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RESEARCH ARTICLE

Surface soil organic carbon losses in Dongting Lake floodplain as evidenced by field observations from 2013 to 2022

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Highlights

- The surface soil organic carbon (SOC) stock of Dongting Lake in 2022 was 6.82 Tg C (2.87–13.48 Tg C).
- Surface SOC was lost in Dongting Lake because of climatic and hydrological changes.
- Above 21.4 m elevation, SOC loss accelerated with increasing elevation.
- Raising the water level during drought periods may be an important way to enhance the carbon sequestration potential of wetlands.

Abstract

In floodplain wetlands, alterations in hydrological patterns resulting from climate change and human activities could potentially diminish the carbon sequestration capacity of the soils, thereby having a negative impact on global climate change. However, the magnitude of the influence of hydrological regime change on soil carbon remains inadequately monitored. To address this research gap, we collected 306 upper layer (0–20 cm) soil samples from the Dongting Lake floodplain between 2013 and 2022. The random forest (RF) algorithm was used to analyze the spatial distribution of soil organic carbon (SOC) in the upper soil layer of Dongting Lake floodplain and the impact of climate and hydrological changes in the past decade on surface SOC in the East Dongting Lake area was studied. In 2022, the SOC concentration of the Dongting Lake floodplain upper layer soil ranged from 3.34 to 17.67 g kg^{-1}, averaging 10.43 g kg^{-1}, with a corresponding SOC density of (2.65±0.49) kg m^{-2} and total SOC stock of 6.82 Tg C (2.87–13.48 Tg C). From 2013 to 2022, the SOC concentration of the upper soil layer of the East Dongting Lake area decreased from 18.37 to 10.82 g kg^{-1}. This reduction could be attributed to climate and hydrological changes which reduce SOC input by reducing vegetation growth and accelerating SOC decomposition. Above 21.4 m elevation, the amount of SOC loss increased with elevation, the loss being related to the decline in *Miscanthus* community biomass and greater susceptibility of higher altitude areas to climate and hydrological changes. Our results highlight the need for strengthening wetland SOC management to increase SOC in the soils to help combat climate change.

Keywords: floodplain wetland, soil organic carbon, spatial pattern, dynamic change

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1. Introduction

Despite covering only 5–8% of the Earth's land surface, wetlands store a substantial 20–30% of the global terrestrial carbon stock (Zedler and Kercher 2005; Mitsch *et al.* 2013). Changes in wetland soil carbon storage may affect global carbon cycling and atmospheric carbon dioxide concentrations (Bradford *et al.* 2016). Consequently, estimation of wetland soil organic carbon (SOC) content is of widespread global concern and is vital in addressing global climate change.

The SOC content of floodplains is influenced by various factors, including climate, hydrology, and vegetation (Heger *et al.* 2021). Researchers generally believe that in areas with warmer climates and lower precipitation, soil respiration and mineralization rates increase and the stability of aggregates encasing organic matter decreases, thereby reducing soil carbon storage (Lal 2008). For instance, soils located in floodplains within the sub-humid to arid climate of northeastern Brazil (wetter regions) accumulate more carbon than soils in semi-arid climates (drier regions) (Oliveira 2023). In floodplain wetlands, SOC content is significantly affected by periodic flooding. The frequency, duration, and water level of floods are crucial factors that influence SOC content (Bai *et al.* 2005; Yin *et al.* 2019; Ren *et al.* 2022). These hydrological conditions affect the formation and decomposition of SOC by regulating processes such as soil oxygen supply, microbial activity, and litter decomposition (Unger *et al.* 2009). Previous research indicates that compared to low-frequency floods, high-frequency floods create wetter conditions in wetlands, which are more conducive to the accumulation of organic matter, thereby significantly increasing soil carbon content (Bai *et al.* 2020). Extending the flooding time in flooded wetlands can promote the decomposition of plant litter, thereby increasing SOC content (Zhu *et al.* 2022). However, lower water levels promote the decomposition of organic matter, resulting in a decrease in SOC content (Hooijer *et al.* 2012). Vegetation affects SOC stocks by altering the plant residue input. Surveys have indicated that vegetation degradation in wet meadows on the eastern Tibetan Plateau results in a decrease in biomass and a loss of approximately 50% of the SOC content (Alhassan *et al.* 2018). Thus, environmental changes caused by climate and human disturbance may lead to the risk of SOC loss in wetlands.

In recent years, the hydrological conditions in numerous river basins have undergone substantial changes owing to climate change and disturbances arising from human activities, particularly those related to hydraulic engineering (Habersack *et al.* 2016). Several studies have demonstrated that the construction of water conservation projects has had a pronounced impact on downstream hydrological conditions. Specifically, these projects have led to reductions in flood duration, volume of water resources, and water levels (Magilligan and Nislow 2005; Talukdar and Pal 2017; Zheng *et al.* 2019). These reductions are likely to accelerate the loss of SOC in downstream areas. However, the impact of changes in hydrological conditions on the SOC content in wetlands located in the middle and lower reaches of rivers has not been effectively evaluated.

Dongting Lake, situated downstream of the Three Gorges Dam on the Yangtze River, is the second-largest freshwater lake in China. According to our previous research, the Dongting Lake floodplain wetland is a continuous and stable carbon sink (*Miscanthus* net ecosystem exchange: –403.7 g C m^{-2} yr^{-1}, *Carex* net ecosystem exchange: –148 g C m^{-2} yr^{-1}), which plays an important role in reducing atmospheric greenhouse gas concentrations and mitigating climate change (Wang *et al.* 2024). Due to the influence of climate and human interference (such as the construction of the Three Gorges Dam), the water level of Dongting Lake has dropped significantly during the flood season from September to October. The water level decline rate has increased from 0.058 to 0.114 m d^{-1}, and the dry season has advanced by nearly half a month (Lai *et al.* 2016). The influence of these alterations in hydrological conditions on SOC content within wetlands has not yet been effectively studied. Among soil carbon pools, surface SOC is more susceptible to the effects of climate, hydrological conditions and human activities, resulting in a higher carbon turnover rate than in deeper pools. In this study, we surveyed the wetland surface soils in Dongting Lake over a period of 10 consecutive years. The objectives of this study were: (1) to investigate the spatial distribution of surface SOC content and assess surface SOC stocks in the Dongting Lake floodplain, and (2) to discern the changes in SOC content within the surface layer of Dongting Lake floodplain over the past decade that have occurred in response to both climate change and anthropogenic disturbances.

2. Materials and methods

2.1. Study area

Dongting Lake (28°30′–30°20′N, 111°40′–113°10′E) is the second largest inland freshwater lake in China, with an area of 2,564 km^2. Dongting Lake comprises three sub lakes: East Dongting, South Dongting, and West Dongting. East Dongting Lake is the largest of the three sub-lakes with an area of 1,328 km^2. The lake receives its water inflow from the Yangtze River *via* three main channels (the Songzi, Hudu, and Ouchi Rivers) and four tributaries (the Xiang, Zi, Yuan, and Li Rivers). Eventually, the water flows into the Yangtze River from Chenglingji (Xie *et al.* 2015). The water level of the wetland fluctuates substantially seasonally. The flooding periods generally last from June to September, with significant annual variation. The wetland types from the edge of the water to the upper extremity of the wetlands can be broadly categorized into mudflat zones, *Carex brevicuspis* (Cyperaceae) communities, and *Miscanthus sacchariflorus* (Poaceae) communities (Xie and Chen 2008; Xie *et al.* 2015).

2.2. Data collection

Soil data Soil samples were collected between December 2013 and December 2022. In 2013, the sampling region was primarily the East Dongting Lake floodplain, whereas in 2022, the sampling region expanded to cover the entire Dongting Lake floodplain. Prior to sampling, we designated sampling sites on a grid at 2-km intervals on the map. However,

some of the sampling sites could not be reached on foot or by boat due to problems with water levels, disturbance from human activities and road blockages. Finally, 106 and 120 sampling sites were selected in 2013 and 2022, respectively, and a total of 226 soil samples were collected (Fig. 1-C). We selected the East Dongting Lake area to explore the changes in SOC content over the past decade. Although the sampling sites of East Dongting Lake in 2013 and 2022 were inconsistent (the sampling locations were different), the sampling sites were evenly distributed to cover the whole East Dongting Lake, and included the different wetland types, so that they represent the SOC content of the East Dongting Lake wetlands. Some sites in the mudflat area were sampled in June because they were inaccessible in December. A handheld global positioning system (GPS) device was used to record the latitude and longitude of each sampling site. At each sampling site, a 1 m×1 m quadrat was selected, and five surface soil samples (0–20 cm deep) were collected from the center and corners of the quadrat using a soil auger (0.3 m in length and 0.1 m in diameter). These five surface soil samples were blended into one sample for subsequent measurements. A total of 67 soil samples were collected from the *Miscanthus* community, 63 soil samples from the *Carex* community, 96 soil samples from the mudflat community. Five sampling sites in the *Miscanthus* and *Carex* communities and three sampling sites on the mudflat were selected to measure the soil bulk density. Standard containers with an internal diameter of 5 cm and a volume of 100 cm³ were used to collect the samples.

In addition to the extensive sampling described above, sampling sites for the years between 2014 and 2021 were located at the permanent monitoring plot (29°27′46′′N, 112°47′29′′E) of Dongting Lake Station for Wetland Ecosystem Research. The permanent monitoring station primarily contains two plant communities, *Miscanthus* (29°27′30.3′′N, 112°47′11.5′′E) and *Carex* (29°27′38.8′′N, 112°47′20.3′′E). Within each plant community, we established a sampling transect of 1,000 m×100 m (Fig. 1-B) and selected five quadrats (1 m×1 m) within the sampling transect in an "S" pattern, with at least 50 m between each quadrat. Between 2014 and 2021, a total of 80 soil samples were collected, with 5 samples collected each year from both *Miscanthus* and *Carex* communities. In total, 306 soil samples between the years of 2013 and 2022.

All soil samples were collected and transported to the laboratory. Visible animal and plant residues were removed from the samples, which were then air-dried under cool and ventilated conditions. Subsequently, the soil was ground and passed through a 0.147 mm sieve. The SOC content of the ground samples was determined using the potassium dichromate-sulfuric acid oxidation technique. The soil moisture content is determined by drying the soil samples to a constant mass at 105°C. Concurrently, we first harvested the aboveground plants from the quadrat and collected the aboveground litter. Then, we collected the belowground roots by carefully digging them out of the soil with a shovel. All plant samples were taken back to the laboratory, dried at 60°C, and weighed. The plant samples were collected monthly during the non-flooding period. In this study, the maximum monthly average biomass per year was used to perform the statistical analysis. The formulas used for calculating soil organic carbon density (SOCD) and stock (SOCS) were as follows:

$$SOCD=SOC\times BD\times D \quad (1)$$

$$SOCS=SOCD\times A \quad (2)$$

where SOC is soil organic carbon (g kg^{-1}), BD is the soil bulk density (g cm^{-3}), D is the soil thickness (m), and A is the area of each wetland type (km^2).

Hydrology and climate data Daily water level data for East Dongting Lake were obtained from recordings taken at the Chenglingji Hydrological Monitoring Station at 8:00. The water level data at Chenglingji serve as an important indicator of the hydrological conditions of East Dongting Lake and have been widely utilized in studies on the hydrological characteristics, hydrodynamic mechanisms, and water balance of Dongting Lake (Geng *et al.* 2021). The daily water level data were analyzed to derive the highest, lowest, and mean water levels for each year during the study period. The hydrological conditions of wetland plants in Dongting Lake are closely related to surface elevation (Xie *et al.* 2015). When water levels rise to a certain level, plants are considered submerged. Therefore, based on the daily water level and elevation data, we calculated the inundation duration of the different vegetation types. The elevation data for mudflat, *Carex*, and *Miscanthus* communities incorporated their respective optimal distribution elevations, which were 21, 24.5, and 26 m, respectively (Tang *et al.* 2013b; Zhou *et al.* 2020). The water depth (WD) was measured as the distance from the ground surface to the water surface, and the inundation duration (ID) was calculated as follows:

$$WD=WL-E \quad (3)$$

$$ID=\sum_{WD>0}^{n} I_{WD} \quad (4)$$

where WL is the water level at the Chenglingji Hydrological Station, E is the elevation, I_{WD} is the number of days when WD>0, and n is the number of days per year.

Rainfall and temperature data originated from the meteorological observation point of the Wetland Ecosystem Observation and Research Station of the Chinese Academy of Sciences, located at 29°28′49.66′′N, 112°48′10.64′′E. Daily average temperature and daily average rainfall were calculated as the mean values of temperature and rainfall measured daily at 8:00, 14:00, and 20:00.

Environmental data Based on a literature review of factors influencing SOC content, we selected four environmental variables that influenced SOC and constructed an inverse model of SOC content in Dongting Lake wetland.

(1) Vegetation information. The decay and decomposition of vegetation litter provides a significant source of SOC; thus, vegetation growth conditions exert a crucial influence on SOC content (Xi *et al.* 2023). As the sampling period was December, the images captured during this period did not adequately reflect the vegetation growth status of the study area. Therefore, we selected images from the period of vigorous vegetation growth. Owing to differences in water recession periods, the peak vegetation growth periods in 2013 and 2022 were October–November and August–September, respectively. However, the images from October to November 2013 were incomplete owing to uncontrollable

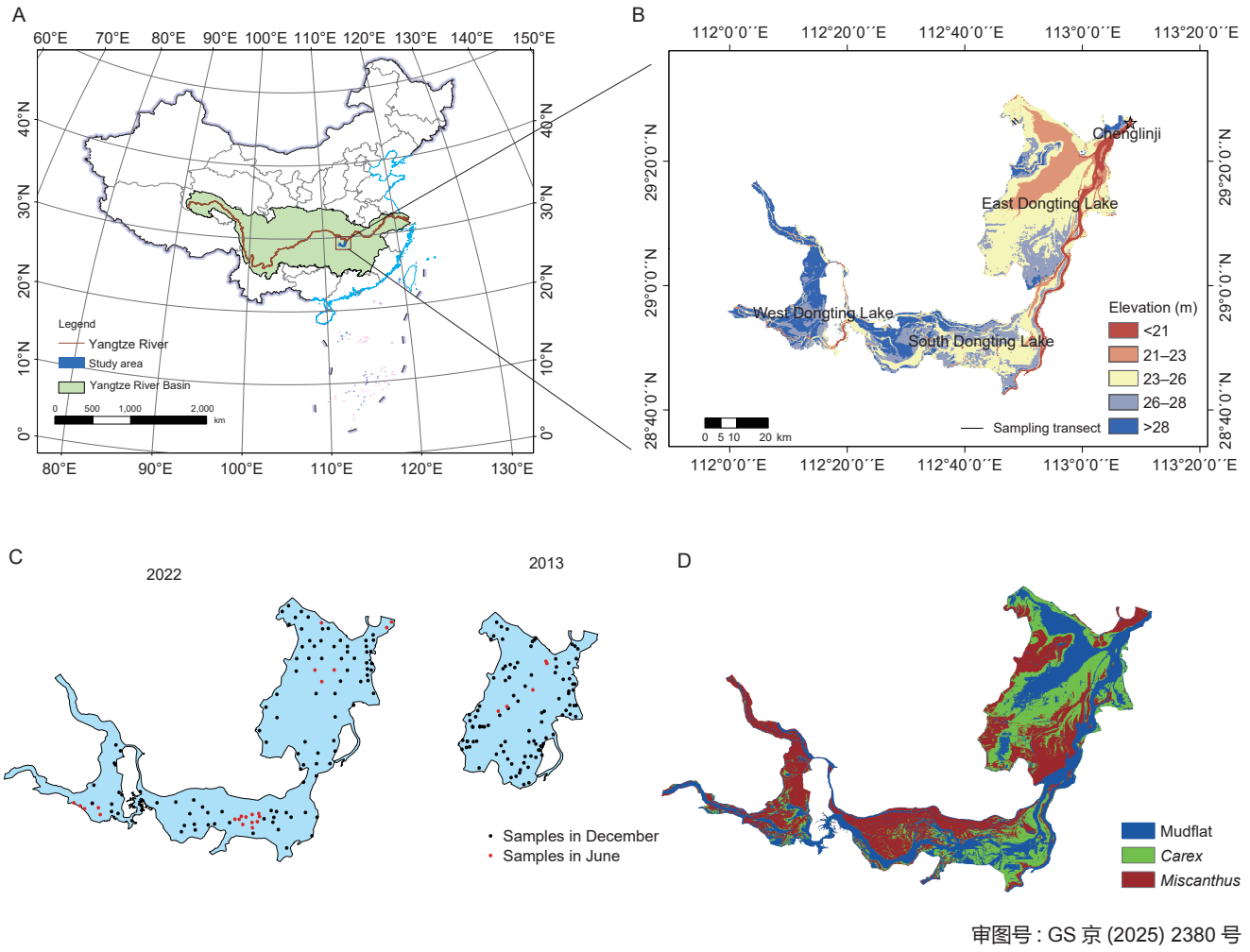


Fig. 1 Map of China (A), elevation map and sampling transect (2014–2021) of the Dongting Lake floodplain (B), location of sampling sites in 2022 and 2013 (C), and distribution of mudflat and *Carex* and *Miscanthus* vegetation communities in 2020 (D).

factors, such as insufficient image data and the presence of numerous clouds. Therefore, we utilized images from September to December 2013 and from August to September 2022, sourced from Landsat-8 and Landsat-9 Level 2 Tier 1. These images were downloaded from the Google Earth Engine (GEE).

We used the normalized difference vegetation index (NDVI), a commonly used metric that represents surface vegetation information regarding plant growth status and vegetation coverage, as follows:

$$NDVI=\frac{NIR-R}{NIR+R} \quad (5)$$

where NIR is the near-infrared band and R is the red band.

(2) Soil moisture. Soil moisture has a significant impact on plant biomass and the SOC decomposition rate (Xu *et al.* 2015; Yin *et al.* 2019). We employed land surface wetness (LSW) derived from the Tasselled Cap Transformation applied to the Landsat-8 and Landsat-9 Level 2 Tier 1 datasets as a proxy for soil moisture data (Zhang *et al.* 2023).

(3) Soil texture. The soil clay index is frequently utilized as a predictor of SOC content (Sakhaee *et al.* 2022; Zeraatpisheh *et al.* 2022). We constructed a clay index (CI) based on landsat remote sensing images to represent soil clay content (Taghizadeh-Mehrjardi *et al.* 2016). The calculation formula is as follows:

$$CI=\frac{SWIR_1}{SWIR_2} \quad (6)$$

where SWIR1 and SWIR2 represent shortwave infrared bands 1 and 2.

(4) Elevation. In lake ecosystems, the variable hydrological conditions at different elevations significantly affect SOC formation and decomposition (Xie *et al.* 2017; Qian *et al.* 2021). The elevation data were sourced from the digital elevation model of the Dongting Lake Wetland, which was derived from the Geospatial Data Cloud (http://www.gscloud.cn/).

All environmental variable images were resampled at a spatial resolution of 30 m×30 m equal-area grid with the same origin and extent to ensure the consistent resolution of the image. The correlations between the environmental variables and SOC are presented in Appendix A, and the factors with significant correlations were selected. We calculated VIF, and all environmental variables exhibited VIF values of less than 10, indicating the absence of multicollinearity issues and overfitting (Marquardt 1970; Mason *et al.* 2003). The environmental variables chosen for modelling the spatial

distribution of SOC in Dongting Lake in 2022 and East Dongting Lake in 2013 were elevation, NDVI, LSW, and CI. For the spatial distribution of SOC in East Dongting Lake in 2022, the selected variables were elevation, NDVI, and CI.

2.3. Modelling techniques

Random forest (RF) is a machine learning method proposed by Breiman (2001) that is particularly suited for handling classification and regression problems. The RF algorithm randomly selects multiple samples from the original dataset and then selects a subset of features to construct a decision tree for each sample. Finally, the average of all decision-tree predictions are used for the final prediction of SOC concentrations. Each decision tree in the RF algorithm utilizes a unique combination of samples and features, thereby providing an algorithm with high accuracy, low overfitting risk, and high robustness compared to other traditional algorithms (Breiman 2001). The RF model has been extensively applied to predict SOC and has shown good prediction performance (Zhang *et al.* 2017, 2022; Nabiollahi *et al.* 2019). Therefore, this study used the RF to construct an inversion model for the measured SOC data of Dongting Lake wetland, and finally used the inverted SOC content to represent the SOC content of the entire Dongting Lake.

2.4. Model validation

The dataset was divided into training (80%) and test (20%) data, which were used for model training and validation, respectively. The coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE) were calculated to validate the model. The model validation results and the importance of SOC variables in the RF algorithm are presented in Appendices B and C.

2.5. Statistical analysis

Pearson's correlation analysis was used to assess the relevance of environmental data for predicting SOC. Soil carbon density and carbon stocks of different wetland types were compared using one-way analysis of variance (ANOVA), and multiple comparisons were made using the least significant difference (LSD) test. Univariate linear regression was used to analyze the linear relationships between *Miscanthus* and *Carex* SOC content and year, water level and year, inundation time and year, and *Miscanthus* biomass and SOC. Segmented linear regression was used to analyze the linear relationship between SOC loss and elevation. R-squared values were used to assess the goodness of fit of the linear regression models. The Shapiro-Wilk and Levene tests for normality and homogeneity, respectively, were used before statistical analyses. A threshold of $P<0.05$ was used to denote statistically significant differences. Statistical analyses and plots were performed using R version 4.3.2 software.

3. Results

3.1. Spatial pattern of SOC on Dongting Lake in 2022

The SOC concentration of soil in the Dongting Lake floodplain in 2022 varied between 3.34 and 17.67 g kg^{-1}, with an average of 10.43 g kg^{-1} (Fig. 2). The SOC concentration observed in the central area of East Dongting Lake, the southeastern section of South Dongting Lake, and the southern part of West Dongting Lake was low (Fig. 2). The SOCD of Dongting Lake floodplain in 2022 showed no significant difference between the *Miscanthus* community (3.24±0.18 kg m^{-2}) and *Carex* community (3.02±0.20 kg m^{-2}), whereas it was significantly lower in the mudflat (1.68±0.09 kg m^{-2}) ($P<0.05$, Fig. 3-A). The SOCS of the Dongting Lake floodplain was 6.82 Tg C (2.87–13.48 Tg C), of which the *Miscanthus* community was (3.07±0.17) Tg C, the *Carex* community was (2.33±0.15) Tg C, and the mudflat was (1.42±0.08) Tg C in 2022 (Fig. 3-B).

3.2. Changes in SOC of East Dongting Lake from 2013 to 2022

In East Dongting Lake, the SOC concentration had an average value of 18.37 g kg^{-1} in 2013, whereas in 2022, the average value was significantly lower at 10.82 g kg^{-1} (Fig. 4-A and B). The spatial distribution pattern of SOC at East Dongting Lake in 2013 and 2022 was similar, with both years showing lower SOC concentration in the central part of the lake (Fig. 4-A and B).

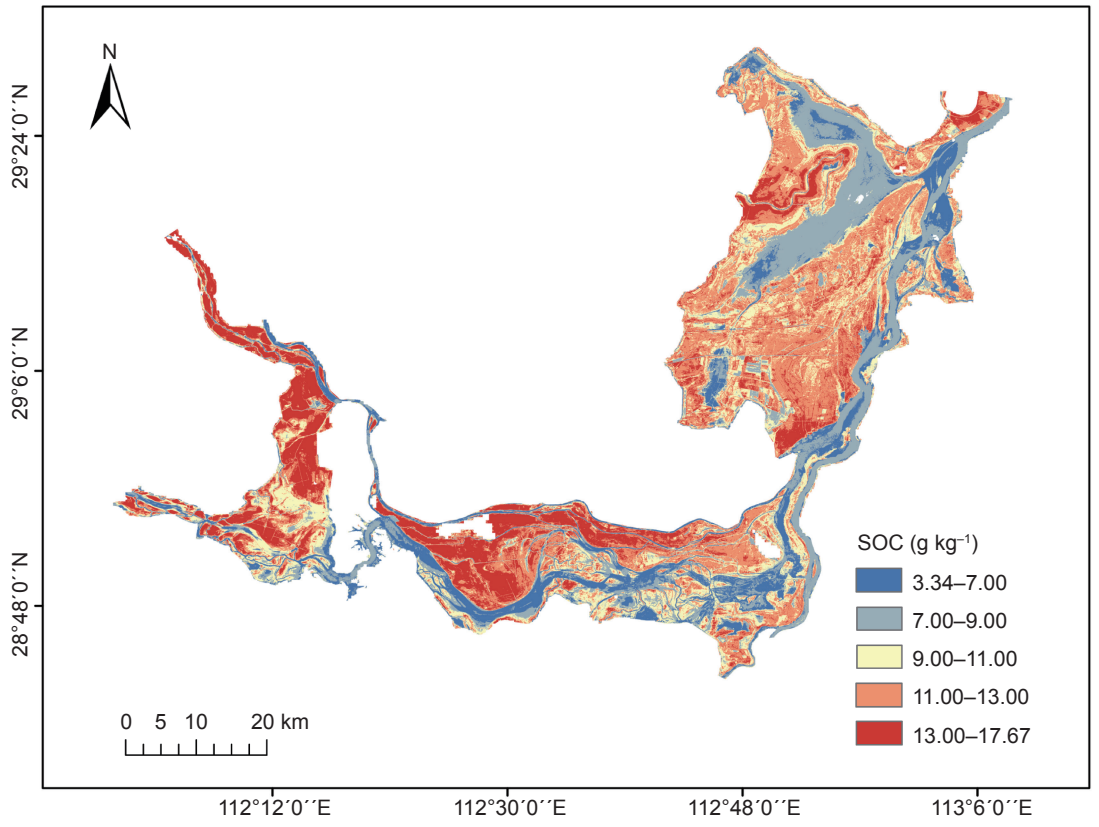
Variable SOC losses were observed in different areas. Specifically, lower reductions in SOC concentrations were observed in the central part of the lake (at lower elevations), whereas higher reductions in SOC concentrations were observed in the *Carex* and *Miscanthus* areas at higher elevations (Fig. 4-C). In total, 600 points were randomly selected from the SOC loss map between 2013 to 2022, with 200 points allocated to each wetland type (Fig. 4-C). These data showed that SOC loss accelerated with increasing elevation above 21.43 m (R^2=0.38, $P<0.01$). The lowest reduction in SOC concentration was observed in the mudflat ((3.06±0.17) g kg^{-1}), followed by the *Carex* community ((7.82±0.33 g) kg^{-1}), while the greatest reduction in SOC concentration occurred in the *Miscanthus* community ((11.39±0.25) g kg^{-1}) (Fig. 4-E).

3.3. Factors controlling the reduction in SOC concentration

From 2013 to 2022, the SOC concentrations in the *Miscanthus* community ranged from 9.09 to 23.61 g kg^{-1}, while the SOC concentrations in the *Carex* community ranged from 12.26 to 27.22 g kg^{-1}, with both communities showing a notable downward trend in SOC concentration with sampling year ($P<0.05$, Fig. 5).

From 2013 to 2022, the lowest water level showed a significant downward trend ($P<0.05$, Fig. 6-A), with 2022 having the lowest low-water level of 19.14 m. There were no significant trends over time in highest water levels, mean water levels or inundation duration. In terms of temperature, the annual and dry-season temperatures both showed increasing trends over time (Fig. 6-C). However, rainfall showed no evident trends over time (Fig. 6-D).

Aboveground biomass, belowground biomass and aboveground litter biomass of *Miscanthus* declined from 2013 to 2022, whereas *Carex* biomass showed no evident trend with sampling year (Fig. 6-E and F). In the *Miscanthus*



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Fig. 2 Spatial distribution of soil organic carbon (SOC) concentrations of the Dongting Lake floodplain in 2022.

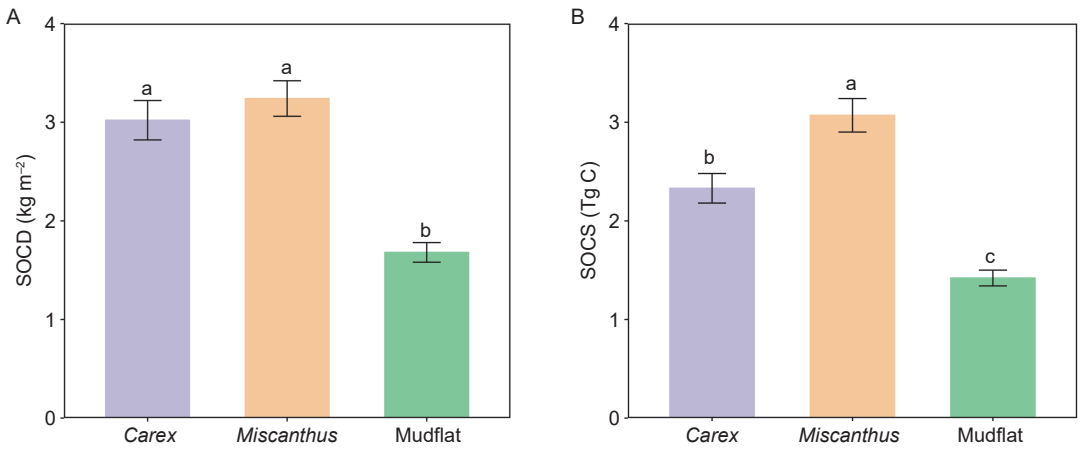


Fig. 3 Soil organic carbon density (SOCD; A) and stock (SOCS; B) of different communities of the Dongting Lake floodplain. Community types without a letter in common are significantly different at the $P<0.05$ level of significance. Bars show SE (*Carex*: $n=29$; *Miscanthus*: $n=34$; Mudflat: $n=57$).

community, a significant positive correlation was observed between aboveground and belowground biomass and SOC concentration, and a positive correlation between aboveground litter biomass and SOC concentration (Fig. 7).

4. Discussion

4.1. Spatial distribution of SOC

Our results showed that the SOCS in the Dongting Lake floodplain was 6.82 Tg C, which is a relatively large carbon reservoir. The mean SOC concentration and SOCD at the surface soil in Dongting Lake wetland were 10.43 g kg^{-1} and 2.65 kg m^{-2}, respectively. The SOC concentration in the surface layer of Dongting floodplain is close to that of Poyang Lake in Jiangxi Province (10.2 g kg^{-1}) (Zhang *et al.* 2024), but lower than that of the Amazon floodplain (42.0 g kg^{-1}) (Sanders *et al.* 2018). The high SOC concentration in the Amazon floodplain mainly results from long-term vegetation deposition coupled with a humid environment, which favors

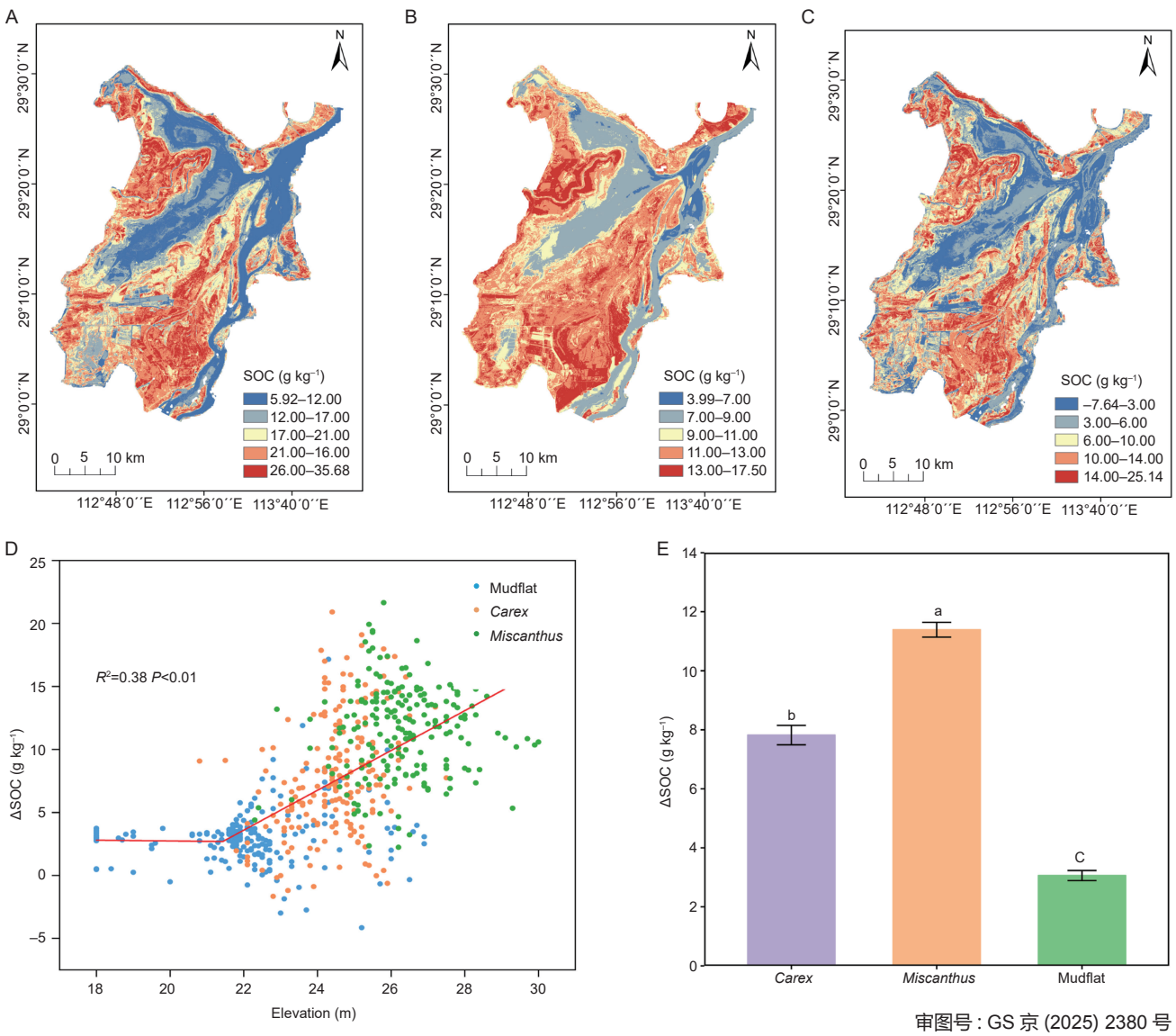


Fig. 4 Spatial distribution of soil organic carbon (SOC) concentrations of the East Dongting Lake floodplain in 2013 (A) and 2022 (B), spatial distribution of SOC loss values between 2013 to 2022 (C), and correlation between SOC loss and elevation (D), and SOC loss in the three community types (E). ΔSOC, soil organic carbon loss value. Community types without a letter in common are significantly different at the $P<0.05$ level of significance. Bars show SE ($n=200$).

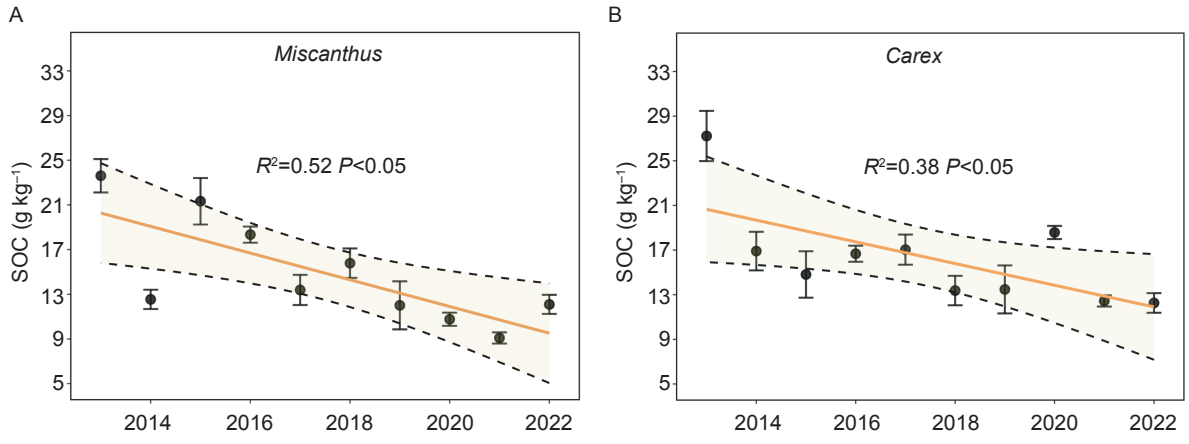


Fig. 5 Dynamic changes in soil organic carbon (SOC) concentrations in *Miscanthus* (A) and *Carex* (B) communities during 2013–2022.

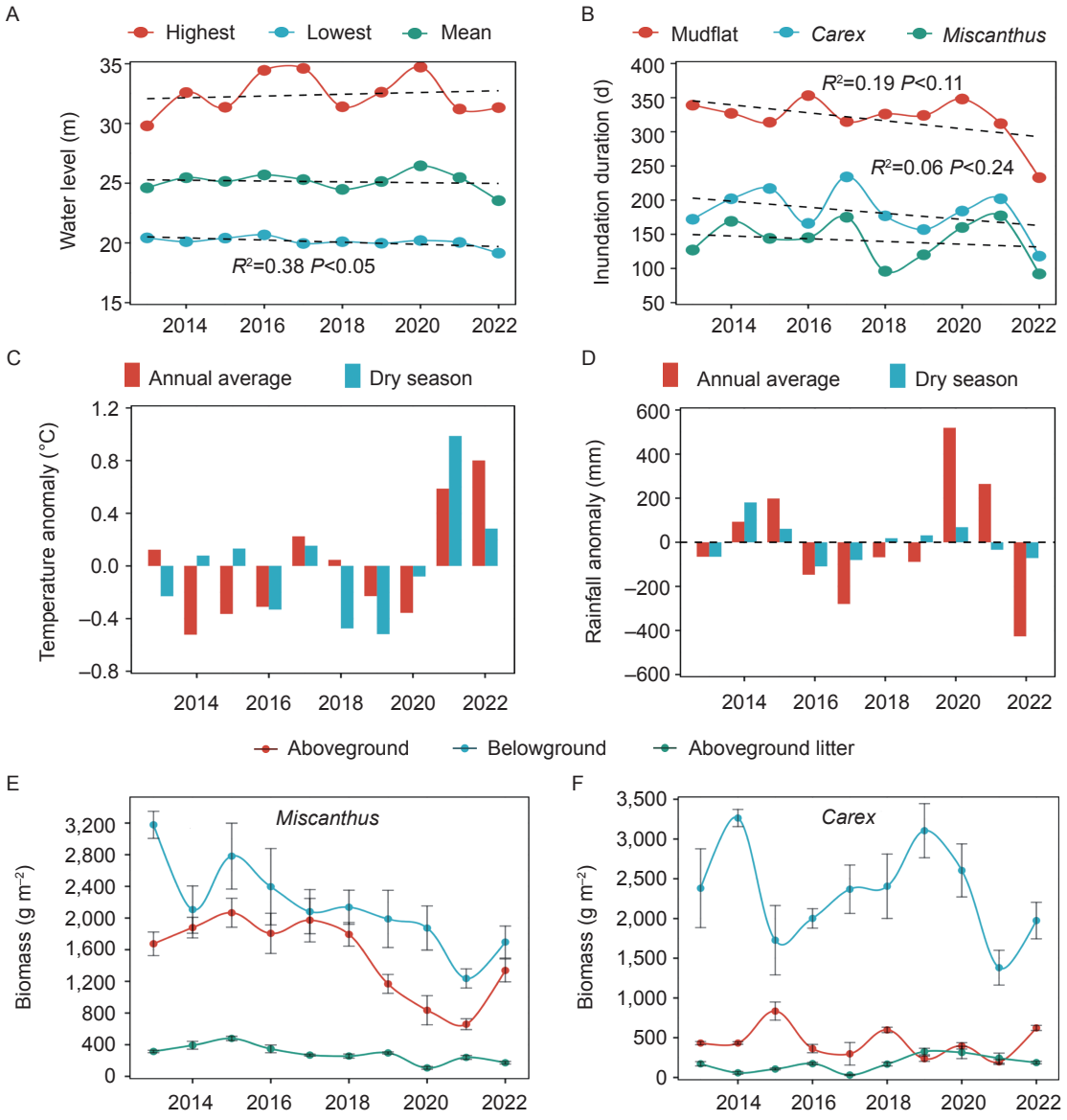


Fig. 6 Hydrological regimes (A and B), climate conditions (C and D), and vegetation biomass data (E and F) for East Dongting Lake wetlands during 2013–2022. Error bars show SE (n=5).

the accumulation of SOC.

The main sources of SOC in floodplain wetlands are local biomass inputs and upstream sediments transported by rivers. Our results showed that SOC concentrations were relatively low in the central part of East Dongting Lake, southeastern part of South Dongting Lake, and southern part of West Dongting Lake. These low concentrations were mainly due to the mudflat wetland type in these areas which has low vegetation cover and is often disturbed by floods, resulting in minimal vegetation colonization. Furthermore, the soil mechanical composition in the mudflats is dominated by sand particles that pose a weak capacity for adsorbing organic carbon, thereby facilitating the mineralization and decomposition of organic carbon (Kennedy *et al.* 2002).

The SOC concentration in other areas was higher than in the mudflat because of the presence of *Miscanthus* and *Carex* vegetation, in which a large amount of plant litter provided a large amount of endogenous organic carbon to the soil. Our research on the contribution of vegetation litter decomposition to SOC in Dongting Lake revealed that the *Miscanthus* and *Carex* litters contribute 275.24 and 283.68 g C m^{-2} yr^{-1}, respectively, to SOC (Zhu *et al.* 2022). In addition, our previous research on the Dongting Lake floodplain showed that during floods, vegetation growth areas can facilitate the settlement of suspended matter (Pan *et al.* 2012, 2018). This process enhances the input of exogenous carbon, thereby increasing the SOC content in the surface layer.

4.2. Changes in soil organic carbon from 2013 to 2022

East Dongting Lake is the largest sub-lake of Dongting Lake wetland. In 1992, this area became the first internationally important wetland to join the Ramsar Convention. Lower levels of human intervention provide a more accurate

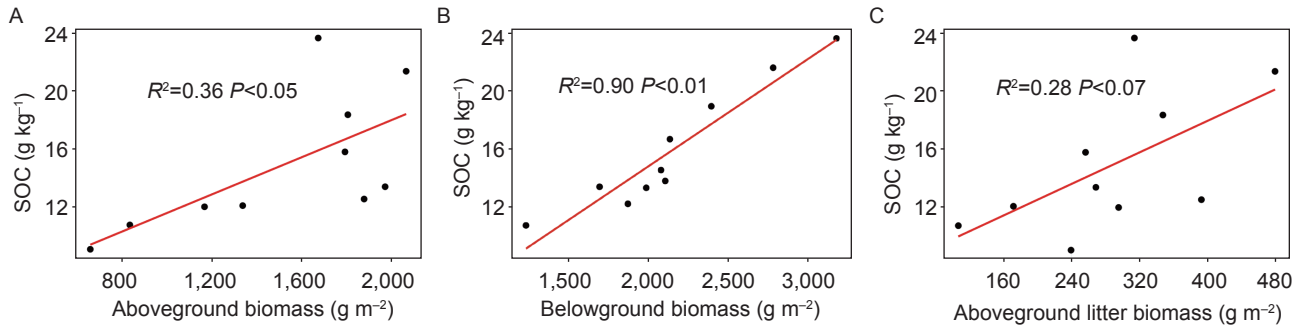


Fig. 7 Linear regressions between soil organic carbon (SOC) concentration and aboveground biomass (A), belowground biomass (B) and aboveground litter biomass (C) of *Miscanthus* communities.

portrayal of the evolution of SOC in the Dongting Lake wetland (Tang *et al.* 2013a). Our results showed that the SOC concentrations in the surface soil layer of East Dongting Lake decreased from 18.37 g kg^{-1} in 2013 to 10.82 g kg^{-1} in 2022. This decline may be attributed to the decrease in the lowest water level and the rise in temperature in the East Dongting Lake region during this period (Fig. 6-A and C). Variation in these environmental factors would have altered the redox conditions of the soil, subsequently affecting the community structure and activities of soil microorganisms and thereby accelerating SOC decomposition (Zhou *et al.* 2017; Walker *et al.* 2018). Other floodplains located in the middle and lower reaches of the Yangtze River have experienced SOC loss. For example, the SOC concentration of the *Carex* community in Poyang Lake decreased from 28.54 g kg^{-1} in 2009–2013 to 12.41 g kg^{-1} in 2021–2022 (Wu *et al.* 2012; Wang *et al.* 2014, 2016; Hu *et al.* 2015; Sun *et al.* 2023; Zhang *et al.* 2024). Additionally, the SOC concentration of the *Miscanthus* community decreased from 23.9 g kg^{-1} in 2011 to 10.09 g kg^{-1} in 2021 (Wu *et al.* 2012; Ren *et al.* 2022; Sun *et al.* 2023). In recent years, the frequency of extreme weather events has increased and studies have shown that extreme drought and warm weather can lead to SOC losses (Wang *et al.* 2023). In 2022, Dongting Lake experienced extremely dry weather (Xia *et al.* 2022), which may have contributed to the loss of SOC. The delayed flood recession in 2020 and 2021 coupled with an extreme drought year in 2022, may have contributed to reduced biomass of the vegetation. Delayed flood recession curtails the growth of wetland plants, potentially diminishing plant biomass (Qin *et al.* 2013).

Our results show that above 21.4 m, SOC loss increased with elevation (Fig. 4-D). The *Miscanthus* communities experienced the greatest loss of SOC (Fig. 4-E), which correlated with a decrease in plant biomass (Fig. 7). *Miscanthus* is a high-quality papermaking material. To protect the environment, the papermaking industry in the Lake Dongting district was closed in March 2018. Consequently, the *Miscanthus* community does not receive manual management, resulting in an increase in aboveground standing dead material and poorer lighting conditions. Changes in the community growing environment may be responsible for the decline in *Miscanthus* biomass (Fig. 6-E). In addition, the decline in biomass of *Miscanthus* may also be related to disturbances in climate and hydrology. Vegetation biomass is a crucial factor that influences SOC content and directly determines the SOC input (Kang *et al.* 2024). Our findings indicate that the SOC concentration of the *Miscanthus* community was significantly and positively correlated with its biomass (Fig. 7). This finding may have been due to areas with higher elevation being more affected than lower elevation areas by the lowering of the lowest water level. Therefore, SOC would have been more susceptible to mineralization reactions in higher elevation areas, resulting in a greater loss of SOC in those areas. There was no apparent change in *Carex* biomass during the study period. In the *Carex* community, the SOC concentration was particularly high in 2013, and there was a decreasing trend in SOC concentration in the *Carex* community over the last decade. The SOC concentration of the *Carex* community should be monitored for a longer period to determine future changes in the SOC content.

Our study found that changes in hydrological and climatic conditions in the Dongting Lake floodplain region may cause SOC loss, especially in the area above 21.4 m elevation. Therefore, in Dongting Lake floodplain management and restoration practices, raising the water level during dry periods to appropriate levels may be an important way to increase the carbon sequestration potential of the wetlands in the region.

4.3. Impact of environmental factors on the spatial distribution of SOC

Temperature is an important factor affecting the decomposition rate of SOC (Lu and Xu 2014). An increase in temperature enhances microbial activity and alters microbial community composition, thereby accelerating SOC decomposition (Waldrop and Firestone 2004; Wallenstein *et al.* 2011). Furthermore, rising temperatures facilitate the desorption of SOC-mineral interactions as well as the diffusion and dissolution of substances, thereby enhancing the accessibility of soil microorganisms to the substrate and accelerating SOC decomposition (Xu and Saiers 2010; Conant *et al.* 2011). The response of SOC decomposition to warming is influenced by substrate quality, aggregate protection, and microbial characteristics (Hartley and Ineson 2008; Qin *et al.* 2019).

Water levels in wetlands are declining worldwide because

of climate change and human activity (Zedler and Kercher 2005). A decrease in water levels enhances the availability of oxygen, subsequently increasing soil phenol oxidase activity, which eliminates phenolic substances. The elimination of phenolic compounds stimulates hydrolase activity, thereby promoting the decomposition of soil organic matter (Freeman *et al.* 2001, 2004). In this study, the lowest water level decreased from 2013 to 2022, which may be one of the reasons for the decrease in SOC content in the surface soil layer of Dongting Lake.

Plant litter is an important SOC source (Tian *et al.* 2019). Reduced plant productivity reduces soil litter input, leading to a reduction in SOC content (Lange *et al.* 2015). In our study, the decline in the SOC concentration of the *Miscanthus* community was related to biomass. The SOC in wetlands is influenced by intricate environments and interactions. Therefore, it will be important to elucidate the key factors contributing to surface soil carbon loss in flooded wetlands in future research.

5. Conclusion

In this study, the mean value of the soil surface SOC concentration of the Dongting Lake floodplain in 2022 was 10.43 g kg^{-1} (3.34–17.67 g kg^{-1}) while the SOC storage of the floodplain was 6.82 Tg C. We found that SOC was lost from the Dongting Lake wetland between 2013 and 2022, indicating that floodplain wetlands in subtropical regions may be at a high risk of SOC loss. This finding may be attributed to alterations in climate and hydrological conditions influencing vegetation growth, resulting in a reduced SOC input. In addition, significant fluctuations in climatic and hydrological conditions directly contributed to the loss of SOC through decomposition. Future studies should focus on the impacts of changes in hydrological and climatic conditions on SOC transformation in floodplain wetlands. In the context of wetland conservation and ecological restoration efforts, implementing measures such as raising the minimum water level appropriately and extending the flooding period may help slow carbon loss, thereby enhancing the carbon sequestration capabilities of wetlands.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used Deepseek to assist in improving the clarity and readability of the language. All content generated was carefully reviewed and revised by the authors as necessary, and the authors take full responsibility for the final content of the article.

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