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Sensitivity analysis of soil particulate organic carbon to sea-level rise in coastal salt marsh

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SUMMARY: *This study aims to improve the monitoring and prediction ability of soil particulate organic carbon (POC) in coastal salt marsh wetlands in response to sea level rise, and provide a scientific basis for carbon pool management in coastal wetlands. This paper constructs an ensemble learning sensitivity model based on multi-source environmental data, and compares the prediction performance of machine learning methods such as Random Forest (RF) and XGBoost. The data included multi-dimensional variables such as elevation, flooding frequency, pore water salinity, sedimentation rate, vegetation index and soil particle size. The data were imputed with missing values, excluded with outliers and standardized. Combined with the Shapley additive explanatory value (SHAP), the contribution of each environmental factor to the sensitivity of POC and regional differences were analyzed. The results show that the POC of coastal low-lying salt marshes is the most sensitive to sea rise disturbance, and the response of central salt marshes and inland high salt marshes is weakened in turn, showing obvious spatial heterogeneity. In the typical salt marsh area, the predicted* R^2 *of the model can reach 0.88, RMSE and MAE are 0.015 and 0.012, respectively, indicating that the ensemble learning method has good performance in capturing the nonlinear coupling and spatial heterogeneity of environmental variables. SHAP analysis showed that flooding frequency, deposition rate and pore water salinity were the key drivers of POC change, and their direction and strength varied with regional conditions. This study provides quantitative methods and decision support for blue carbon management, ecological restoration and digital monitoring of coastal wetlands.*

KEYWORDS: *coastal salt marsh wetland; Particulate organic carbon; Sea level rise; Sensitivity analysis*

1 Introduction

In the context of global change, the continuous rise of sea level has become a key external driver affecting the evolution of coastal ecosystem structure and function. Coastal salt marsh is located in the sea-land transition zone, which has multiple ecological functions such as tidal regulation, sediment interception, shoreline protection and carbon sink maintenance. The changes in soil carbon pool not only affect the stability of the wetland itself, but also directly affect the regional carbon cycle process and coastal ecological security. Compared with total organic carbon, soil particulate organic carbon has the characteristics of faster turnover speed and sensitivity to water and salt changes and deposition disturbances. It can not only reflect the changes in the balance of accumulation and decomposition of soil organic matter in salt marshes earlier, but also be used as an important indicator to identify the vulnerability of

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wetland carbon pools. With the rapid rise of relative sea level, the tidal flooding frequency, sedimentary supply conditions, vegetation community structure and pore water salinity pattern continue to adjust, and the formation, migration and conservation mechanisms of soil particulate organic carbon in salt marshes are undergoing more complex reorganization.

Existing studies on carbon processes in coastal wetlands mainly focus on changes in soil organic carbon storage, carbon burial rate and the overall response of wetlands to sea level rise, which reveal the regulatory relationship between deposition accumulation, vegetation production and hydrodynamic effects on carbon sink function to a certain extent. However, the research on particulate organic carbon, the active component, is still relatively insufficient, especially the lack of sensitivity identification and differential interpretation for sea level rise scenarios. On the one hand, the particulate organic carbon is affected by the composition of sediment particle size, root input, REDOX environment and the exchange process of tidal channel, and the change is not simple linear. On the other hand, under the conditions of different sea rise rates, land surface elevation and vegetation cover, the response characteristics of particulate organic carbon may show stage enhancement, threshold transition and spatial heterogeneity. Traditional empirical judgment is difficult to fully reveal its action path. It is often difficult to provide more targeted basis for salt marsh carbon sequestration assessment, wetland restoration priority area identification and adaptive management if only staying at the qualitative description level.

In recent years, the development of remote sensing monitoring, geographic information systems, machine learning and interpretable computational methods have provided new technical conditions for the quantitative analysis of complex ecological processes. Compared with the research path relying solely on statistical regression or static correlation analysis, the calculation method based on multi-source data fusion can simultaneously deal with multi-dimensional variables such as elevation, tide, water and salt, vegetation index, particle size distribution, and soil physical and chemical properties, which is more suitable for describing the nonlinear coupling relationship between salt marsh environmental change and particulate organic carbon response under the background of sea level rise. At the same time, the introduction of sensitivity analysis and feature contribution interpretation framework can not only improve the accuracy of model recognition, but also help to identify the key driving factors and their effect strength from the global and local levels, and enhance the interpretability and application value of research conclusions.

Based on this, this paper focuses on the response of soil particulate organic carbon to sea level rise in coastal salt marsh wetlands. Combined with sea level rise scenario setting, coupling analysis of environmental factors and computer modeling methods, this paper constructed a sensitivity analysis framework of particulate organic carbon, and systematically identified its change characteristics and main control factors under different scenarios. This study tries to answer three questions: how will salt marsh environmental factors change in tandem under the background of sea level rise; Whether there are significant situational and spatial differences in the sensitivity of particulate organic carbon; Which factors play a dominant role in the different response phases? The results of this paper could provide methodological support for the dynamic assessment of carbon pools in coastal salt marsh wetlands, coastal ecological risk identification and digital monitoring and management.

2 Related Research

In recent years, scholars at home and abroad have carried out systematic studies on the carbon sequestration process of coastal salt marshes, the ecological effects of sea level rise, and the evolution of soil organic carbon components. The relevant results have continuously promoted the field from overall carbon storage estimation to the detailed analysis of sub-groups, sub-processes and sub-scenarios. Early studies considered salt marsh wetland as a typical blue carbon ecosystem with significant carbon burial potential, and focused on the combined effects of relative sea level change, deposition rate and vegetation productivity on organic carbon accumulation. Herbert et al. [1] pointed out that sea level rise can enhance the carbon accumulation capacity of tidal wetlands in the United States under certain conditions. Wang et al. [2] further believed that the more resilient wetlands are to sea level rise, the more likely their carbon sequestration potential is to be maintained. Such studies reveal that the relationship between carbon sinks and sea rise is not unidirectional, but a dynamic balance regulated by sedimentary recharge, surface uplift and vegetation response.

With the deepening of research, scholars begin to pay attention to the reorganization of sedimentary environment, the turnover of plant community and the change of soil carbon stabilization mechanism caused by sea level rise. Mudd et al. [3] earlier analyzed the coupling relationship between sedimentation, sea level rise and biomass production from the perspective of dynamic feedback, and pointed out that the process of near-surface stratum development and carbon accumulation had obvious synergistic feedback characteristics. Studies by Rogers et al. [4] and Gonneea et al. [5] showed that changes in relative sea level had a profound impact on wetland carbon storage patterns in a long time scale, and ecosystem structural reorganization sometimes enhanced elevation resilience and carbon storage capacity. Kulawardhana et al. [6] further incorporated the elevation and sea level change history and vegetation succession into a unified framework, emphasizing that carbon distribution has strong dependence on geomorphological location and community transition. These results provide an important basis for understanding the spatial heterogeneity of soil organic carbon in salt marshes. However, the analysis object is still mainly total organic carbon or overall carbon pool, and the attention on particulate organic carbon, which is a component with strong activity and rapid response, is still insufficient.

In the study of soil organic carbon grouping, the progress has accelerated significantly in recent years. Luk et al. [7] investigated the development and turnover characteristics of soil organic carbon in natural and disturbed salt marsh environments, and showed that different environmental disturbances would change the path of organic matter formation and renewal. Neiske et al., Wu et al., Kang et al. Analyzed the distribution pattern and stability mechanism of different soil organic carbon components from the perspective of tidal gradient, the difference of coastal wetland types and the comparison of vegetation communities, and pointed out that particulate organic carbon was often controlled by sediment source, particle size composition, root input and water and salt environment. And its changes tend to appear before the more stable mineral-bound organic carbon [8-10]. Puppin et al. [11] found through the study of profile depth distribution that tidal deposition conditions and local environmental background would leave clear traces in the vertical structure of soil organic matter, which means that particulate organic carbon is not only an indicator of the change of carbon pool quantity, but also an important window to identify the disturbance intensity of sea level rise.

In addition to the vertical accumulation, the lateral transport process is also concerned. Yuan et al. [12] and Ganju et al. [13] respectively studied the exchange of organic carbon between salt marshes and adjacent water bodies, the stability of tidal flats and the lateral flux of particulate organic matter, showing that particulate organic carbon is not statically stored in the soil, but continuously migrated in the process of exchange in tidal gully, erosion and transport, and deposition redistribution. These results remind us that judging the impact of sea level rise on particulate organic carbon only based on static sampling results is often difficult to fully grasp the true response process.

From the perspective of research methods, the traditional salt marsh carbon process research mostly adopts the path of combining field sampling, indoor grouping measurement, statistical regression and process modeling. This kind of method has obvious advantages in mechanism identification. However, when facing the research object with multi-source driving variables coupling, frequent scenario changes and prominent spatial heterogeneity, it also has the problems of large number of parameters, insufficient nonlinear description and single interpretation scale. In recent years, remote sensing, geographic information system, digital elevation model, scene simulation and machine learning methods have gradually entered the field of wetland ecological research. Schile et al. [14] used models to assess the role of vegetation, sedimentation and upland habitats in salt marsh resilience, which promoted the quantification of sea level rise scenario simulations. Sandi et al. [15] pointed out through a case study that accelerated sea level rise would limit the carbon sequestration capacity of vegetation, providing more targeted evidence for scenario analysis. Maxwell et al. [16] systematically integrated the global tidal salt marsh soil carbon, indicating that large-scale data collection and computational analysis have become an important development direction in this field. The related studies are summarized in Table 1.

Table 1: Summary of related studies

Study	Research object / method	Data type	Main conclusion	Limitation
Herbert et al. (2021) [1]	Analysis of carbon accumulation in tidal wetlands	Wetland observational data + regional environmental data	Sea-level rise can enhance carbon accumulation under certain conditions	Focused mainly on the overall carbon pool and did not provide a detailed analysis of particulate organic carbon
Wang et al. (2019) [2]	Analysis of the relationship between wetland resilience and carbon sequestration	Wetland environmental observations + model data	Wetlands with stronger resilience are more likely to maintain carbon sequestration capacity	Insufficient discussion of the responses of soil carbon fractions
Luk et al. (2021) [7]	Analysis of the development and turnover of soil organic carbon in salt marshes	Soil sample measurement data	Disturbance can alter the formation and renewal pathways of organic carbon	Did not focus on differences under sea-level-rise scenarios
Mudd et al. (2009) [3]	Dynamic feedback model of sedimentation, sea-level rise, and biomass	Process-based simulation data	The feedback between sedimentation and biomass jointly affects carbon accumulation	The process is complex, and the threshold for scenario application is relatively high
Rogers et al. (2019) [4]	Relationship between relative sea-level change and wetland carbon storage	Long-term stratigraphic and environmental data	Relative sea-level change controls the pattern of wetland carbon storage	The temporal scale is relatively large, with insufficient sensitivity to local conditions
Gonneea et al. (2019) [5]	Analysis of ecosystem reorganization and carbon storage	Salt marsh ecological monitoring data	Structural reorganization can improve elevation resilience and carbon storage	The characterization of particulate fractions was not sufficiently detailed
Kulawardhana et al. (2015) [6]	Analysis of elevation, sea-level history, and vegetation transition	Elevation + vegetation + soil data	Carbon distribution is significantly influenced by elevation and vegetation succession	The explanatory framework is still mainly based on correlation analysis
Schile et al. (2014) [14]	Simulation of salt marsh distribution under sea-level-rise scenarios	Model parameters + eco-geomorphic data	Vegetation, sediment, and upland conditions affect salt marsh resilience	Focused more on habitat distribution than on carbon fractions
Sandi et al. (2021) [15]	Analysis of the effects of accelerated sea-level rise on wetland carbon sequestration capacity	Case observations + scenario simulation data	Accelerated sea-level rise can constrain vegetation carbon sequestration capacity	Strong regional case specificity
Neiske et al. (2025) [8]	Study on the stabilization mechanisms of soil organic carbon along tidal gradients	Soil fractionation and environmental gradient data	The distribution of carbon fractions is significantly controlled by tidal gradients	Sensitivity identification of particulate organic carbon remains limited
Wu et al. (2025) [9]	Analysis of drivers of soil organic carbon fractions in coastal wetlands of China	Multi-regional soil and environmental data	Different fractions are driven by environmental factors in different ways	Lacks targeted analysis under sea-level-rise scenarios
Ganju et al. (2019) [13]	Tidal wetland stability and lateral flux of particulate organic matter	Monitoring data + flux analysis	Wetland stability affects the lateral export of particulate organic carbon	Insufficient coupling between vertical storage and scenario analysis
This study	Multi-source data fusion + sensitivity modeling + interpretable analysis	Elevation, inundation, salinity, vegetation, particle size, and soil physicochemical data	Identifies the response intensity and dominant controlling factors of particulate organic carbon under sea-level-rise scenarios	Further validation is still needed with larger regional samples

In general, the existing studies have revealed the complex relationship between sea level rise and carbon processes in coastal wetlands from different levels, but there are still three shortcomings. First, the research focuses more on total organic carbon storage, carbon burial rate or overall carbon sink function, and the scenario sensitivity identification of particulate organic carbon is still insufficient. Secondly, most studies focus on single-factor statistical interpretation or process mechanism description, and the nonlinear coupling between multiple variables such as elevation, flooding frequency, salinity, vegetation index and particle size composition is not sufficiently described. Third, although computer methods have entered wetland research, there are still few studies that integrate multi-source environmental data fusion, scenario simulation, and interpretable sensitivity analysis into a unified framework. Based on this background, this paper introduced the coupling analysis of multi-source environmental variables, sensitivity modeling and characteristic contribution interpretation methods to systematically identify the response intensity, variation interval and main control factors of soil particulate organic carbon in coastal salt marsh wetlands under the scenario of sea level rise, in order to provide a more targeted analysis path for the assessment and digital management of coastal wetland carbon pool.

3 Research Methods

3.1 Analysis of coastal salt marsh wetland environmental change under the background of sea level rise

Sea level rise is not a single process of water level rise, but through tidal flooding, sediment deposition, pore water salinity, vegetation succession and surface elevation adjustment, the ecological environment of coastal salt marsh and wetland is continuously reshaped. In the study, it is necessary to analyze the environmental change chain before further identifying the sensitive response of soil particulate organic carbon. Based on this, this paper constructed an analysis framework consisting of "sea level change -- hydrodynamic disturbance -- deposition and salt reorganization -- vegetation and soil properties change -- response of particulate organic carbon", and its action path was shown in Figure 1. Combined with remote sensing images, digital elevation model, tidal level monitoring data and soil physical and chemical index data, the process of salt marsh wetland environmental change was characterized by computer.

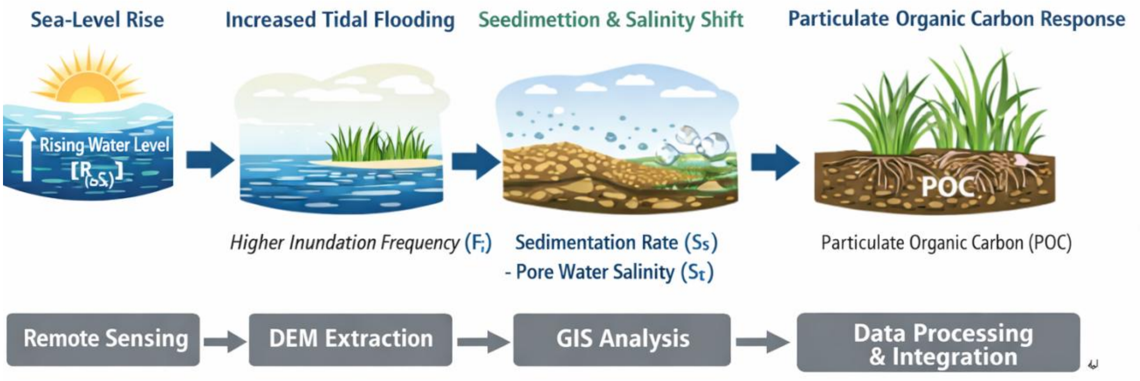

Figure 1: Schematic diagram of the environmental change mechanism of coastal salt marsh wetland under the background of sea level rise

The relative sea-level rise rate is denoted as R_{slr}, and the vertical elevation capacity of wetland surface is denoted as A_e. The difference between the two determines the change degree of the salt marsh flooding pressure, which can be expressed as follows.

$$D_i = R_{slr} - A_e \tag{1}$$

where, D_i is the flooding pressure index; When Di>0, it indicates that the wetland surface uplift is not enough to offset the sea level rise, and the risk of regional flooding is enhanced. When $D_i \leq 0$, it indicates that sedimentary recharge and organic matter accumulation can still maintain relative elevation stability. Considering that the surface increase is not a homogeneous process, this paper further includes the deposition rate S_r and the contribution of underground biomass B_r into the calculation, and the following results are obtained:

$$A_e = \alpha S_r + \beta B_r \tag{2}$$

where α and β are weight coefficients, which reflect the contribution strength of exogenous deposition and vegetation root growth to the maintenance of surface elevation, respectively.

At the data processing level, this paper uses GIS spatial overlay and grid operation to perform unified grid processing on elevation, tidal channel distance, vegetation coverage and salinity distribution, and uses time series algorithm to extract environmental change trajectories under different sea level rise scenarios. In order to describe the coupling effect of multiple factors, the flooding frequency F_t, the pore water salinity S_t, the vegetation index V_i and the median sedimentary particle size G_m were jointly incorporated into the environmental state function:

$$E_c = w_1 F_t + w_2 S_t + w_3 V_i + w_4 G_m \tag{3}$$

where, E_c is the environmental comprehensive change index; w_1 to w_4 are the normalized weights of each variable. This index can be used to identify spatial differences in the intensity of environmental disturbances in different zones in the context of sea level rise. Compared with single factor analysis, this multi-source data fusion method can more completely reveal the stage and nonlinear characteristics of salt marsh wetland environmental change.

3.2 Construction of sensitivity analysis model of soil particulate organic carbon in coastal salt marsh

In order to quantitatively identify the response strength and stage difference of soil particulate organic carbon to sea level rise in coastal salt marsh wetland, this paper constructed a computer analysis framework of "data integration, feature processing, sensitivity modeling, result verification and mechanism explanation" based on environmental change analysis. Different from the method of correlation analysis or linear regression, this framework emphasizes the unified coding of multi-source data and the mining of non-linear relationships, and strives to improve the recognition ability of complex ecological response processes while maintaining the interpretability of results. Its overall process is shown in Figure 2.

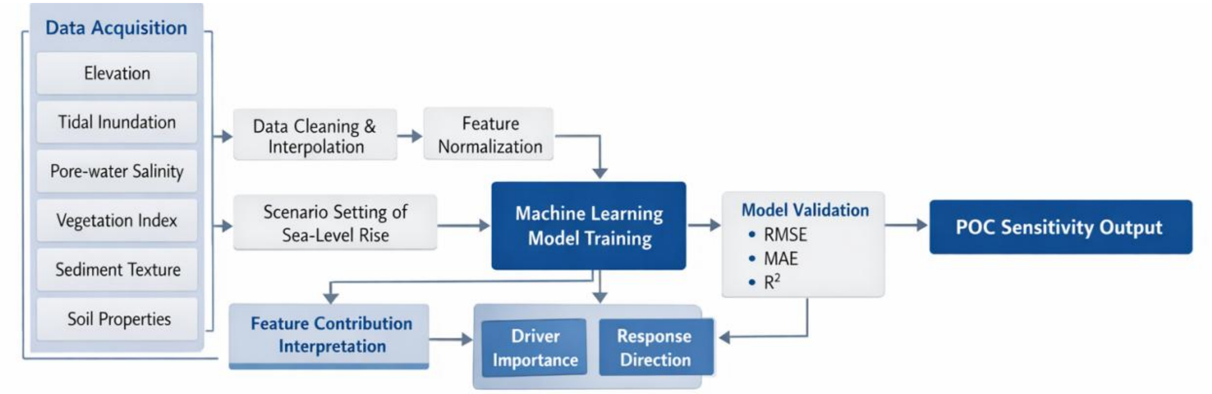

Figure 2: Construction flow chart of soil particulate organic carbon sensitivity analysis model in coastal salt marsh

The model is based on the joint data set of site scale and grid scale, and the input variables mainly include sea level rise scenario value, flooding frequency, deposition rate, pore water salinity, vegetation index, soil median particle size, bulk density, water content and surface elevation. The response variables were set as soil particulate organic carbon content and its rate of change. Considering the large differences in dimensions of different variables and the skewed distribution of some environmental factors, this paper firstly eliminates missing values and locally interpolates the original data, and then uses the range standardization method to complete the dimensionless processing:

$$X_i^* = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{4}$$

where, X_i^* is the normalized value of the variable, X_i is the original observed value, and X_{min} and X_{max} are the minimum and maximum values in the sample of this variable, respectively. After standardization, each input feature is uniformly mapped to the interval [0,1] to weaken the influence of variable scale differences on the stability of model training.

Based on this, this paper defines the sensitivity of particulate organic carbon as the ratio between its relative change magnitude under sea-level rise disturbance and the external pressure increment. If POC_0 represents the content of particulate organic carbon under the baseline scenario, POC_s represents the content of particulate organic carbon under a certain sea-level rise scenario, and ΔH represents the magnitude of sea-level change, the sensitivity index can be expressed as follows.

$$SI_{POC} = \frac{(POC_s - POC_0)/POC_0}{\Delta H/H_0} \tag{5}$$

where, SI_{POC} is the particulate organic carbon sensitivity index and H_0 is the base water level or base sea level height. This index can uniformly measure the change of particulate organic carbon and the intensity of sea level rise. When the absolute value of SI_{POC} is large, it means that the particulate organic carbon is more sensitive to the disturbance of rising sea. When it was positive, it indicated that the particulate organic carbon showed an increasing trend under this scenario. When the value is negative, it indicates that the particulate organic carbon decreases due to the rising sea.

In order to enhance the ability of the model to describe the complex nonlinear relationship, this paper uses the strategy of combining ensemble learning and regression modeling to construct a prediction model for the sensitivity of particulate organic carbon. In the process of model training, the multi-source environment variables form a feature matrix $F = \{f_1, f_2, \cdots, f_n\}$, and the sensitivity index SI_{POC} is used as the target output to establish the mapping function:

$$\hat{Y} = g(F, \theta) \tag{6}$$

where, $\hat{Y}$ is the sensitivity value of particulate organic carbon predicted by the model, $g(\cdot)$ is the machine learning mapping function, and θ is the set of parameters to be optimized. Considering the obvious coupling effect between ecological environment variables, this paper introduces the cross-validation and parameter optimization mechanism in the training stage, and obtains the better parameter combination through iterative search to reduce the interference of local optimal solutions on the results. The data set is divided into training set and test set according to the principle of mixed temporal and spatial stratification. The training set is used for model learning, and the test set is used to test the generalization ability.

After the model output, we further introduce a feature contribution interpretation module to decompose the marginal contributions of factors such as sea level rise, flooding frequency, salinity, sedimentation rate, and vegetation conditions to identify key drivers and their directional effects. If the contribution value of a variable is positive, it means that the increase of the variable will enhance the accumulation of particulate organic carbon or improve its positive response. On the contrary, it indicates that it may accelerate the loss of particulate organic carbon or inhibit the input. In order to test the effect of the model, root mean square error, mean absolute error and determination coefficient are selected as evaluation indexes in this paper, and their expressions are as follows.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{7}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{8}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{9}$$

where, y_i is the measured sensitivity value, $\hat{y}_i$ is the predicted value, y is the sample mean and n is the number of samples. The smaller RMSE and MAE are, the lower the model fitting error is. The closer R^2 is to 1, the more explanatory the model is. In general, the sensitivity analysis model of particulate organic carbon constructed in this paper not only realizes the unified coupling of multi-source environmental information and sea-level rise scenarios, but also provides a computable and verifiable technical path for subsequent comparison of different scenarios and interpretation of the main control factors.

3.3 Interpretation and analysis of influencing factors of soil particulate organic carbon sensitivity

In order to quantitatively evaluate the contribution of various environmental factors to the sensitivity response of soil particulate organic carbon (POC) in coastal salt marsh wetlands, this paper introduced the interpretable machine learning method based on Shapley value (SHAP) [27]. In the specific implementation process, considering that the sensitivity prediction model mainly uses tree models (such as random forest and XGBoost), this paper uses the TreeSHAP algorithm variant to improve the computational efficiency and interpretation accuracy. TreeSHAP is optimized for tree structure and can calculate feature contributions quickly and accurately, while ensuring the fair distribution principle of Shapley value, which is suitable for sensitivity analysis of large-scale multi-source environmental data.

Let the set of features be $F = \{f_1, f_2, \ldots, f_D\}$, where D denotes the total number of features. For any subset $S \subseteq F$, define its value function v(S) as follows.

$$v(S) = E[SI_{POC} \mid X_S = x_S] \tag{10}$$

where, X_S represents the eigenvalues in subset S, x_S is the sample observations, and SI_{POC} is the particulate organic carbon sensitivity index. The Shapley value ϕ_k then represents the marginal average incremental contribution of the KTH feature over all possible combinations and is calculated as follows.

$$\phi_k = \sum_{S \subseteq F \backslash \{k\}} \frac{|S|!\,(D - |S| - 1)!}{D!} [v(S \cup \{k\}) - v(S)] \tag{11}$$

The model prediction was regarded as a cooperative game process, and the overall sensitivity increment was reasonably allocated to each feature, so as to clarify the contribution strength and direction of each environmental factor to the response of particulate organic carbon under different sea level rise scenarios. Specifically, when $\phi_k<0$, it means that the increase of this factor will enhance the cumulative or positive response of POC. When $\phi_k>0$, then it indicates that the factor may inhibit the increase of POC or accelerate the loss.

In the implementation process, we first use the trained sensitivity model to predict the POC response of each grid or sample point, and then calculate the TreeSHAP value for each sample to generate a local explanation, and further obtain the global feature contribution by global average. Finally, the key drivers were sorted according to their contributions to form an impact factor priority table, which provided a quantitative basis for subsequent management and repair strategies. In order to visually show the factor contribution relationship, Figure 3 constructs the POC sensitivity feature interpretation flow chart.

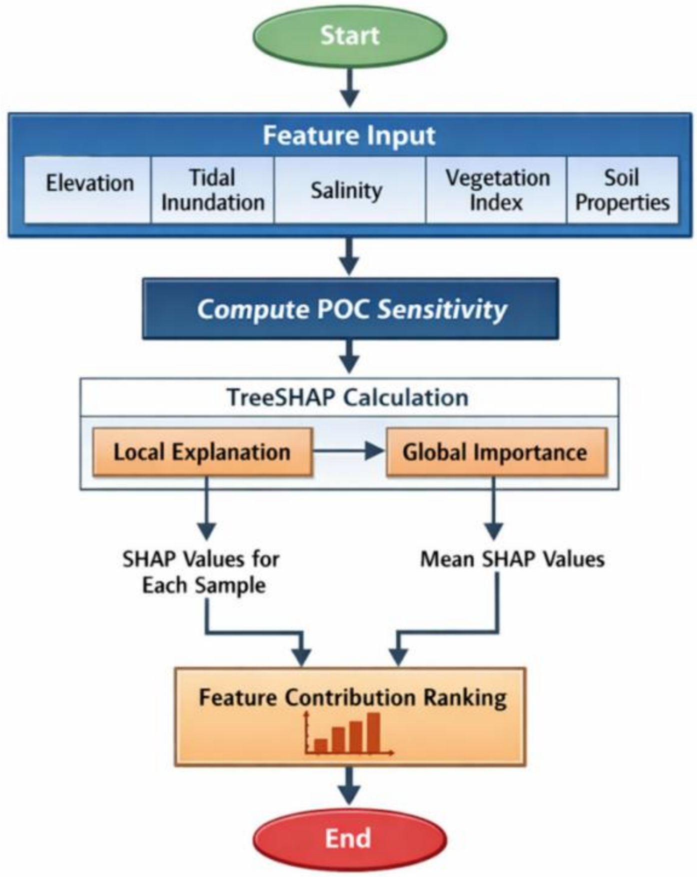

Figure 3: Interpretation process of granular organic carbon sensitivity characteristics in coastal salt marsh wetlands

This analysis method can not only quantify the separate effects of factors such as sea level rise, flooding frequency, salinity, sediment particle size and vegetation index on POC sensitivity, but also reveal possible synergistic or hedging effects among these factors, which provides a scientific basis for further scenario comparison and ecological management. In addition, combined with computer visualization, the local Shapley value was mapped to the spatial grid, which could intuitively show the sensitivity distribution differences of different wetland units under the action of various factors, and provide decision support for precise wetland restoration and blue carbon management.

4 Experimental results and analysis

4.1 Results of soil particulate organic carbon sensitivity analysis

Based on the sensitivity analysis model, this study systematically simulated and evaluated the soil POC response of coastal salt marsh wetlands under different sea level rise scenarios. The input of the model included sea level increment, tidal flooding frequency, deposition rate, pore water salinity, vegetation index, sediment particle size and soil physical and chemical properties, and the output was particulate organic carbon sensitivity index (SIPOC). The higher the value of SIPOC, the more sensitive the POC was to the disturbance of rising sea. Rolling time series 5-fold cross validation was used to train the model. The results show that the average RMSE is 0.015, MAE is 0.012, and R^2 reaches 0.88 in typical salt marsh areas in China, indicating that the model prediction is stable and has spatial generalization ability.

Figure 4 shows the trend line chart of the POC sensitivity index for three typical salt marsh areas under variation in sea elevation magnitude. The average SIPOC of the eastern coastal low-lying salt marsh was 0.13 under the light sea elevation (0-10 cm/yr), 0.19 under the moderate sea elevation (10-15 cm/yr), and 0.28 under the high sea elevation (>15 cm/yr), showing a nonlinear enhancement trend. The average index under the corresponding scenario of central salt marsh was 0.09, 0.13 and 0.18. The average index of the inland high salt marsh area is 0.06, 0.09, 0.12, showing obvious spatial gradient. The line charts are also annotated with error margins (± standard deviation) for each scenario, which facilitates visual observation of response fluctuations in different regions. The trend in the figure shows that the coastal low-lying area is the most sensitive to the rising sea disturbance, while the inland high salt marsh area has a relatively stable response.

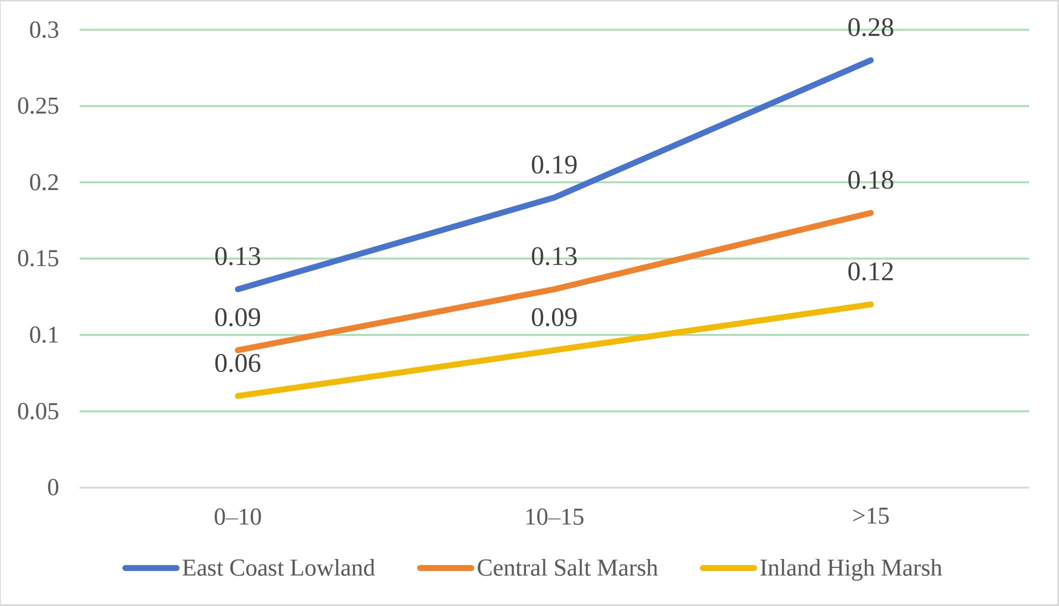

Figure 4: Average value of soil Particulate Organic Carbon Sensitivity Index (SIPOC) in coastal salt marsh area

At the same time, in order to quantitatively show the statistical characteristics of POC response in each region under sea rise scenario, Table 2 lists the average sensitivity index, maximum value, minimum value and standard deviation of different regions. The data show that the average sensitivity index of coastal low-lying salt marsh under extreme sea rise scenario is 0.28, the maximum value is 0.41, the minimum value is 0.15, and the standard deviation is 0.07, indicating that there is local vulnerability in this area. The mean index of the central salt marsh and the inland high salt marsh were 0.18 and 0.12, respectively, with a small range of extreme values, indicating significant spatial heterogeneity of the effect of sea rise on POC.

Table 2: Statistics of POC sensitivity indices in typical salt marsh areas

Region	Scenario (cm/yr)	Mean SI_POC	Max SI_POC	Min SI_POC	Std Dev
East Coast Lowland	0–10	0.13	0.20	0.06	0.04
East Coast Lowland	10–15	0.19	0.28	0.09	0.05
East Coast Lowland	>15	0.28	0.41	0.15	0.07
Central Salt Marsh	0–10	0.09	0.15	0.04	0.03
Central Salt Marsh	10–15	0.13	0.22	0.06	0.04
Central Salt Marsh	>15	0.18	0.30	0.09	0.05
Inland High Marsh	0–10	0.06	0.10	0.02	0.02
Inland High Marsh	10–15	0.09	0.16	0.03	0.03
Inland High Marsh	>15	0.12	0.22	0.06	0.04

In order to further show the trend of POC response, the data line chart in Figure 4 is independent of the table. The X-axis represents the sea rise amplitude (0-10, 10-15, >15 cm/yr), the Y-axis represents the average sensitivity index SIPOC, and the three broken lines represent the eastern coastal low-lying salt marsh, the central salt marsh and the inland high-lying salt marsh, respectively. The line chart showed that the amplitude of sea rise was positively correlated with the sensitivity of POC, and the sensitivity of coastal low-lying areas increased the most under extreme sea rise conditions, from 0.13 to 0.28, with an increase of 0.15. The central salt marsh increased by 0.09, and the inland high salt marsh increased by 0.06. The error bars in the line chart reflect the fluctuation range in each scenario and provide a visual basis for assessing the differences within the region.

Based on the analysis of Table 2 and Figure 4, it can be seen that the impact of sea rise amplitude on POC sensitivity presents obvious spatial and nonlinear characteristics: coastal low-lying salt marshes have the strongest response and the largest fluctuation, central salt marshes are in the middle, and inland high salt marshes have the slowest response. These results provide a scientific basis for the subsequent sensitivity comparison, identification of key driving factors and blue carbon management of coastal wetlands under different sea rise scenarios, and reflect the application value of computer spatial grid simulation and trend visualization in wetland ecological research.

4.2 Comparison of response characteristics of soil particulate organic carbon under different sea-level rise scenarios

Based on the absolute values and fluctuation ranges of the soil particulate organic carbon sensitivity index in different regions already given in 4.1, this section turns the analysis focus to the response differences between different sea level rise scenarios to avoid simple repetition of the mean, extreme value and dispersion degree. The results of rasterization calculation, scenario simulation output and regional grouping statistics showed that the response of soil particulate organic carbon to sea level rise was not uniform linear accumulation, but had a relatively clear stage progressive characteristics. Under the condition of mild sea rise, most of the sample areas could still maintain relatively stable particulate organic carbon state by sedimentary replenishment, vegetation root input and local elevation buffering. When the range of sea rise entered the moderate range, the increase of tidal flooding duration, the rise of pore water salinity and the reorganization of sedimentary environment began to act together, and the amplification response of particulate organic carbon to external disturbances gradually appeared. Under the background of high intensity sea elevation, this amplification effect is further enhanced, and the response gap between different regions is continuously widened.

From the regional comparison results, the eastern coastal low-lying salt marshes showed the most significant increase in scenario conversion. Taking the mild sea rise scenario as the benchmark, the average response is increased by 46% under moderate sea rise and 115% under high sea rise, which indicates that this type of region has a strong cumulative amplification effect on sea rise disturbance. The average increase of the central salt marsh was 44% and 100%, respectively, and the overall change direction was consistent with that of the coastal low-lying salt marsh, but the enhancement was slightly lower, indicating that it still retained some buffering capacity. The average increase of inland high salt marsh under moderate and high intensity sea elevation is 50% and 100% respectively, which is not low in relative proportion. However, due to the low absolute level of sensitivity under the baseline scenario, the overall response intensity is still significantly weaker than that of coastal low lying salt marsh even after entering the stage of high intensity sea elevation. This means that the comparison of different scenarios should not only be based on the proportion of increase, but also be judged by the absolute level of the baseline state, otherwise it is easy to overestimate the actual vulnerability of inland high salt marshes.

To more intuitively present the differences in regional responses under different sea-level rise scenarios, Table 3 lists the increases in the response of particulate organic carbon in three types of typical salt marsh regions relative to the baseline scenario. It can be seen from Table 3 that the eastern coastal low-lying salt marsh not only has the highest average increase, but also has the maximum response increase of 105% and the minimum increase of 150% under the high-intensity sea elevation scenario, indicating that the local units have shown strong instability under the background of extreme sea elevation. In contrast, the average increase of the central salt marsh under the same scenario is 100%, and the maximum and minimum increase are 100% and 105%, respectively. The change is relatively concentrated, indicating that although the region has entered the high response stage, the internal differences have not been fully amplified like the coastal low-lying salt marsh. The average increase of the inland high salt marsh also reached 100%, but because of its low initial sensitivity level, the response was closer to a sustained uplift than a rapid jump. Salt marshes under different geomorphologic locations, vegetation backgrounds and sedimentary conditions thus show a hierarchical scene response structure.

Table 3: Comparison of POC response increase in typical salt marsh areas under different sea-level rise scenarios

Region	Scenario	Mean Increase (%)	Max Increase (%)	Min Increase (%)
East Coast Lowland	10–15 cm/yr	46	40	50
East Coast Lowland	>15 cm/yr	115	105	150
Central Salt Marsh	10–15 cm/yr	44	47	50
Central Salt Marsh	>15 cm/yr	100	100	105
Inland High Marsh	10–15 cm/yr	50	60	50
Inland High Marsh	>15 cm/yr	100	110	95

In order to further summarize the stage differences of the response of particulate organic carbon under different sea-level rise scenarios, this paper summarized the response states, dominant environmental changes and regional performance under the three sea-level rise scenarios based on numerical comparison, as shown in Table 4. It can be seen that the mild sea rise corresponds to the relatively buffer stage, at this time, although the water and salt disturbance has occurred, the sedimentary supply and vegetation input can still maintain a local balance. The composition of moderate sea elevation changed from a gentle transition to a significant enhancement, and the salt marsh system began to show a response reconstruction dominated by water and salt conditions. The coastal low-lying salt marshes entered a state of high sensitivity, and the response of the central salt marsh was significantly enhanced. Although the inland salt marsh still maintained a low absolute level, its rising trend could not be ignored. Such a phase division not only strengthens the logic of scenario comparison, but also helps to reconnect numerical changes with ecological processes.

Table 4: Summary of soil particulate organic carbon response characteristics under different sea-level rise scenarios

Sea-level rise scenario	Response intensity of POC	Main environmental changes	Regional response characteristics
0–10 cm/yr	Low to moderate	Slight increase in inundation frequency; sediment supply and vegetation input still maintain partial balance	East Coast Lowland already shows initial sensitivity; Central Salt Marsh remains relatively stable; Inland High Marsh changes slowly
10–15 cm/yr	Moderate	Flooding duration increases; pore-water salinity rises; sedimentary environment begins to reorganize	East Coast Lowland shows accelerated increase; Central Salt Marsh enters obvious response interval; Inland High Marsh starts to show cumulative change
>15 cm/yr	High	Water–salt stress strengthens; sediment fluctuation intensifies; vegetation input stability declines	East Coast Lowland enters high-sensitivity state; Central Salt Marsh shows clear enhancement; Inland High Marsh continues to rise but remains weaker than coastal lowland

Combined with Table 3 and Table 4, it can be concluded that the impact of sea level rise on soil particulate organic carbon in coastal salt marsh wetland has a distinct scenario dependence and regional differentiation. Moderate sea rise is the key interval from gentle maintenance to obvious enhancement of response, while high sea rise will significantly amplify the original ecological differences between different regions. The coastal low-lying salt marsh showed the highest sensitivity due to its low elevation, strong direct tidal effect, and more active lateral material exchange. Although the central salt marsh also showed a significant increase in response, sedimentation and vegetation cover still delayed the rapid fluctuation of particulate organic carbon to a certain extent. The inland high salt marsh showed a continuous increase in response but a relatively gentle slope. It can be seen that the scale of static carbon pool cannot fully reflect the real vulnerability degree of salt marsh system under the background of sea rise, and it is still necessary to combine computer scenario simulation and dynamic response analysis to identify and assess different types of salt marsh more specifically.

4.3 Discussion

The sensitivity model of multi-source data fusion and ensemble learning constructed in this study shows significant advantages in quantitatively characterizing the response of soil particulate organic carbon (POC) to sea level rise in coastal salt marsh wetlands. Compared with the traditional single factor statistical analysis or static process model, the proposed model can simultaneously deal with the nonlinear coupling relationship of multi-dimensional variables such as elevation, flooding frequency, pore water salinity, deposition rate, vegetation index and soil particle size, and accurately simulate the spatial and scenario dependence of POC response. In the typical salt marsh area, the average RMSE of the model prediction is 0.015, the MAE is 0.012, and the R^2 reaches 0.88, showing strong fitting ability and generalization performance, indicating that the method combining ensemble learning and feature selection can effectively capture the complex mechanism of environmental factors on POC change.

Based on SHAP feature contribution analysis, this study revealed clear spatial heterogeneity in the dominant drivers of POC response in different regions. In the coastal low-lying salt marsh area, the POC sensitivity index SIPOC is significantly nonlinear enhanced under the light to high intensity sea rise scenario, which is mainly regulated by the positive regulation of flooding frequency and sedimentation rate. In the central salt marsh area, the POC response was moderately enhanced due to the influence of both pore water salinity and vegetation index. The inland high salt marsh area has the smallest variation in POC, showing relative stability to rising sea disturbances. The analysis shows that the POC sensitivity of different regions is not only related to the absolute surface elevation, but also regulated by the dynamic coupling between sedimentation and vegetation productivity, which reflects the complex feedback characteristics of coastal salt marsh ecological processes at spatial scales. Furthermore, the model results show that the average increase of POC of coastal low-lying salt marshes can reach 115% under the extreme sea rise scenario, while that of central salt marshes and inland high salt marshes are 100% and 100%, respectively, highlighting the local vulnerability of coastal low-lying areas. This nonlinear enhancement trend indicated that there was a threshold effect of POC accumulation under sea rising disturbance, and the positive contribution of sediment input and vegetation biomass to soil particulate carbon began to accelerate and increase when the flooding pressure index Di exceeded a certain critical value. Combined with computer spatial grid simulation, the spatial distribution characteristics of POC response in different sea rise amplitudes and regions can be clearly presented, which provides a quantitative basis for identifying high-risk sensitive areas.

In terms of factor contribution, SHAP analysis showed that flooding frequency Ft and deposition rate Sr had the largest marginal contribution to POC sensitivity, and their increase could significantly enhance POC accumulation. The pore water salinity St plays a major regulatory role in the central salt marsh, while the vegetation index Vi has a relatively prominent contribution in the inland high salt marsh. This result suggests that wetland management and blue carbon protection strategies should be regulated differently according to the regional dominant driving factors. For example, for coastal low-lying salt marshes, we should focus on water level regulation and sediment deposition management to alleviate carbon pool fluctuations caused by extreme sea rise. For the central salt marsh, vegetation restoration and water-salt collaborative management will be more conducive to maintaining the stability of POC. The inland high salt marsh can achieve the maintenance of microenvironmental carbon homeostasis by optimizing soil physical and chemical conditions and root biomass input. At the same time, the model also reveals the possible synergy or hedging effect between environmental factors. For example, the synergy of high flooding frequency and high deposition rate significantly enhances POC accumulation, while local salinity elevation may counteract the positive effect of deposition input on carbon storage in some scenarios. This finding further indicates that the POC response mechanism of coastal salt marsh wetland is complex, and it is difficult for single factor regulation to fully explain soil carbon dynamics, so it is necessary to combine multi-factor comprehensive regulation strategy in management practice.

Overall, this study achieves a complete path from quantitative simulation to factor analysis of POC sensitivity under sea level rise scenarios through ensemble learning modeling with SHAP interpretable analysis. The results not only verified the effectiveness of the coupling modeling of multi-source environmental variables in the analysis of wetland carbon process, but also provided a scientific basis for the blue carbon management of coastal wetlands, which could support the formulation of differentiated protection measures and the implementation of digital monitoring and management.

5 Conclusion

Based on multi-source environmental data fusion, GIS spatial grid analysis and ensemble learning sensitivity model, this paper systematically revealed the response characteristics and main control factors of soil particulate organic carbon (POC) in coastal salt marsh wetlands under different sea level rise scenarios. The results show that POC of coastal low-lying salt marsh is the most sensitive to the disturbance of rising sea, showing a significant nonlinear enhancement trend. The response of the central salt marsh was moderate, and the inland high salt marsh was relatively stable, reflecting the spatial heterogeneity and regional vulnerability differences of coastal wetlands. Through SHAP feature contribution analysis, this study identified flooding frequency, deposition rate, pore water salinity and vegetation index as the key drivers of POC change, and their direction and strength were significantly different in different regions and sea rise amplitudes, indicating possible synergistic or hedging effects among environmental factors. This finding provides a quantitative basis for the identification of high-risk sensitive areas and blue carbon management in coastal wetlands. The model shows good stability and generalization ability in the process of training and prediction, and the prediction R^2 of typical salt marsh area reaches 0.88, RMSE and MAE are 0.015 and 0.012, respectively, indicating that the ensemble learning method can effectively capture the nonlinear coupling relationship of environmental variables, and provide a reliable technical path for the quantification of coastal salt marsh POC sensitivity. At the same time, computer simulation combined with spatial rasterization visualization realizes the intuitive presentation of POC response trends and regional differences, which provides operational reference for wetland management and ecological restoration.

However, there are still some limitations in the research. Firstly, the model input is limited by the existing environmental monitoring data and available variables, and some short-term extreme sea rise events and complex ecological disturbances are not fully covered. Secondly, the heterogeneity of multi-source data in spatial and temporal scales may affect the local prediction accuracy. In addition, external drivers such as socioeconomic factors, policy interventions, and human activities have not been incorporated into the model, limiting the ability to explain the global ecological response. Future research can improve the adaptability of the model to extreme events and nonlinear changes by adding high-frequency monitoring data, expanding socio-economic variables, and introducing coupled hydrodynamic-ecological models. At the same time, more efficient calculation strategies or model compression methods can be explored to balance the prediction accuracy and computational cost, and provide operational scientific support for wetland carbon dynamic management.

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