# Changes of Soil Organic Carbon Stabilization and Stock in Yancheng Huang-Bohai Sea Migratory Bird Habitat Coastal Marsh Wetland with a Long-term Follow-up Study

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In the important coastal marsh wetland ecosystem, the soil organic carbon content is subject to multiple environmental factors in Yancheng. The research objectives were to explore the effects of sampling time, soil depth, and vegetation types on soil organic carbon content by screening the core data of related literature and analyzing with the descriptive statistics, Kendall's consistency test, Spearman's Rank correlation, and principal component analysis (PCA). The analysis showed that the effects of the factors on soil organic carbon content were significantly different. The plant growth was vigorous, resulting in relatively high soil organic carbon content (80 to 50 t/ha·yr), especially in the spring and summer seasons. In addition, the organic carbon content of the topsoil (0 to 20 cm) was significantly higher than that of the soil at depths below 20 cm, showing higher levels (20 to 50 t/ha·yr). Among different vegetation types, the carbon storage capacity of *Spartina alterniflora* showed superior performance compared to other vegetation (10 to 25 t/ha·yr). The results provide a scientific basis for the assessment and protection of the carbon storage function of wetlands, intending to promote the sustainable management of wetland ecosystems.

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## INTRODUCTION

Coastal marsh wetlands, as a key component of wetland ecosystems, are highly valued for their remarkable capacity for carbon storage and deposition (Davidson *et al.* 2018). The wetlands not only constitute an important part of the global carbon sink but also play a crucial role in reducing greenhouse gas emissions by protecting and enhancing carbon storage functions (Duarte *et al.* 2013; Hopkinson *et al.* 2019). The soil organic carbon stocks in coastal marsh wetlands are crucial for a deeper understanding of the region's role in the global carbon cycle, especially in Yancheng City, Jiangsu Province, on the eastern coast of China (Ke *et al.* 2011). In the face of global climate change and intensified human activities, the carbon storage function of these wetlands faces several challenges (Guo *et al.* 2021). The assessment and protection of carbon stocks in these wetlands are of great scientific and practical significance for mitigating the increase of greenhouse gas concentrations and addressing climate change. Against the backdrop of China's "carbon peak" and "carbon neutral" targets, the role of coastal marsh wetlands in carbon storage and deposition is critical and has become an important ecological support for the realization of these ambitious targets (Barbier 2019; Wei *et al.* 2022).

Soil organic carbon, as the sum of carbon-containing organic matter in the soil, including humus, plant, and animal residues, and microbial bodies, has a profound impact on soil fertility and the Earth's carbon cycle (Blanco-Canqui *et al.* 2013; Stockmann *et al.* 2015). Coastal marsh wetlands are capable of storing carbon stably over a long period due to their strong carbon sink function (Shepard *et al.* 2011). Compared with terrestrial ecosystems, the decomposition process of plant residues in coastal marsh wetlands is significantly slowed down by the influence of seawater tides after they are deposited into the soil (Day *et al.* 2024). Sea level rise cause these sediments to be buried in deeper layers of soil, further impeding the degradation of organic matter, allowing carbon to remain stable over time scales of hundreds to thousands of years, and reducing carbon emissions to the atmosphere (Morris *et al.* 2002). The carbon sequesters in these wetlands and seagrass beds ecosystems, which has been called "blue carbon" in the coastal zone, plays an indispensable role in the global carbon cycle and climate change response strategies (Macreadie *et al.* 2019; Feng *et al.* 2023). The soil organic carbon means the carbonaceous material in the soil solid phase, including humus, decomposition products of plant and animal residues, and microbial bodies, and excludes the carbon in the aboveground portion of the living plant. In general, plant residue contents are the main source of soil organic carbon.

To gain an in-depth understanding of the factors affecting soil organic carbon content in coastal marsh wetlands, this study analyzes the three core variables of sampling time, soil depth, and vegetation type from multiple perspectives by systematically integrating and analyzing key data from related literature, using analysis software. The descriptive statistics, Kendall's consistency test, Spearman's Rank Correlation analysis, and principal component analysis are used to delve into how these factors specifically affected soil organic carbon content. These comprehensive analyses provide a solid theoretical foundation and empirical support for the scientific assessment and effective protection of wetland carbon storage functions and further strengthen the key role of coastal marsh wetlands in the global carbon cycle and climate change response strategies.

## EXPERIMENTAL

### Overview of the Study Area

The Yancheng Coastal Marsh Wetland, located on the eastern coast of Jiangsu Province, is a key area in the study of coastal marsh wetland ecosystems in China (Fig. 1). The north-south boundary of this wetland extends roughly from the mouth of the Irrigation River to the mouth of the Fangtang River, with geographic coordinates covering (32°38'28.5"N-34°32'32.2"N, 119°46'56.5"E-121°6'31"E). As a core area for the development of the Yellow River delta and the offshore radial sand ridges in the north of Jiangsu Province, the Yancheng Coastal Marsh Wetland is not only a key component of the ecosystem but also highly regarded for its unique conservation value (Xu *et al.* 2017; Chen *et al.* 2022). It is an important part of the Elk National Nature Reserve and the Rare Birds National Nature Reserve, and its rich biodiversity makes it a treasure trove of ecological habitats. In the coastal marsh wetland of Yancheng, the vegetation mainly consists of three communities: the *Spartina alterniflora* community, the *Suaeda salsa* community, and the

*Phragmites australis* community. The *Spartina alterniflora* is the most dominant plant. It dominates the wetland with its rapid growth and reproduction ability and plays a key role in carbon storage and deposition (Zhang *et al.* 2020). *Phragmites australis* is a perennial herb with a well-developed root system that usually formed a transition zone with *Spartina alterniflora*. The biomass of *Phragmites australis* is significantly affected by fluctuations in hydrological conditions, resulting in the carbon storage showing high spatial heterogeneity. The *Suaeda salsa* is a saline plant with relatively low photosynthetic efficiency. It is mainly distributed in the middle and upper regions of the intertidal zone. The carbon storage mainly relies on biological residues and is less stable. The region has a typical subtropical monsoon climate, with average annual precipitation ranging from 1000 to 1600 mm, and average annual temperature of about 15 °C, and a range of temperature variation from -10 °C to 38 °C. The climate of the region is typical of a subtropical monsoon climate. Such climatic conditions not only provide a suitable environment for plant growth in coastal wetlands, but also have a significant impact on the storage characteristics of soil organic carbon. The water table in the area is significantly affected by tidal action, with an average depth of about 0.5 to 1.2 meters. During the rainy season, the rising water table has led to short-term waterlogging, which in turn has affected soil aeration and organic carbon decomposition processes. In terms of vegetation biomass, the aboveground biomass of the mutualistic *Spartina alterniflora* community reached 10 to 15 t/ha, which is significantly higher than that of *Phragmites australis* (5 to 8 t/ha) and *Suaeda salsa* (2 to 4 t/ha), providing a rich source of inputs for soil organic carbon.

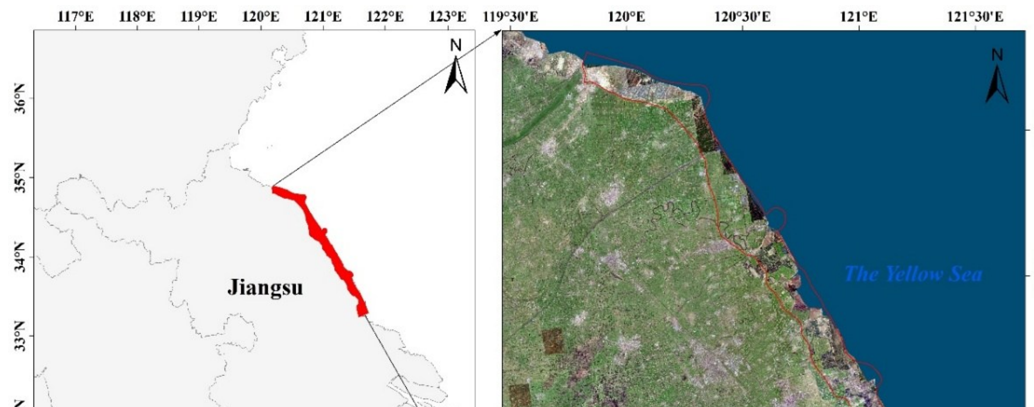


**Fig. 1.** Geographic location map

## Data Collection and Organization

In order to deeply investigate the soil organic carbon content of coastal marsh wetlands in Yancheng, this study collected more than 50 research papers related to coastal wetlands and soil organic carbon in Yancheng through extensive literature research with "Yancheng" and "organic carbon" as the core keywords in the CNKI database (Table A1). To ensure the accuracy and relevance of the data, the authors excluded those data with missing values or not closely related to the research topic. After careful screening and organization, 1694 valid data were obtained, which covered key information such as publication date, sampling time, sampling location, ecological characteristics, and vegetation types involved in the study. The data ranged from 2009 to 2024. Within this range, 2015 to 2020 was the peak period of published literature, accounting for 58% of the total. The spatial extent of the study covered the north-south coastal zone of Yancheng wetland with a length of about 200 kilometers, including core protection areas (*e.g.*, Dafeng Elk Reserve) and development and utilization zones (*e.g.*, Sheyang estuary), which ensured that the samples had a good regional representativeness. In terms of vegetation type distribution, *Spartina alterniflora* accounted for 29%, *Phragmites australis* for 18%, *Suaeda salsa* for 14%, other vegetation for 33%, and mudflat for 6% (without plants). In terms of soil depth stratification, 62% of the surface soil from 0 to 20 cm, 25% of the middle soil from 20 to 40 cm, and 13% of the deep soil were greater than 40 cm, which was consistent with the characteristics of a wetland dominated by surface carbon.

## Data Analysis

Several commonly used analytical methods in statistical software (SPSS 19.0, SPSS Institute, Chicago, IL, USA) were used to perform a series of analyses, including Kendall's consistency test, Spearman’s correlation analysis, and principal component analysis.

Kendall’s consistency test was used to assess the consistency and correlation between multiple observations, *i.e.*, sampling time, vegetation type, and soil depth (Hühn and Piepho 1994). This method was typically applied to determine the consistency of multiple reviewers or multiple variables (factors) in ranking a series of objects. Kendall’s W (*i.e.*, Kendall’s Coefficient of Consistency) is a core statistic that measures the consistency of multiple rankings and was used to determine the degree of consistency of multiple evaluators’ rankings of the same set of objects. Its value ranges from 0 to 1. The closer the W value is to 1, the higher the consistency of the rankings; the closer it was to 0, the lower the consistency. The Kendall's W coefficient was calculated using Eq. 1,

$$W = \frac{12\sum_{i=1}^{n}(R_i - \bar{R})^2}{n^2(m^3 - m)} \tag{1}$$

where $n$ denoted the number of indicators, $m$ denoted the number of samples, $R_i$ denoted the sum of the rankings of the reviewer, and $\bar{R}$ denoted the average of the sum of the rankings of all samples.

Spearman’s Rank Correlation is a statistical method used to measure the existence of a monotonic relationship between two variables, *i.e.*, a measure of whether one variable increases or decreases as the other increases or decreases, which is not necessarily a linear relationship (Sedgwick 2014). It is based on the rank order (rank) of the two variables and does not require the data to conform to a normal distribution. It is therefore suitable for measuring the correlation of non-normally distributed variables or ordered categorical data. The Spearman's rank correlation coefficient p was calculated using Eq. 2,

$$p = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)} \tag{2}$$

where $d_i = R(x_i) - R(y_i)$ is the difference in rank of the ith data point (*i.e.*, the difference between $x_i$'s rank and $y_i$'s rank), $n$ was the sample size, *i.e.*, the number of data points, and $R(x_i)R(y_i)$ denoted the rank of xi and yi, respectively.

Principal component analysis revealed the key structures in a dataset by demonstrating the loading coefficients and commonalities of the variables on the extracted principal components, *i.e.*, the variance of the common factors, providing an important basis for understanding the main trends in the sample data (Greenacre *et al.* 2022). When making a principal component analysis for sample data, it is necessary to first construct the covariance matrix of the data, which describes the linear relationship between different features in the data. Through analyzing the covariance matrix, the main direction of change in the data was identified. Then the principal components were extracted that represent most of the information in the data set. The formula for the covariance matrix is given in Eq. 3,

$$\sum = \frac{1}{n-1}\bar{X}^T\bar{X} \tag{3}$$

where $X$ denotes the matrix and $n$ denoted $n$ samples. The eigenvectors with the largest eigenvalues were selected as the principal components because they corresponded to the largest variance and explained the largest variation in the data. Through sorting the eigenvalues, the eigenvectors corresponding to the top $k$ largest eigenvalues were selected as the new principal components. The original data was projected into the new principal component space to obtain the dimensionality-reduced data, thus Eq. 4,

$$\mathrm{Y} = \bar{\mathrm{X}}\mathrm{V}_\mathrm{k} \tag{4}$$

where $\mathrm{V}_\mathrm{k}$ denoted the largest eigenvector, Y was the dimensionally reduced data matrix, where each column represented a principal component, the dimension of the reduced dataset was usually lower than that of the original dataset, which reduced the dimensionality and retained most of the variance information.

These methods were effective in assessing the effects of different time points, different vegetation types, and different soil depths on soil organic carbon content. Among them, Kendall’s consistency test was mainly used to assess the correlation and consistency of the data between different time points; Spearman’s rank correlation analysis was used to explore the relationship between soil depth, vegetation type, and organic carbon content; and principal component analysis was used to extract the most critical factors from multiple variables by dimensionality reduction, to reveal the main drivers affecting the organic carbon content of soil. To further analyze the influence of different vegetation types, the Excel pivot tables were used to organize the collected literature data and counted the frequency of studies on the main vegetation types in the coastal marsh area of Yancheng. These vegetation types mainly included *Spartina alterniflora*, *Phragmites australis*, *Suaeda salsa*, and other vegetation. After organizing and analyzing the data, the authors were able to make a comprehensive assessment of the soil depth of the samples and the selection of vegetation types and then gained a deeper understanding of how these factors worked together to change the soil's organic carbon content.

## RESULTS

### Descriptive Statistical Analysis

Through analyzing the descriptive statistics in Table 1, the key statistical indicators of several variables included the maximum value, minimum value, mean value, and standard deviation. Quantitative analysis of these statistical values revealed that there were 35 different sampling depths for the selection of soil depth, of which the depth of 0 to 20 cm had been studied most frequently, indicating that most researchers tended to focus on the organic carbon content of the surface soil (0 to 20 cm) in the study of coastal marsh wetlands in Yancheng. The kurtosis value of the data was 22.71, which was much higher than the expected kurtosis value of 3 for a normal distribution, indicating that the data distribution was sharper and had more extreme values than a normal distribution. The minimum value of 2 corresponded to soil depths from 0 to 5 cm, suggesting that only a few studies had dealt with very shallow soils. The standard deviation of soil depth was 103.92 cm. This was much higher than the mean value of 49.89 cm, which showed the wide range and high variability in soil depth selection by the researchers, implying that the sampling depths of many studies deviated considerably from the mean value and that there might be some extreme values. The coefficient of variation was as high as 2.083, which was far more than 1, indicating that the data of soil depth studies were highly variable, probably due to the different focuses. Some studies focused on carbon storage in surface sediments, while others studied carbon storage in soils with different vegetation root systems, resulting in a large difference in the selection of soil depths, which led to large coefficients of variation and variances in the statistical results. This high degree of variability suggested that the possible effects of depth selection in different studies needed to be considered when analyzing soil organic carbon content.

From the results of descriptive statistics, the research data of *Spartina alterniflora* showed significant variability, with the standard deviation (30.82) far exceeding the mean (12.35), suggesting that scholars had taken a diverse approach to studying this species. In particular, the large ratio of the standard deviation to the mean indicated significant diversity. For example, some researchers classified *Spartina alterniflora* according to the year to explore the community characteristics in different years, while others classified it according to the plant height, subdividing the same species into different research subjects. The coefficient of variation was as high as 2.497, further confirming the diversity of research methods. The skewness was 3.672, showing that the data were significantly right-skewed, implying that the study of *Spartina alterniflora* was more detailed in its classification. The kurtosis was 13.58, far exceeding the expected value of 3 for a normal distribution, showing that the distribution of this data showed a higher peak value and uneven distribution pattern, reflecting the discrete and skewed distribution of the study selection and species classification.

**Table 1.** Results of Descriptive Statistical Analysis

| Variable | Sample Size | Max | Min | Average | SD | Median | Variance | Kurtosis | Skewness | CV |
|---|---|---|---|---|---|---|---|---|---|---|
| soil depth | 35 | 591 | 2 | 49.89 | 103.92 | 19 | 10798.34 | 22.71 | 4.482 | 2.083 |
| *Spartina alterniflora* | 29 | 144 | 1 | 12.35 | 30.82 | 2 | 949.88 | 13.58 | 3.672 | 2.497 |
| *Phragmites australis* | 10 | 144 | 2 | 27.20 | 46.66 | 5 | 2177.29 | 4.56 | 2.212 | 1.715 |
| *Suaeda salsa* | 14 | 144 | 1 | 19.21 | 38.82 | 3 | 1507.10 | 19.31 | 2.956 | 2.020 |
| mudflat | 3 | 187 | 1 | 63.00 | 107.39 | 1 | 11532.00 | - | 1.732 | 1.705 |
| Others | 58 | 26 | 1 | 11.52 | 11.24 | 5 | 136.36 | -1.72 | 0.475 | 0.976 |

Note: The unit of measure for all variables was the frequency of the study. The max/min referred to the division based on the depth of the soil layer. The median, average, standard deviation and variance of the data for the same soil depth in the sample were further calculated on this basis. Kurtosis is used to characterize the steepness or flatness of the data distribution, reflecting the sharpness or flatness of the data distribution. Skewness is a measure of the symmetry of the data distribution, which is used to determine whether the data distribution is symmetrical and its direction of symmetry. The coefficient of variation (CV) is the ratio of the standard deviation to the mean, which is used to measure the relative dispersion of the data. It is particularly suitable for comparing different data sets with large differences in mean values. SD: standard deviation; CV: Coefficient of variation.

Similar to *Spartina alterniflora*, the study data for *Phragmites australis*, *Suaeda salsa*, and mudflat showed some variability. The standard deviation of the *Phragmites australis* (46.66) was significantly higher than its mean (27.20) and the variance (2177.29) was larger, indicating a significant difference in study selection for *Phragmites australis*. The coefficient of variation was 1.715 showing high dispersion. The skewness was 2.212, indicating that the data were right-skewed, suggesting that the study of *Phragmites australis* was more concentrated in a small number of samples. The kurtosis was 4.56, indicating that there were more extremes in the data set, *i.e.*, outliers than would have been expected from a normal distribution. This might have been because studies of *Phragmites australis* were often not conducted alone and mixed with vegetation, such as recommended grasses and *Suaeda salsa*, or focused on their interspersed areas with *Spartina alterniflora* and *Suaeda salsa*. The diversity of studies on *Suaeda salsa* was relatively low, with a variance of 1507.10 and a coefficient of variation of 2.020, indicating that most of the studies focused on *Suaeda salsa* wetlands, while a few focused on the fringing zones of *Suaeda salsa* with other vegetation or the fringing zones of *Suaeda salsa* communities. The standard deviation (107.39) and variance (11,532) of the mudflat showed some dispersion, with a higher standard deviation compared to the mean (63), suggesting fluctuations in the mudflat studies. The coefficient of variation was 1.705, which indicated that the relative variability of the data was high, the volatility or instability of the data was large compared to its mean value, and the data was more discrete. The research division of the mudflat also showed significant characteristics of the differences, because most of the scholars did not focus on a certain type of research, but rather, combined it with the transition zones of other vegetation to synthesize the research. Therefore, the studies on mudflats were also characterized by a certain degree of diversity.

The studies of the other vegetation types showed less variability compared to the *Spartina alterniflora*, *Phragmites australis*, *Suaeda salsa*, and mudflat. Specifically, the standard deviation (11.24) for these vegetation types was significantly lower than the mean (11.52), suggested that the study data were relatively concentrated and the variability was limited. Compared to other variables such as soil depth and *Spartina alterniflora*, these vegetation types showed less variability in the study and a smoother trend. The coefficient of variation was 0.976, which was close to 1, and indicated that the studies for the other vegetation types were selected relatively more homogeneously with little variation. The skewness was 0.475, which indicated that the data were skewed to the right, *i.e.*, the number of classifications and selections against other vegetation was high in most samples, and only a few samples had lower numbers. The kurtosis of -1.719 was low, indicating that the peaks of the data distribution were less pronounced, with the data more concentrated around the mean and with fewer extreme values away from the mean. These statistical features pointed out that in the study of coastal marsh wetlands in Yancheng, the research on these other vegetation types was relatively concentrated and had a more balanced distribution in the study, with no extremely high or low values, reflecting the consistency and stability of the researchers on these vegetation types.

## Kendall's Consistency Test Analysis

The results of Kendall's consistency test analysis are shown in Table 2, in which Kendall's W coefficient is a key indicator for assessing the consistency among variables. The analysis found that the sampling time, vegetation type, and soil depth of the coastal marsh wetland in Yancheng had a significant effect on soil organic carbon content, but the consistency between these variables was not high (the Kendall's W value was generally low, close to 0.08), implying a weak correlation between them. This low consistency might be due to fluctuations between the data due to factors, such as ecological diversity and climate change. In particular, the low consistency of the effect of sampling time on soil organic carbon content (Kendall's W value of 0.08) suggested that the time factor had a limited effect on the results of the study, but some degree of variability still was observed in data collection across years. The p-values for all variables were less than 0.05, which indicated that the statistical results were significant enough to reject the original hypothesis, thus confirming that there was indeed a correlation between the different factors and soil organic carbon content.

**Table 2.** Results of Kendall's W Analysis Between Sampling Time, Vegetation Type, and Soil Depth

| Name | Rank Average | Median | Kendall's W Ratio | $X^2$ | P |
|---|---|---|---|---|---|
| Sampling time | 1.785 | 7.0 | 0.08 | 15.97 | 0.001*** |
| Vegetation type | 2.305 | 8.5 | 0.07 | 14.82 | |
| Soil depth | 1.910 | 9.0 | 0.09 | 16.35 | |

***, **, * represent 1%, 5%, and 10% significance levels, respectively

## Spearman's Rank Correlation Analysis

After analyzing the results, the table of parameter results of the model test was obtained, as shown in Table 3, which demonstrated the correlation coefficient, and the p-value level of significance. Meanwhile, to observe the correlation more intuitively, the correlation was plotted using the Origin software as shown in Fig. 2.

**Table 3.** Spearman's Rank Correlation Coefficient Between Sampling Time, Vegetation Type, and Soil Depth

| Name | Sampling Time | Vegetation Type | Soil Depth |
|---|---|---|---|
| Sampling Time | 1(0.000***) | -0.232(0.020**) | 0.941(0.000***) |
| Vegetation Type | -0.232(0.020**) | 1(0.000***) | -0.257(0.010***) |
| Soil Depth | 0.941(0.000***) | -0.257(0.010***) | 1(0.000***) |

***, **, * represent 1%, 5%, and 10% significance levels, respectively.

The results of Spearman's Rank Correlation analysis showed that when the p-value was less than 0.05, it indicated that the correlation between the two variables was statistically significant. Specifically, if the correlation coefficient was close to "+1", there was a strong positive correlation between the two variables; while if the correlation coefficient was close to "-1", there was a strong negative correlation between the two variables. In Table 3, Spearman's Rank Correlation coefficient between sampling time and vegetation type was -0.232, with a p-value of 0.020, which was lower than the significance level of 5%, indicating that there was a weak negative correlation between the two. The multiple ecological factors indirectly influenced relationship among them. Changes of the vegetation types were regulated by multidimensional factors in the ecosystem. Among the differences in the adaptive range of temperature, seasonal distribution, and inter-annual variations in precipitation, as well as variations in the intensity and duration of light had a significant impact on the distribution of vegetation. The interactions between vegetation's biology (*e.g.*, reproductive strategies and life-history cycles) and environmental factors further exacerbated the complexity of this process (Miller *et al.* 2012). The Spearman's Rank Correlation coefficient between sampling time and soil depth was 0.941 with a p-value of 0.000, which was well below the 1% significance level, showing a significant positive correlation. This suggested that the soil depth tended to show a more consistent increasing trend as the sampling time increased. The sampling depth tended to progressively deepen with time-lapsed research and monitoring strategies during long-term monitoring and sampling. The Spearman's Rank Correlation coefficient between vegetation type and soil layer depth was -0.257 with a p-value of 0.010, which was below the 5% significance level, indicating a significant negative correlation. This indicated that with the increase of soil depth, the studied vegetation types changed, and the study of the same vegetation types at different depths produced different experimental results, *i.e.*, the vegetation types were affected by the depth of the soil, and there was a significant difference in the effect of different depths of soil on different vegetation types.

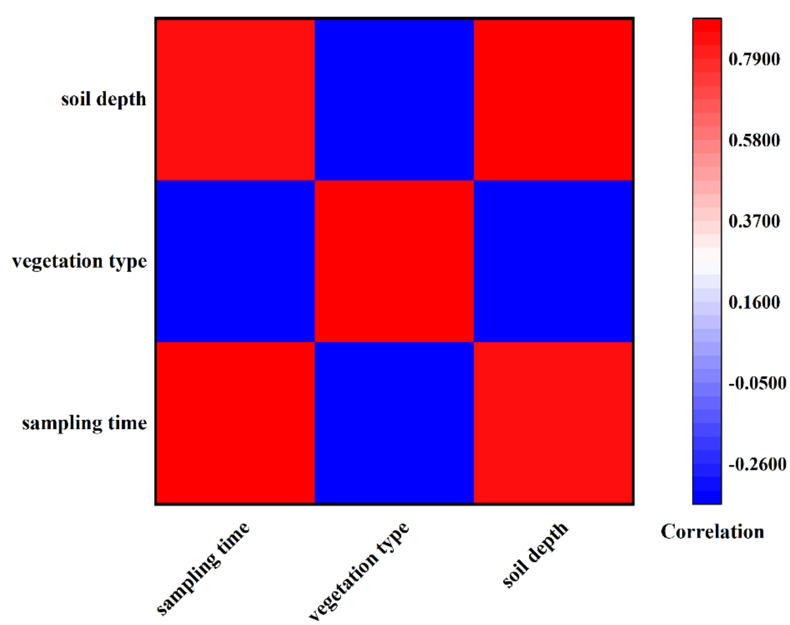


**Fig. 2.** Spearman's Rank Correlation coefficient plot between sampling time, vegetation type, and soil depth

From the statistical results, although the correlation was low (correlation coefficient of -0.232), the p-value of 0.020 indicated that the relationship was statistically significant, which was attributed to some seasonal changes or inter-annual changes over time, resulting in some transformation of the same vegetation in the wetland ecosystem. In addition, the continuation of time also brought about different research concerns or objects of study, so the vegetation types changed in different years of sampling. The significant positive correlation between sampling time and soil depth suggested that the deeper soils were used as the study progressed, or long-term soil monitoring programs were more likely to collect data on deeper soils. Thus, deeper soils were typically sampled as the study duration increased. The low negative correlation between vegetation type and soil depth, although the low correlation was also statistically significant with a p-value of 0.010, suggested that different vegetation types were adapted to soils at different depths. Specifically, plant types in shallow soils differed from those in deeper soils, and vegetation types changed accordingly with soil depth (Chen and D'Arcy 2016). The dependence of plants on soil depth was particularly pronounced in wetland ecosystems, suggesting that soil depth had a significant effect on the distribution of vegetation types (Dusza *et al.* 2017).

## Principal Component Analysis (PCA)

The Factor Loading Matrix and Scree Plot with Principal component analysis results were obtained as shown in Table 4 and Fig. 3, respectively. Specifically, the first extracted principal components in the principal component analysis significantly reflected the information on vegetation types and their related ecological factors. In terms of factor loading coefficients, *Spartina alterniflora* (0.939), *Phragmites australis* (0.798), mudflat (0.768), and other vegetation (0.987) formed a tight clustering. These items were synergistic in terms of their carbon storage characteristics, and consistent with the ecological process in which high biomass input from *Spartina alterniflora* and *Phragmites australis* and tidal deposition from the mudflat together contributed to surface carbon accumulation. The *Suaeda salsa* (-0.947) was significantly separated from the other vegetation, suggesting a competitive or substitutive relationship between the carbon storage pattern and the dominant vegetation. The *Suaeda salsa* was mostly distributed in the dry area of the upper intertidal zone, where the annual biomass residue decomposed rapidly and had low carbon stability, which contrasted with the perennial high carbon inputs of *Spartina alterniflora*. The soil depth (0.188) made a negligible contribution to the principal component, confirmed that vegetation type was the dominant factor in carbon storage. The deep soil carbon stocks were mainly influenced by long-term deposition and decomposition equilibrium, which had relatively little variation.

**Table 4.** Factor Loading Matrix

| Variable Name | Principal Component Factor Loading Coefficients | Commonality |
|---|---|---|
| Soil depth | 0.188 | 0.036 |
| Spartina alterniflora | 0.939 | 0.881 |
| *Phragmites australis* | 0.798 | 0.638 |
| Mudflat | 0.768 | 0.589 |
| *Suaeda salsa* | -0.947 | 0.896 |
| Other Vegetations | 0.987 | 0.974 |

In terms of commonality (variance of the common factor), the commonality of *Spartina alterniflora*, *Phragmites australis*, mudflat, *Suaeda salsa*, and other vegetation were all relatively high, 0.881, 0.638, 0.589, 0.896, and 0.974, respectively, indicating that these variables were better retained in the principal components and were the key part of the composition of the principal components. For the selection of different depths of soil layers, on the other hand, the loading coefficient on the principal component was low (0.188) and the commonality was small (0.036), indicating that the depth of soil layers did not contribute much to the principal component, and was not the main factor influencing this principal component. These results revealed the complex interactions between vegetation types and ecological factors and pointed to variables that should be emphasized in ecological studies.

The invasion of *Spartina alterniflora* significantly expanded the vegetation cover of the intertidal zone in the positive correlation clustering (*Spartina alterniflora* - *Phragmites australis* - mudflat). The dense root system and *Phragmites australis* enhanced the water-holding capacity of the soil, thus slowing down the decomposition of organic matter. Though the vegetation cover on the mudflat was absent, the suspended organic matter from the tides was deposited in the vegetative root zone, indirectly contributing to carbon storage. The synergistic effect led to the formation of a "high carbon storage community" in the principal component space. The negative segregation of the *Suaeda salsa* resulted in a community with significantly lower soil organic carbon content than *Spartina alterniflora*. The distribution area of the *Suaeda salsa* was often reduced by the expansion of *Spartina alterniflora*, resulting in a vegetation substitution effect. The results of the principal component analysis revealed this ecological niche competition, *i.e.*, *Suaeda salsa* was suppressed by dominant vegetation in the carbon storage function. There was high carbon content of the topsoil (0 to 20 cm), but there was no significant association between the soil depth variable and vegetation type. The carbon input patterns of vegetation (e.g., depth of root distribution, type of detritus) explained more of the differences in carbon storage than the soil horizons themselves.

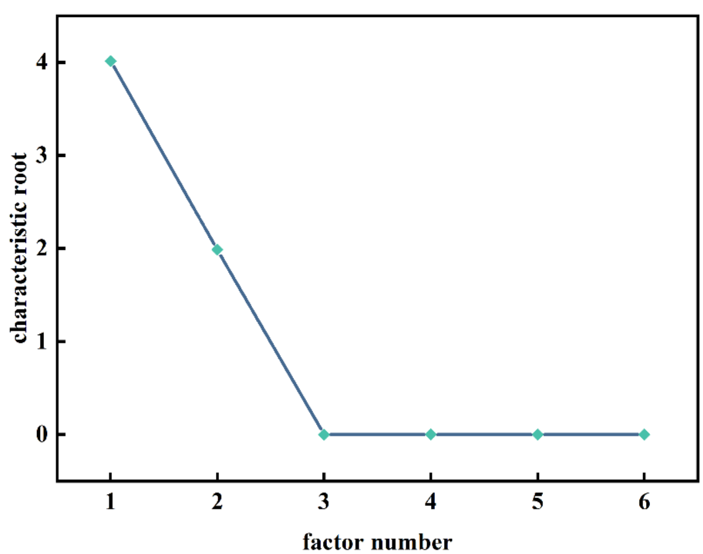


**Fig. 3.** Scree Plot

## DISCUSSION

### Storage Capacity of Plant Organic Carbon in The Surface Layer of Yancheng Coastal Marsh Wetland

There was a close relationship between the carbon storage capacity and vegetation types in the coastal marsh wetland of Yancheng. In this wetland ecosystem, different vegetation types showed different carbon storage characteristics. Through statistical and correlation tests on studies related to vegetation, soil depth, and organic carbon storage, it was found that the surface plants of coastal marsh wetlands, including *Spartina alterniflora*, *Phragmites australis*, and *Suaeda salsa*, had strong organic carbon storage capacity. The results of the principal component analysis indicated that vegetation type was a central driver of carbon storage. Especially, *Spartina alterniflora*, as an exotic invasive species, played a key role in carbon storage in coastal marsh wetlands in Yancheng (Liu *et al.* 2020). Due to its high photosynthetic efficiency and strong net primary productivity, the biomass of the aboveground part of *Spartina alterniflora* significantly exceeded that of other vegetation, especially *Suaeda salsa* (Didham *et al.* 2005; Jia *et al.* 2024). These abundant plant residues provided an important source of soil organic carbon accumulation when they entered the soil. The invasion of *Spartina alterniflora* also increased the rate of organic carbon accumulation in the surface soil, and its carbon sequestration capacity was quite significant, making an important contribution to wetland carbon storage. The data indicated that the rate of soil organic carbon (SOC) accumulation in the 0 to 100 cm soil layer under the influence of *Spartina alterniflora* invasion increased linearly with the invasion time. The accumulation rates in the 0 to 20 cm, 0 to 40 cm, and 0 to 100 cm soil layers were 0.10 kg C $m^{-2}$ $yr^{-1}$, 0.13 kg C $m^{-2}$ $yr^{-1}$, and 0.40 kg C $m^{-2}$ $yr^{-1}$ (Zhang *et al.* 2021). In the 0 to 30 cm soil layer, the average SOC concentration in the seaward expansion was 8.39 g C $kg^{-1}$ and the carbon sequestration capacity was 253.8 g C $cm^{-2}$, which was significantly higher than that in the landward expansion of 6.26 g C $kg^{-1}$ and 193.7 g C $cm^{-2}$ (Qi *et al.* 2019). In addition, 10 years after the invasion of *Spartina alterniflora*, the SOC content in the 5 to 30 cm soil layer increased by 3 to 5 times that compared with the native salt marsh. The rate of SOC accumulation in the seaward expansion could reach 1.46 g C $kg^{-1}$ $yr^{-1}$ in the first 11 years of invasion, and at the same time, the invasion of *Spartina alterniflora* also increased the carbon content and storage capacity of *Phragmites australis* wetland soil (Seliskar *et al.* 2002; Ehrenfeld 2003). The *Spartina alterniflora* reduced the soil carbon storage function of the tidal flat wetland ecosystem due to the action of the soil enzyme system (Hopkinson *et al.* 2012).

*Phragmites australis*, another common plant in coastal marsh wetlands, also had some carbon storage, but its organic carbon was unevenly distributed and spatially variable. In contrast, the carbon storage capacity of *Suaeda salsa* was weak, and as a C3 plant, its photosynthetic efficiency was low and its biomass is relatively small, leading to its limited carbon storage capacity. When *Spartina alterniflora* replaced *Suaeda salsa* as the dominant vegetation in the wetland, the organic carbon content and accumulation rate of the soil were significantly enhanced. In contrast, the organic carbon content of a mudflat, an area without vegetation cover, was relatively low. Due to the lack of protection and fixation by vegetation, the organic matter on the mudflat was more affected by tides, with poor deposition and retention capacity, resulting in a weaker organic carbon enrichment capacity. Therefore, the carbon storage capacity of coastal marsh wetlands in Yancheng was closely related to the vegetation type, and *Spartina alterniflora* played an important role in wetland carbon storage due to its high photosynthetic efficiency and abundant plant residues. In contrast, areas without vegetation cover, such as mudflats, had poor carbon retention capacity due to severe tidal influence, resulting in their low organic carbon content. These findings not only revealed the mechanism of carbon storage in coastal marsh wetlands in Yancheng but also provided a scientific basis for the protection and restoration of wetland ecosystems.

### Factors Affecting the Organic Carbon Content of Yancheng Coastal Marsh Wetland

The carbon storage capacity of wetland ecosystems was significantly affected by seasonal climate change and plant growth cycles. The coastal marsh wetland of Yancheng, located in the subtropical monsoon climate zone, had large annual average precipitation and temperature variations, and these factors led to seasonal fluctuations in plant growth and organic matter accumulation. In the spring and summer growth period, the biomass of wetland plants, such as *Spartina alterniflora* increased, which promoted the accumulation of organic carbon; while in the fall and winter seasons, plant growth slowed down and organic carbon accumulation decreased accordingly. In addition, wet and dry changes in wetlands might also affect the content of organic carbon in the soil, *e.g.*, the anaerobic decomposition process increased when the humidity was too high, leading to a decrease in organic carbon storage (Xu *et al.* 2020). Strong plant photosynthesis and increased biomass input promoted carbon accumulation in the spring and summer seasons. High water levels in the wet season enhanced anaerobic decomposition, resulting in a dynamic balance between carbon storage and decomposition. Therefore, the choice of sampling time was crucial for the study of organic carbon in wetland soils.

Soil depth was a key factor affecting the organic carbon storage in wetland soils. Usually, the top soil layer (*e.g.*, 0 to 20 cm) contained higher organic carbon, which was mainly due to the accumulation of plant residues and active microbial activities (Balesdent *et al.* 2018). In the coastal marsh wetland of Yancheng, a large amount of plant residues of *Spartina alterniflora* entered the top soil layer, which significantly increased the organic carbon content of this layer. However, with the increase of soil depth, the permeability of the plant root system decreased and the input of organic matter decreased, resulting in lower organic carbon content in deeper soils (*e.g.*, 20 to 40 cm). Nonetheless, deeper soils had accumulated organic matter deposited over time, and there was long-term storage of organic carbon due to lower oxygen availability and slower decomposition rates.

Vegetation type was also found to be an important factor affecting soil organic carbon content in coastal marsh wetlands in Yancheng (Quideau *et al.* 2001). Different plant types affect the accumulation and decomposition of soil organic carbon through growth mode and root structure. As the main dominant plant in coastal wetlands, *Spartina alterniflora* had high photosynthetic efficiency and biomass, and its aboveground biomass far exceeded that of *Artemisia salina*. The invasion of *Spartina alterniflora* significantly increased the soil's organic carbon content, especially in the topsoil. Through increasing biomass and sedimentation rate, *Spartina alterniflora* increased the primary productivity of the wetland and promoted the accumulation of organic carbon. However, its root system altered the soil enzyme system and affected the carbon decomposition process, with some impacts on the long-term carbon storage capacity. In contrast, the biomass of *Phragmites australis* was usually lower than that of *Spartina alterniflora* and contributed less to soil organic carbon. However, in a long-term stable wetland environment, *Phragmites australis* gradually replaced other plants and contributed to carbon storage in wetlands. The spatial variability of the *Phragmites australis* zone was large, and its organic carbon content was affected by multiple factors such as hydrological changes in the wetland and plant community dynamics. As a saline plant, *Suaeda salsa* had low biomass, and carbon storage in the wetland was not significant, which was mainly reflected in the deposition of plant residues. There was no vegetation cover in the mudflat, which led to poor carbon accumulation capacity, and the organic carbon mainly came from nutrients and algal residues in the water body. Due to the lack of plant roots and biomass, the organic carbon deposition and retention capacity of the mudflat was low, and it was affected by the tidal action and easily washed away or transported to other places.

Overall, *Spartina alterniflora* was the main plant for carbon storage in the coastal marsh wetlands of Yancheng, and high biomass and strong depositional capacity made it a key influence on soil organic carbon content in the region (Wang *et al.* 2008). The *Spartina alterniflora* community contributed to organic carbon accumulation in the surface soil but might also reduce long-term carbon storage capacity by affecting the soil enzyme system (Yang *et al.* 2013; Yang and Guo 2018). The interaction between vegetation type and soil depth determined the spatial distribution of soil organic carbon. In addition, the seasonal and hydrological variability of wetland ecosystems led to the choice of sampling time being critical for the determination of carbon content. By sampling in different seasons, at different soil depths, and under different vegetation types, the carbon storage potential of the coastal marsh wetlands in Yancheng was assessed more comprehensively.

## CONCLUSIONS

1. Kendall's consistency test showed significant correlations between sampling time, soil depth, vegetation type, and soil organic carbon content, reflecting the complexity of ecological factors.
2. Spearman's Rank Correlation analysis revealed a weak negative correlation between vegetation type and soil depth, implying different adaptations of different vegetation types to soil depth.
3. The principal component analysis further identified the main ecological factors affecting soil organic carbon storage, showing that vegetation types, such as *Spartina alterniflora*, *Phragmites australis*, and mudflat, played key roles in the wetland ecosystem, while *Suaeda salsa* showed an opposite trend to the other vegetation types.
4. The soil organic carbon content of coastal marsh wetlands was affected by a combination of factors, such as sampling time, soil depth, and vegetation type, among which *Spartina alterniflora*, as a key plant, played an important role in promoting soil organic carbon accumulation. In the future, monitoring and research on wetland ecosystems should be further strengthened to better understand and protect the carbon storage function of wetlands.

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## AUTHORSHIP CONTRIBUTION STATEMENT

**Chaowei Yue:** Writing – review & editing, Software, Data curation. **Zhu Yun, Haochuan Ge:** Writing – original draft, Investigation. **Hui Wang**: Data curation, Software, Formal analysis. **Guixiang Quan**: Writing – review & editing. **Liqiang Cui**: Software, Methodology. **Jinlong Yan:** Writing – review & editing, Validation, Resources, Funding acquisition.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## APPENDIX

### Data Selection Criteria

All data of the soil organic carbon (SOC) were screened for studies using standardized sampling methods (*e.g.*, ring knife method, potassium dichromate oxidation) to ensure consistency in SOC determination methods. In order to ensure the reliability of the results, data screening followed the criteria:(1) Consistency of methods: Soil sampling was done by ring knife method (0~20 cm in the surface layer) or soil auger method (>20 cm in the deep layer), and the sampling density was ≥3 replicates/sample plot. (2) SOC determination was unified using potassium dichromate oxidation method, supplemented by elemental analyzer in some studies (error ±5%). (3) Vegetation types were categorized with reference to the Chinese Vegetation Journal to ensure that the communities of *Spartina alterniflora* and *Phragmites australis* were defined consistently. (4) Limitations of temporal and spatial scopes: Spatial, only studies in which the sampling site was located in the coastal marsh wetland of Yancheng (32°38'N-34°32'N, 119°46'E-121°06'E). Time, the year of publication of the literature was from 2009 to 2024, excluding historical data with large differences in earlier methods. The data quality control was listed as: (1) exclusion criteria, exclude the outliers of soil organic carbon content (e.g. <1g/kg or >200g/kg, screened by Grubbs test); exclude the data of mixed vegetation communities, and keep only the data of single dominant vegetation sample plots. (2) Confidence test: The consistency test for repeated studies (*e.g*. data from different years in the same region) found that the coefficient of variation of organic carbon content of the same vegetation type was <15%, which indicated that the data stability was high.

**Table A1.** Summary of Data Collection

| Sample | Sampling Time | Depth (cm) | Vegetation Type | Ecological Environment | Number of Sampling Points |
|---|---|---|---|---|---|
| Pan *et al.* | 2013.05 | 0~20 | *Spartina alterniflora* | mudflats native grass flats | 26 |
| Quan *et al.* | 2008.09 | 0~15 | *Spartina alterniflora/Phragmites australis/Mudflat* | mudflat wetland | 32 |
| Nie *et al.* | 2020 | 10 | *Spartina alterniflora/Phragmites australis* | coastal wetland | 26 |
| Liu *et al.* | 2020.10 | 0~20<br>20~40 | *Spartina alterniflora/Phragmites australis* | coastal wetland | 4 |
| Xia *et al.* | 2019.06 | 0~10 | *Spartina alterniflora/Suaeda salsa* | coastal mudflat wetland | 6 |
| Yan *et al.* | 2016.08 | 0~5 | *Phragmites australis* | coastal mudflat | 61 |
| Pen *et al.* | 2021.08 | 0~10 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | saltmarsh wetland | 47 |
| Lou *et al.* | 2021.08 | 0~6 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | saltmarsh wetland | 53 |
| Chen *et al.* | 2022.08 | 0~30 | *Spartina alterniflora* | Yancheng Coastal Wetland | 45 |
| Yan *et al.* | - | - | *Spartina alterniflora/Phragmites australis* | coastal mudflat wetland | - |
| Yang *et al.* | 15$^{th}$ of | surface | sewage from pigs | coast | 12 |

| | | | | | |
|---|---|---|---|---|---|
| | each month | layer | | | |
| Xu *et al.* | 1987-2007 | 0~20 | *Spartina alterniflora/Phragmites australis/Suaeda salsa/Mudflat* | coastal wetland | 5 |
| Xu *et al.* | 2021.03 | 0~20 | *Spartina alterniflora/Phragmites australis/Suaeda salsa/Mudflat* | tidal flat wetland | 73 |
| cheng *et al.* | 2019.01 | 5 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | coastal wetland | 3 |
| Mo *et al.* | 2020.10 | 0~10 | *Spartina alterniflora/Phragmites australis/Suaeda salsa/Mudflat* | coastal wetland | 11 |
| He *et al.* | 2020.09 | 0~40 | *Phragmites australis/Suaeda salsa* | coastal wetland | 12 |
| Mo *et al.* | 2021.01 | 0~10 | *Spartina alterniflora/Phragmites australis/Suaeda salsa/Mudflat* | coastal wetland | 4 |
| Mao *et al.* | 2007.01 | 0~20 20~40 | *Spartina alterniflora Suaeda salsa/Mudflat* | coastal wetland | 13 |
| Mao *et al.* | 2008.05 | 0~20 | *Spartina alterniflora Suaeda salsa/Mudflat* | coastal mudflat wetland | 10 |
| Mao *et al.* | 2008.05 | 0~20 | *Spartina alterniflora Suaeda salsa/Mudflat* | coastal mudflat wetland | 10 |
| Zhou *et al.* | - | - | - | coastal wetland | 15 |
| Xi *et al.* | 2018.10 | 0~60 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | coastal wetland | 48 |
| Jia *et al.* | 2013.09 | 0~60 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | mudflat wetland | 27 |
| Jin *et al.* | - | - | - | coastal wetland | - |
| Zang *et al.* | 2015.11 | 0~50 | *Spartina alterniflora/Phragmites australis/Suaeda salsa/Mudflat* | coastal wetland | 10 |
| Xu *et al.* | 2013.06 | 0~5 | *Spartina alterniflora/Phragmites australis/Suaeda salsa/Mudflat* | coastal wetland | 21 |
| Pei *et al.* | 2018-2020 | 0~10 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | coastal wetland | 168 |
| Xiao *et al.* | 2018.05 | 0~60 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | coastal mudflat wetland | 15 |
| Li *et al.* | 2017.10 | 0~5 | *Spartina alterniflora* | mudflat wetland | 82 |
| Wan *et al.* | 2016-2017 | 0~60 | *Spartina alterniflora/Phragmites australis/Suaeda salsa/Mudflat* | mudflat wetland | - |
| Tong *et al.* | 1987.12 | - | *Spartina alterniflora/Phragmites australis/Suaeda salsa/Mudflat* | coastal mudflat wetland | 16 |
| Liu *et al.* | 2017.07 | - | - | coastal wetland | - |
| Chuai *et al.* | 1985-2010 | 0~20 | *Spartina alterniflora/Suaeda salsa* | coastal wetland | - |
| Zhang *et al.* | 2018.06 | 0~40 | *Spartina alterniflora/Phragmites australis/Suaeda salsa/Mudflat* | coastal wetland | 596 |
| Li *et al.* | 2018.10 | 0~60 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | coastal wetland | 18 |
| Wang *et al.* | 2011.06 | 0~20 | *Spartina alterniflora/Suaeda salsa/Mudflat* | coastal wetland | 11 |
| Chen *et al.* | 2014.09 | 5~15 | Oryza sativa community (botany) | coastal wetland | 720 |
| Zhou *et al.* | 2018.10 | 0~30 | *Phragmites australis/Suaeda salsa* | coastal wetland | 18 |
| Xia *et al.* | 2018.10 | 0~60 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | coastal wetland | |
| Xi *et al.* | 2018.10 | 0~60 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | coastal wetland | |
| Lin *et al.* | 2018.10 | 0~30 | *Spartina alterniflora/Phragmites australis/Suaeda salsa* | coastal wetland | |

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