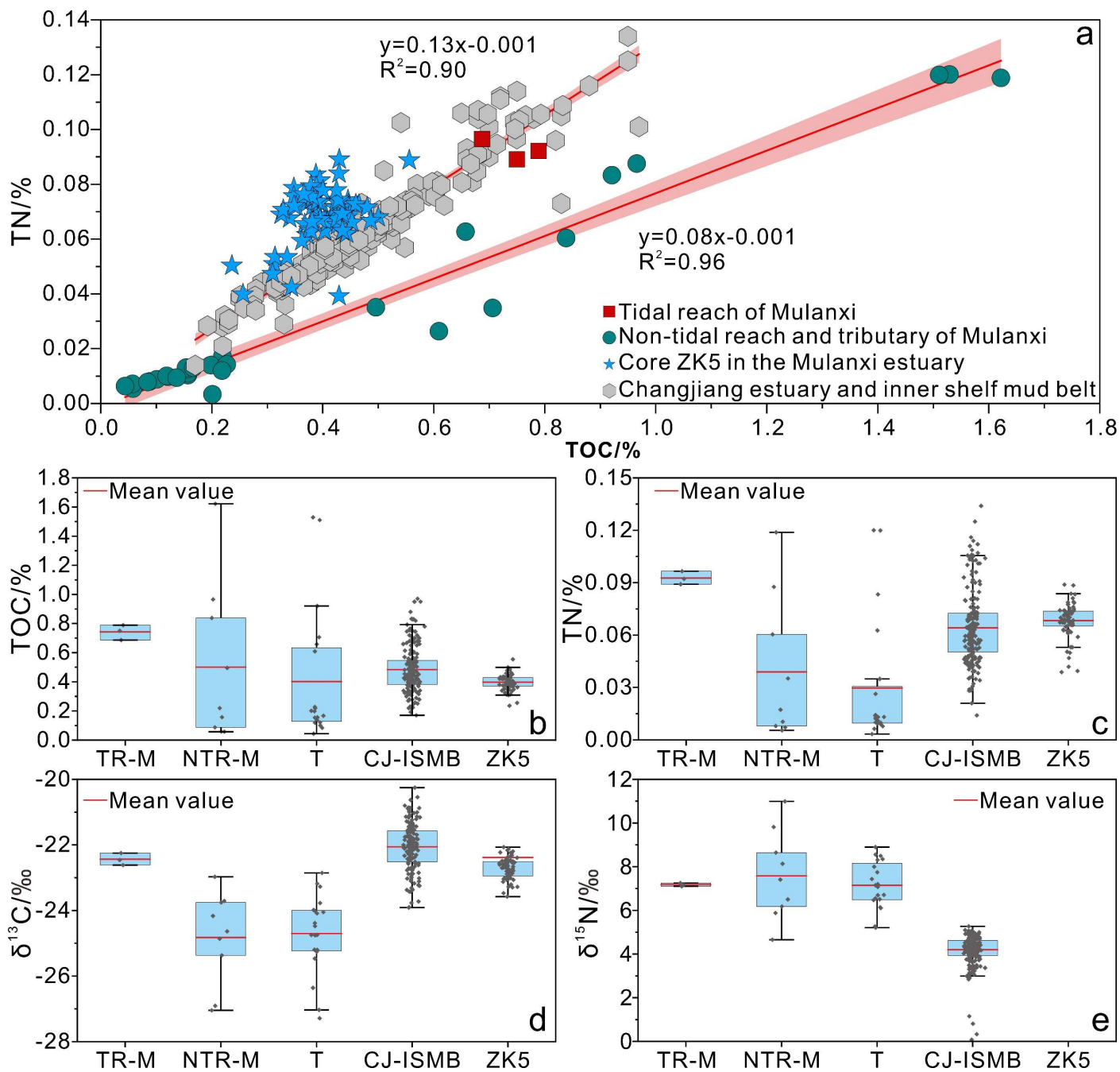


Fig. 3

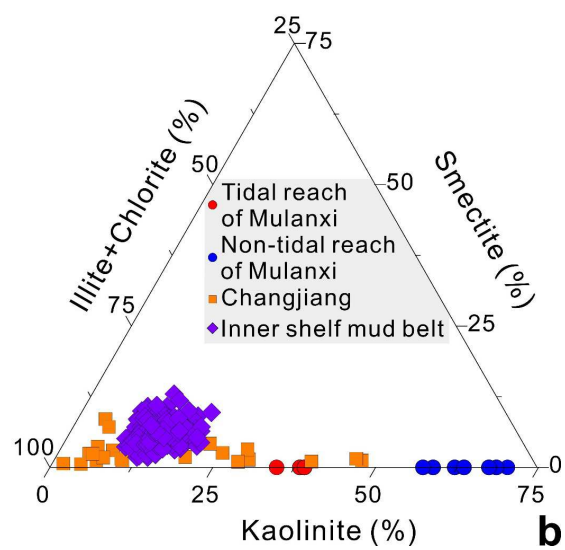
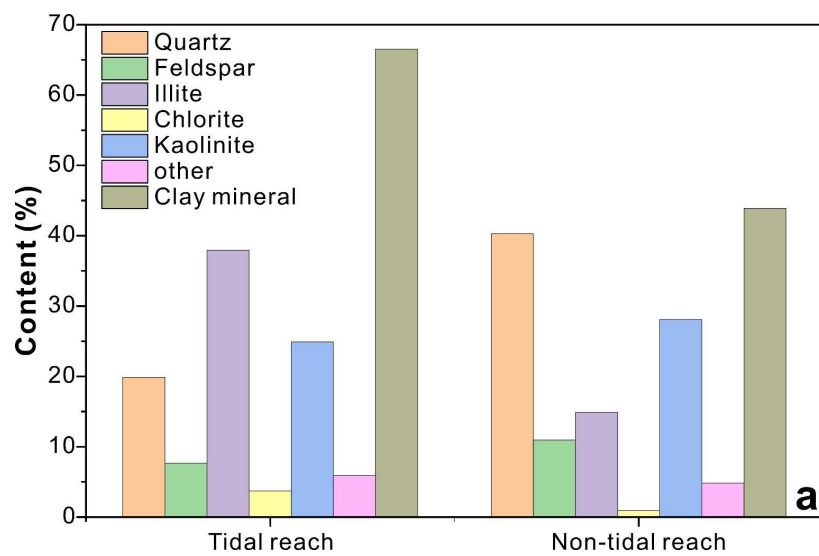


Fig. 4

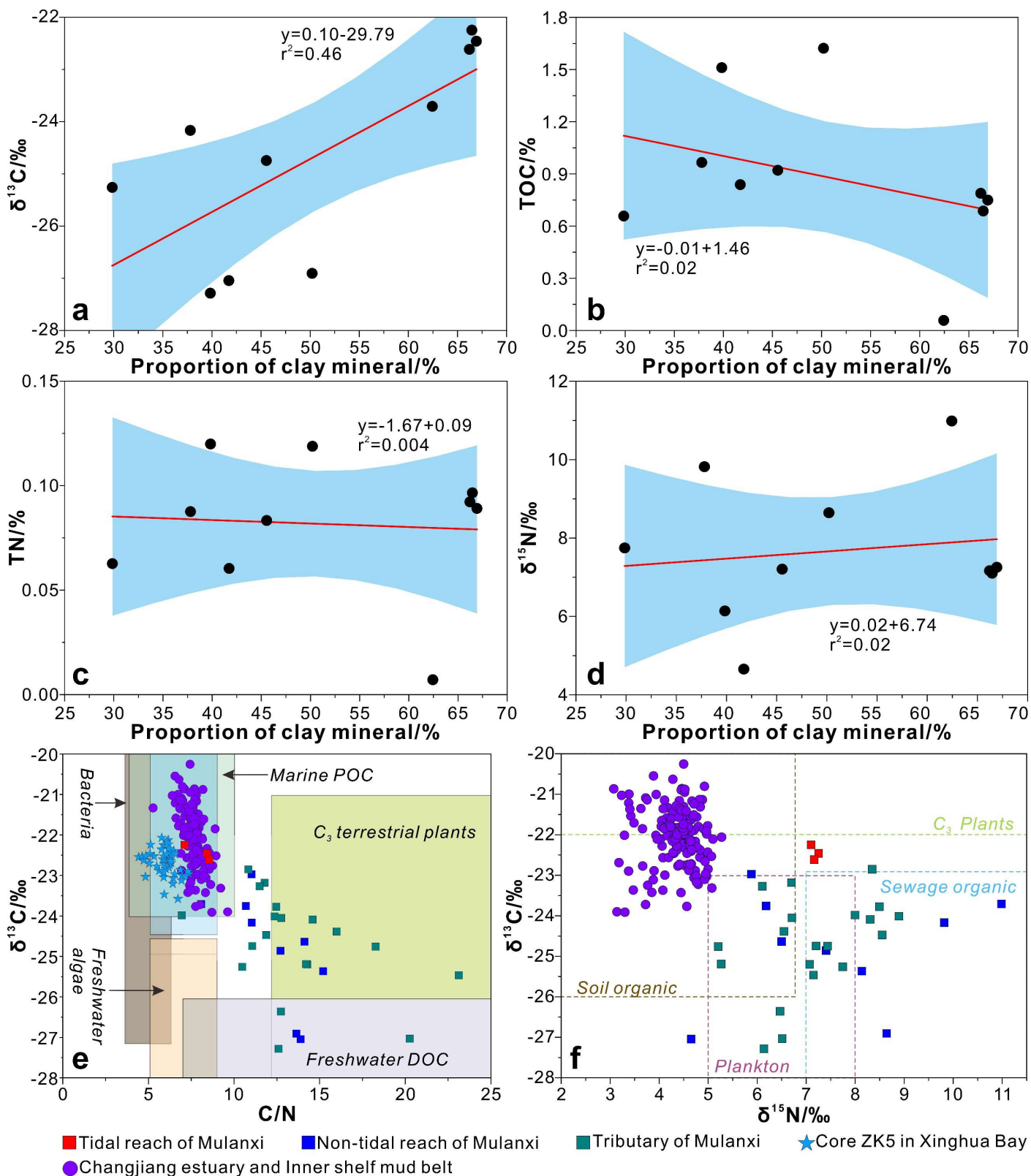
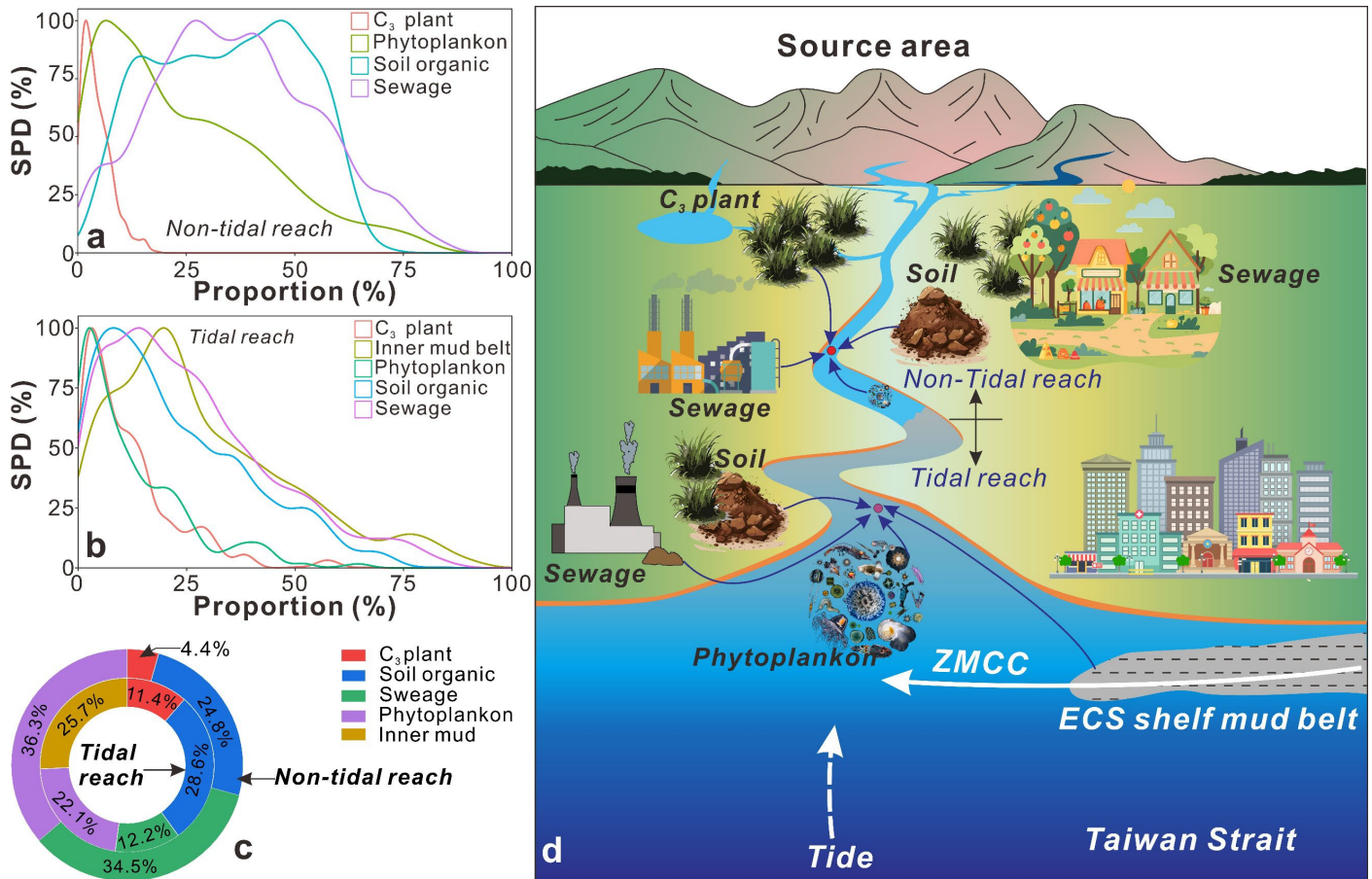


Fig. 5



Supplementary Files

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