Chapter 5

Coastal Wetland Vegetation in Response to Global Warming and Climate Change

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Additional information is available at the end of the chapter

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Abstract

Under the background of global warming, rising sea level, extreme weather and other global climate changes, vegetation has played a targeted and irreplaceable role. The characteristics of individual plant, community landscape and vegetation succession in response to the major driving factor (mainly includes habitat relative elevation, net loss of coastal habitat, salinity, etc.) were analyzed. An obvious development of vegetation landscape fragmentation has results from the competitive advantages of salt-tolerant species or invasive species, which eventually results in the regressive succession and unreasonable secondary succession of vegetation. Compared with the botanical community statistics method, the method of combined of GIS-mapping and remote sensing data provide a more effective way to extract the individual plant stress information, vegetation community structure and dynamic change of vegetation landscape pattern, which can reflect the spatial differentiation of the vegetation at a macro-scale. In addition, in view of the high-efficiency carbon sequestration capability of coastal wetland vegetation, the spatial distribution, temporal dynamic and extraction method of vegetation and soil sequestration were discussed. Synthesize above analysis result, further studies in vegetation response to global climate change were proposed, which need to be improved or expanded.

Keywords: coastal wetland vegetation, climate change, vegetation succession, remote sensing, vegetation carbon sequestration, vulnerability assessment

1. Introduction

1.1. Climate change and sea level rise

It is certain that global mean surface temperature has increased since the late nineteenth century, which increasingly received attention of the governments and academia. Intergovernmental Panel on Climate Change (IPCC) assessed the effect of the global climate change on the natural ecosystems and human socioeconomic system five times from 1990. According to the latest IPCC Fifth Assessment Report (AR5) [1], the global combined land and ocean temperature data showed an increase of about 0.89°C over the period 1901–2012. The global mean sea level has increased by 0.19 m over the period 1901–2010, the mean rate of sea level rise was 1.7 mm year^{-1} between 1901 and 2010. Three-quarters of the contributions to rise in the sea level are the expansion of the ocean water as it warms and the transfer to ocean water from glaciers and ice sheets. The atmospheric abundances of CO_2, CH_4, N_2O were 390.5 ppm, 1803.2 ppb, 390.5 ppb in 2012, respectively, and were highest than experienced on earth for at least the last 800,000 years, which has increased by 40, 150, 20% since pre-industrial times. The observed changes in the frequency and intensity of extreme weather-climate events are increasing on the global scale since the mid-twentieth century. These are clearly showed by the observed increased intensity of extreme precipitation events and frequency of extremely warm.

1.2. Major role of vegetation in the coastal wetland ecosystems

The role of vegetation in the global ecosystem is self-evident, in particular, coastal wetland vegetation plays an even more critical role under the influence of global climate change and human activities, which can be summarized as follows.

1. **Carbon storage, carbon fixation**: coastal wetlands are the important “source” and “sink” of greenhouse gases. Because vegetation have higher rate of carbon sequestration and lower rate of methane emission, which are the most important part of “sink” [2]. In 2009, the United Nations Environment Program (UNEP), Food and Agriculture Organization (FAO) and four departments have jointly issued a report about the ocean carbon sinks – “Blue carbon. A UNEP rapid response assessment”. More than half of global biomedical carbon was captured by the ocean’s vegetated habitats, in particular seagrasses, mangroves and salt marshes, and this carbon was called ‘Blue carbon’. The biomass of coastal wetland vegetation is 0.05% times than terrestrial vegetation, but the carbon fixation rate of blue carbon ecosystem is 10–50 times higher than forest, which were captured and stored 862–1650 Tg CO_2 (Tg = 1012 g) per year and this amount is equivalent to the total carbon emissions of the global transportation [3].
2. **Disaster mitigation**: as the buffer zone between land and oceans, the coastal wetland vegetation can store excess water in the rainy season, and relieve the pressure of the flood disasters. The vegetation also adsorbed the intertidal sediments with its root system, quickens the progress of the promoting deposition and creating land, which plays a great role in mitigating the erosion action of waves on the coastline. In addition, the vegetation protects the building and crops from the damage of strong and salty winds, and one of the

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most remarkable examples is mangrove forest known as the "Chlory The Ocean Guard" [4]. As shown in the **Figure 1**, mangrove roots cover the upper banks of the Daly Estuary, Australia, providing a protective barrier against erosion of the upper banks, although not protecting against undercutting in the lower banks [5].

3. **Marine habitat:** communities of submerged aquatic vegetation found in marine, estuarine and coastal freshwater environments provide critical habitat for fish, shrimp, wintering waterfowl and endangered species such as sea turtles and manatees [6].

4. **Plant purification:** the heavy metal concentration in the tissue of the submerged aquatic vegetation is about 100,000 times higher in the surrounding water. Some typical plants such as bulrush, water hyacinth, etc., have been successfully used to degrade sewage [7].

1.3. Major classes of the coastal wetland vegetation

China is a country with a long mainland coastline of about 18,000 km, across territory north and south of three climatic zones. There are many types of vegetation growing along coastlines, which have typical growth process and research value. Thus, the coastal wetland vegetation classification system of China probably has a guide role for the world, which was classified into three levels [8]. First level is vegetation type groups, which was named by the difference of habitat physiognomy in the constructive species. Second level is vegetation types, which was named by the life forms of the dominant species. Third level is vegetation formations, which was gathered from the same community that includes constructive or dominant species. The detailed classification is shown in **Table 1**.

In this chapter, the global change research of coastal wetland vegetation seeks to (1) identify the influence factors and consequences of climate change to vegetation, (2) develop more efficient methods which extraction the environmental stress information of vegetation and (3) understand the current carbon fixation capacity of various coastal wetland vegetation.

Figure 1. Mangrove roots cover the upper banks of the Daly Estuary, Australia.

Vegetation type groups	Vegetation types	Vegetation formations	Habitat characteristics
Salt marsh	Herbal salt marsh	*Spartina anglica*, *Scirpus mariqueter*, etc.	Mainly distributed in the low-lying areas, grow in the coastal saline soil with high salinity
	Brush salt marsh	*Tamarix chinensis*, *Nitraria sibirica* Pall, etc.	Mainly distributed in the river deltas
Coastal marsh wetland	Herbal marsh	*Phragmites australis*, *Miscanthus sacchariflorus*, etc.	Mainly distributed in the perennial water or seasonal waterlogged marsh, with higher community coverage
	Brush marsh	*Tamarix chinensis*, *Vitex rotundifolia*, etc.	
	Forest marsh	*Pinus elliottii*, *Casuarina equisetifolia*, etc.	
Shallow vegetation wetland	Floating wetland	*Salvinia natans*, *Spirodela polyrhiza*, etc.	Mainly distributed in the middle-upper part of the slanting flat or constructed wetlands, there are standing water for long time or longer period in the surface
	Floating leaf wetland	*Nymphoides peltatum*, *Nelumbo nucifera*, etc.	
	Submerged wetland	*Myriophyllum verticillatum*, *Ceratophyllum demersum*, etc.	
Mangrove swamp	Mangrove vegetation type	*Avicennia marina*, *Rhizophora apiculata*, etc.	Distributed in the tropical or subtropical intertidal zone or the estuary
	Semi-mangrove vegetation type	*Heritiera littoralis*, *Barringtonia racemosa*, etc.	Grow in the intertidal zone
Seaweed wetland		*Halophila ovalis*, *Syringodium isoetifolium*, etc.	

Table 1. Vegetation classification system of coastal wetlands in China.

2. Response analysis and driving factors of vegetation succession under climate change

The coastal wetland vegetation occurs positive succession under the influence of the acceptable natural conditions. However, with the global climate changes, the effect of some environmental factors is beyond the carrying capacity of coastal wetland vegetation, which will lead to the fragmentation of vegetation landscape, regressive succession of vegetation and other consequences.

2.1. Positive succession of vegetation under natural conditions

In this section, three kinds of typical habitats are taken as examples to analyze the normal succession law of coastal wetland vegetation. **(1) Estuary delta:** due to the difference of soil salinity in spatial distribution, the vegetation distribution in estuarine delta is zonal. The vegetation community succession starts from the bare flat, and the highly salt-tolerant community appears first, such as Wing-Alkali. With the increase of vegetation and litter in the

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surface, the medium-low compound vegetation community appears such as Reed-Alkali [9]. Due to the increase in topography and reduction in groundwater level, the non-zonal top community is eventually formed, such as Tamarix Chinensis. **(2) Tidal flat wetland:** the vegetation has a horizontal zonal distribution. Succession starts from the salt-tolerant vegetation, along with the uplift of the coastal beach, soil salinity decreased and perennial wet plants invaded, and vegetation litter accelerated the soil desalination process, resulting in the moist woody plants gradually appeared, such as Tamarix. The soil is further biochemical, and the medium vegetation becomes the dominant community [10]. **(3) Mangrove wetlands:** mangrove forests often form along the estuary or gulf coastline that is a strip distribution. Pioneer communities are often composed of non-mangrove plants, which have stronger adaptability to wind waves and leanness. With the development of the demineralization, the later and typical mangrove communities have developed the dominant positions [11].

To sum up, no matter what type of coastal wetlands, the vegetation succession starts from the salt resistance, waterlogging resistance and barren species, after the pioneer community formation, soil salinity reduction. Then the environment became gradually stable, which provides the conditions for medium vegetation growth. Finally, a complete and stable coastal wetland vegetation ecosystem are formed. Wetland vegetation community development along water table continuum is shown in **Figure 2**.

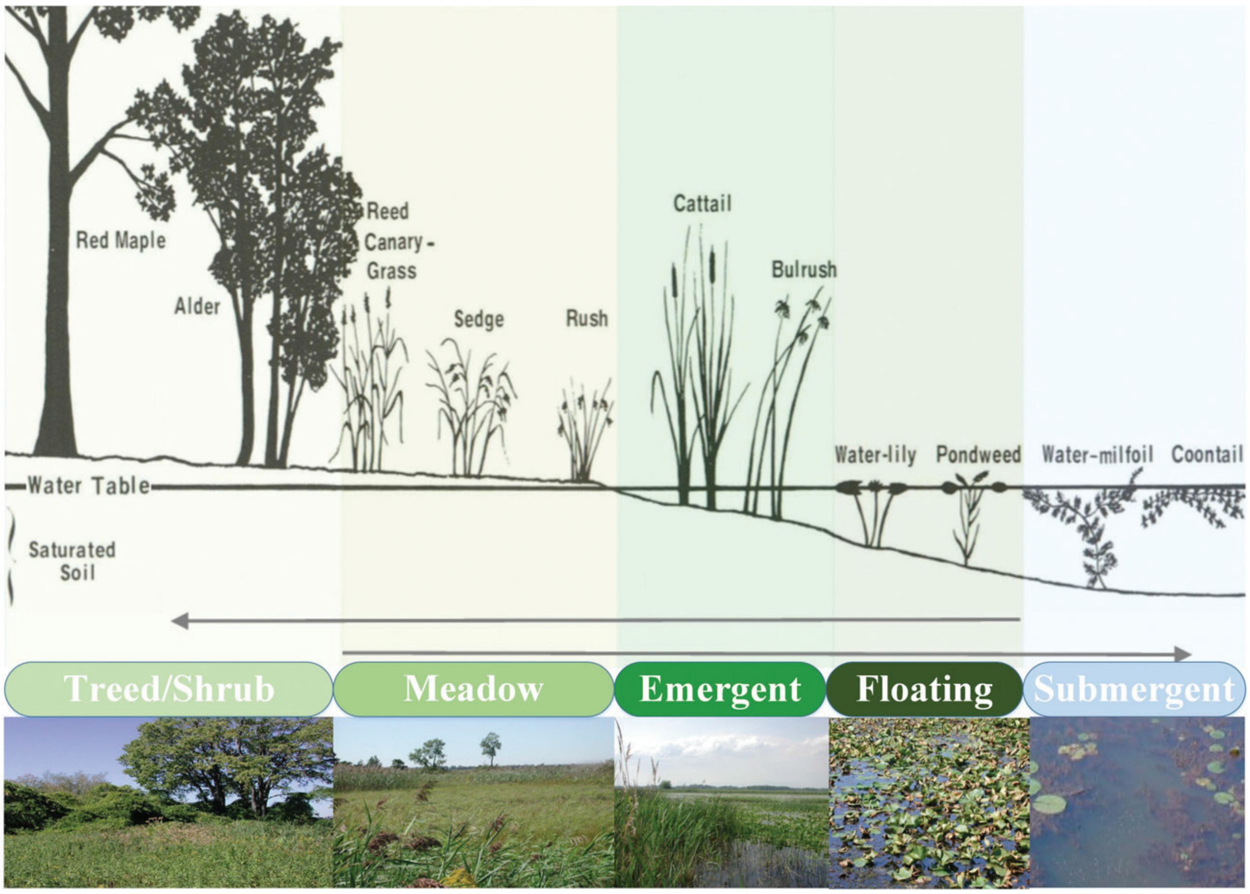

Figure 2. Wetland vegetation community development along water table continuum (adapted from Mortsch et al. [12]).

2.2. Driving factors of vegetation succession under climate change

In addition to the influence of geographical location and elevation, the succession characteristics of vegetation also depend on the factors such as water content, soil nutrient and human activities. However, some of these factors will be magnified and become the dominant factors under climate change.

2.2.1. Changes of habitat relative elevation

The evaluation of coastal wetland will increase with tidal flat sediment accumulation, which can slow down or even offset the influence of sea level rise [13]. Firstly, as shown in **Figure 3a**, if the sea level rise rate equals the sediment accumulation rate, the relative elevation of coastal wetland is constant, the flooding degree of plants remain stable, and their growth are not affected by sea level rise. Secondly, as shown in **Figure 3b**, if the sea level rise rate is smaller than the sediment accumulation rate, the relative elevation is increased, the coastal wetland gradually siltation to the seaward direction and the habitat area for the plant growth is enlarged. Thirdly, as shown in **Figure 3c**, if the sea level rise rate is higher than the sediment accumulation rate, the relative elevation is decreased, the flooding frequency and depth are increased, which will affect the survival and growth of plant [14]. However, other research suggests that time-effect

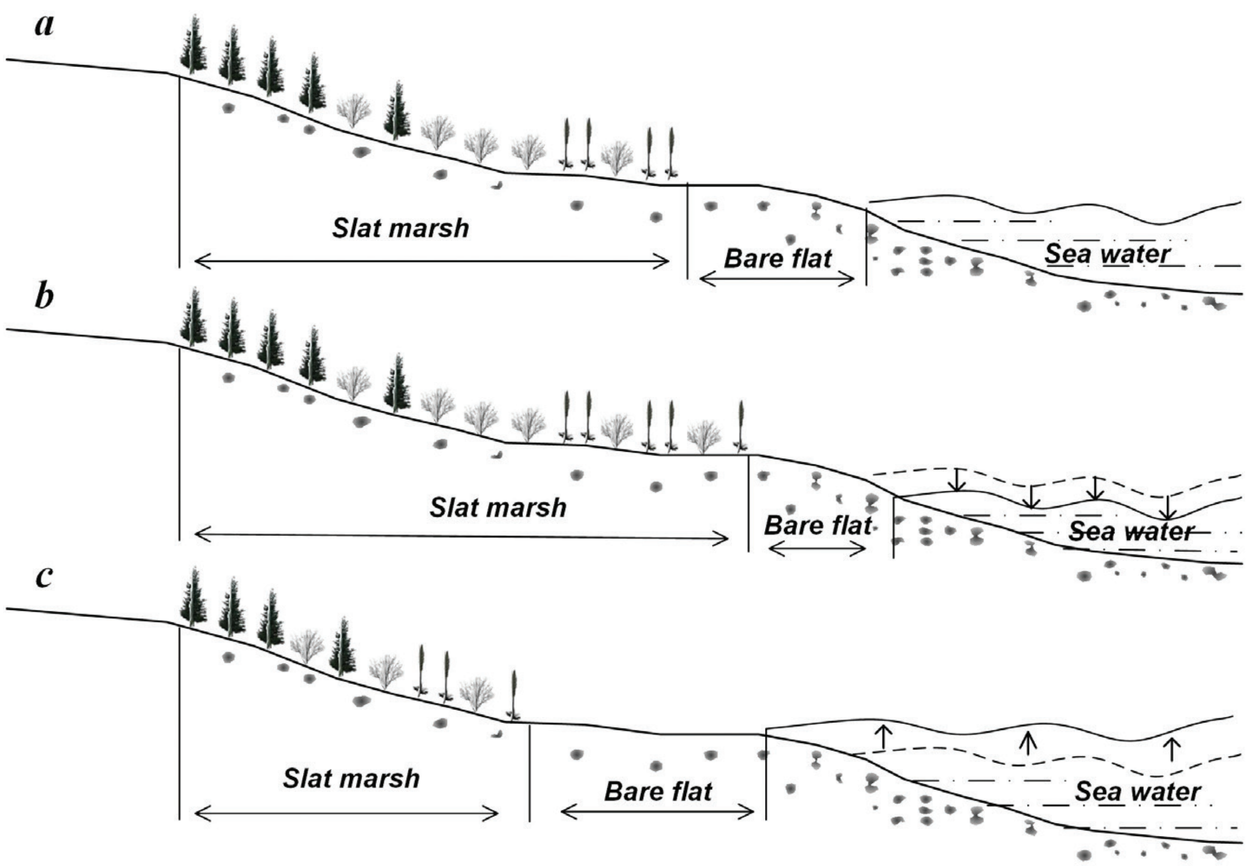

Figure 3. The sketch map of coastal wetland vegetation response to sea level rise. (a) Relative sea level unchanged; (b) relative sea level dropped; (c) relative sea level raised.

of physical-biological processes occurring in the top few meters of the soil are faster than accumulation rate [15]. In addition, in the new shallow strata of coastal wetland such as the estuary delta, the soil surface under the action of artificial coastal engineering is compressed, which is very easy to induce soil subsidence [16].

2.2.2. Net loss of coastal habitat

Coastal wetland can be persisted by extending inland and occupying formerly upland sites under the influence of sea level rise [17]. However, the ability to landward movement of coastal wetland depends on the relationship to topography. As lower elevation sites become submerged, marsh build-up or expansion may occur up the slope of the landward marsh boundary. The slope will present an effective barrier to the growth of some plant communities, effectively squeezing area available for coastal vegetation [18]. Duke University and USGS scientists modeled the movement of the marsh edge in a few typical coastal wetland, which implies that inland marsh movement is controlled not only by sea level rise but also by human activities [15]. The rate of human reclamation is much higher than that of the sediment accumulation, in the early period of reclamation and the inland evolution of coastal wetlands may be speeded up. As shown in the **Figure 4(1)**, subsistence agricultural plantations take place within the wettest zones of the wetlands on the Maputaland Coastal Plain of South Africa. However in the long run, because the purpose of human reclamation is different from the natural evolution of coastal wetland, it will become an obstacle to the inland evolution of the vegetation habitats, and further aggravate the loss of the wetland vegetation habitat [19], for example, a drained and destructed wetland caused by the human reclamation, as shown in **Figure 4(2)**.

2.2.3. Salinity, CO_2 and other factors

As sea level continues to rise, salt water will move farther inland, subjecting vegetation communities to salinity stress. The change of habitat area and relative elevation mainly controlled the direction of vegetation succession by the soil salinity. The high salt-tolerant plants are mostly

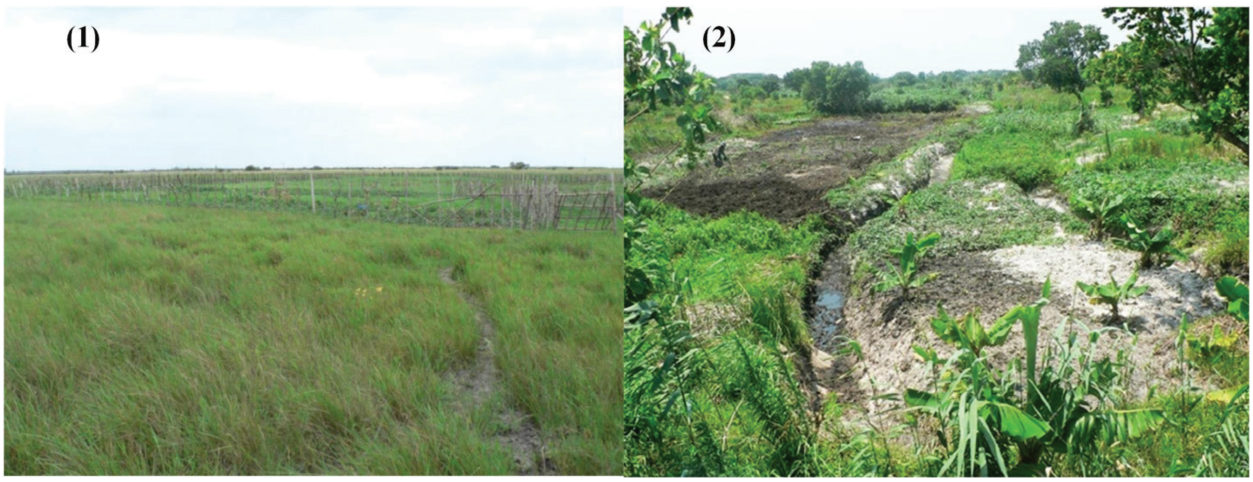

Figure 4. (1) An example of the numerous informal economic plantations that has sprung up on the Maputaland coastal plain over the past 20 years; (2) an example of a drained and destructed wetland.

distributed in the sea near or low-lying where susceptible to tidal erosion. From low to high-tidal flat, soil salinity decreased, plant species tended to diversify and low salt-tolerant. The ground-water depth increases gradually as the elevation from high to low, which is directly related to whether the soil capillary water can reach the surface, and then affected the soil salinity.

Underlying the predicted climatic changes is an overall increase in carbon dioxide concentrations in the atmosphere. Increased atmospheric carbon dioxide concentrations should also result in an increase of dissolved inorganic carbon concentrations in water, such as a change may affect the submerged plant communities [20]. An increase in the severity of tropical storms associated with climate change can also have acute impacts on vegetation communities [21]. Flooding was more important than small increase in salinity in the growth and survival of most tree species, whereas chronic or large increases in salinity were very harmful to all of the species tested regardless of the flooding extent [22].

2.3. Analysis of vegetation in response to the various factors

A large area of land will be quickly converted from coastal salt and freshwater marsh to open water over the next several decades if current trends in sea level rise continue [17]. Large-scale movement of vegetation community and change of vegetation community structure are likely to occur. Field and laboratory experiments analyzed the succession characteristic of vegetation in response to the various factors.

2.3.1. Analysis of individual plants in response to the various factors

Experiments in a greenhouse showed that plants known to be strong competitors for light and nutrients dominated at low salinities but did not grow well at higher salinities because of a physiological intolerance to high salinity [23]. Species tolerant of high salinities proved to be weak competitors at low salinities, however high salt-tolerant species will occupy a leading position of the vegetation community at moderate to high salinities environment. Long-term monitoring help quantify the dynamics of forest structure and response to changes in climate, which suggest that (1) increases in drought associated with changing climate may significantly alter understory seedling populations in bottomland forests and recruitment into the sapling layers, and ultimately influence over story canopy structure [13], (2) increased disturbance associated with flooding and storms may form early successional, shade-intolerant species at the expense of shade tolerant species [21] and (3) damage associated with hurricane disturbance or strong storms also plays major role in the structural composition of mangrove forests, which will likely result in future mangrove forests of smaller stature [11].

The photosynthetic activity of three freshwater submerged plant species such as Wild celery, Coontail and Hydrilla as well as a seagrass species, shoal grass, exposed to higher concentrations of dissolved carbon dioxide were measured in the laboratory. All four species showed an increase in photosynthetic activity in response to higher carbon dioxide concentrations, and exhibited changes in biomass allocation and an increased ratio of carbon to nitrogen in certain plant tissues but did not respond with increased growth. Higher ratios of carbon to nitrogen in plant tissue tend to provide poorer quality forage for wintering waterfowl that rely on aquatic plant species for their food supply [17].

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2.3.2. Changes of vegetation community structure

Various factors induce the change in the internal structure of the community, which caused by climate change such as coastal erosion, storm surge and salinity stress. Vegetation landscape patches showed a discrete distribution and their numbers increased [24, 25]. For example, due to insufficient freshwater, in the process of vegetation transformation from wet-unripe vegetation to saline-marsh vegetation, two kinds of vegetation types were distributed in disorder and the landscape pattern was mottled. In the comparatively macroscopic level between difference types of vegetation community, the change trend of community structure is not fragmentation, but tends to be concentrated distribution, forming a relatively large plaque [26, 27]. For example, in the area where the natural wetland vegetation is connected with the artificial economic crop, the natural wetland vegetation is gradually eroded by artificially killing other interfering plants except cash crops. Considerable variation in salt tolerance existed among natural vegetation populations, and the new salt-tolerant varieties can be developed and used in reforestation efforts where existing populations have been killed by saltwater intrusion. Thus, salt-tolerant, drought-resistant and other artificial cultivated plants with strong environmental tolerance expanded rapidly. In addition, the increased disruptions to the vegetation community will provide recruitment opportunities for exotic species, enhancing their rate of invasion into natural stands.

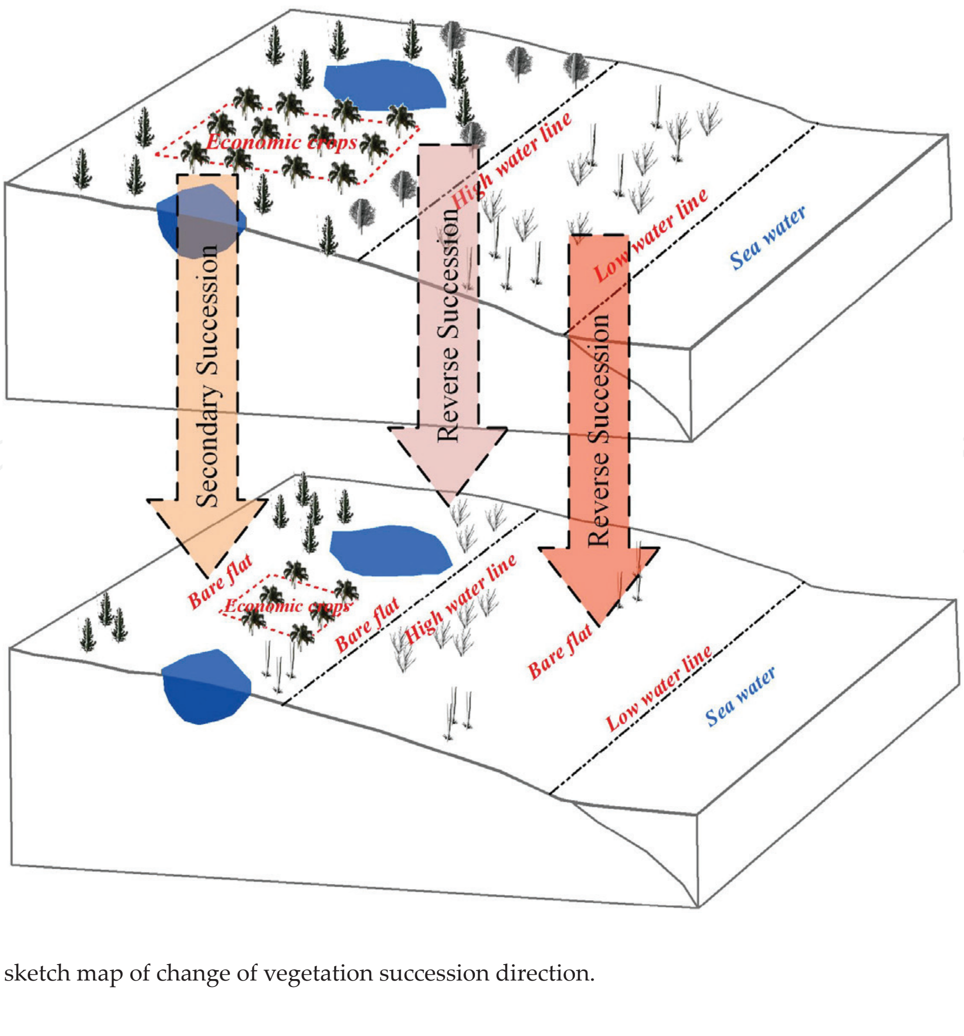

Figure 5. The sketch map of change of vegetation succession direction.

2.3.3. Changes of vegetation succession direction

Perhaps more importantly, climate change has disrupted the natural development process of coastal wetlands, resulting in the reverse or unreasonable secondary succession of wetland vegetation (show in **Figure 5**), which accelerates the function degradation of coastal wetlands [28]. The wet-unripe wetland vegetation is degraded to saline-marsh wetland vegetation caused by the lack of fresh water, when the sea level rise rate is higher than the accumulation rate, which makes the decrease of surface relative elevation. The sparse vegetation community in the intertidal zone is retreated by shoreline erosion, reverse succession into bare-light beach wetland. The economic crops planted by artificial reclamation have blocked the land movement of wetland vegetation caused by sea level rise. However, due to unreasonable tillage, the content of soil organic matter and ammonia nitrogen decreased, which result in secondary succession of vegetation occurs, or is degraded to bare-light beach, or to facilitate the invasion of harmful species [29].

3. Extraction methods of vegetation information in response to climate change

Scholars mainly explore the response mechanism of coastal wetland vegetation under climate change from three scales of 'individual – community – landscape'. Botanical community statistics (BCS) method was widely used for the information extraction of vegetation communities, which mainly consists of three steps [30, 31]. Firstly, according to the characteristics of vegetation community derived from site survey, the reasonable length and width of belt transect are selected and in which the appropriate number and area of the quadrat are set up. Secondly, the plant parameters such as name, height and coverage degree were estimated by counting and visual estimation. Thirdly, using typical statistical methods such as cluster analysis and correlation analysis, to calculate the important value, occurrence frequency, species diversity and other vegetation community parameters, determine the dominant species. Aimed at stress information extraction of individual plant, except sampling in the quadrat is indispensable step, still need to test the content of biochemical substances (pigment, water, etc.) and stress substances in laboratory, and then using the statistical methods to analyze the relationship between two substances, finally the influence mechanism of stress factor to the physiological structure of plants was clarified.

The BCS method has obtained a comparatively ideal result in a much smaller area, but it depends on the quadrat with sufficient density, and a large number of samples testing data are needed. Therefore, the cost of BCS method will proliferate as the range of research area get larger. However, at present, we pay more attention to analyze the dynamic change of coastal wetland vegetation on a larger scale, and BCS method is difficult to obtain real-time update the data. In addition, the implementing prerequisite of BCS method is that the sampling is not limited by topography and climate, which is particularly difficult in coastal wetlands of complex terrain. Thus, in this section, the BCS method is not discussed in detail and we will focus on the remote sensing method.

3.1. Methods for information extraction of individual plant under various stress factors

Coastal vegetation was subjected to salt stress under the influence of sea water encroachment. The increased frequency of extreme drought put forward a challenge to the drought-resistance ability of vegetation. Greenhouse gas dissolved in the water to form excessive amounts of carbon ions, which became the new stress factor of submerged plants. Thus, by studying the response of plants to salt, drought or carbon stress, qualitative identification of stress types and quantitative extraction of stress information were carried out.

Plant leaf spectrum is the result of the interaction between the incident electromagnetic wave, biochemical parameters and intercellular space. Plant physiologists have conducted on the response analysis of plant physiology-ecology to various stress factors. It is concluded that stress factors lead to the variation of biochemical parameters or internal structure, thus forming significant differences of leaf spectrum, which is the theoretical basis for extracting vegetation stress information using leaf spectrum. The waveform differences and diagnostic indices were derived from visible to near-infrared bands to extraction the environmental stress of plants, such as heavy metal [32, 33], salinity [23], hydrocarbon [34], etc.

In the 1990s, with the emergence of hyperspectral technology, the quantitative extraction of vegetation biochemical parameters has been developed rapidly, which are mainly attributed to (1) empirical statistical approach: the regression equation between the content of stress substances and band value was established, and the band values are usually the original reflectance or its transformation form (such as derivative, logarithmic, etc. [35]) which strongly correlated with stress factors. Based on the regression equations, the stress substance contents of unknown samples are predicted. In recent years, the transformation form of vegetation reflectance has improved to extraction the stress information. For example, the plant spectrum after the continuum-removal can suppress the environmental background information, enhance the absorption characteristics [33]. Wavelet transform can extract the detailed energy information by separating the plant spectrum into high and low frequency [36]; (2) semi-empirical statistical approach: also known as vegetation index method, with the deepening of the research on the formation mechanism of vegetation spectrum, a more vegetation indices were developed for estimating the biochemical parameters. Vegetation index is a linear or non-linear combination of two or several band values, resulting in an index that is highly correlated with the certain biochemical substance. Researchers mostly use the existing vegetation indices that can characterize chlorophyll, water and cell structure, etc. (shown in **Table 2**), and test the indication ability of vegetation indices to stress substances, so as to achieve the purpose of monitoring plant stress information [37].

3.2. Methods for discrimination of plant species

A variety of remote sensing methods have been developed for the discrimination of plant species, which can be divided into three types. The first is the discrimination method based on vegetation index, which mainly uses the typical steep slope effect of vegetation spectrum

Biochemical Parameter	Vegetation index	Calculation formula
Chlorophyll	Normalized differential vegetation index (NDVI)	$(R_{864}-R_{671})/(R_{864}+R_{671})$
	Modified chlorophyll absorption ratio index (MCARI)	$\left[(R_{700}-R_{670})-0.2(R_{700}-R_{550})\right](R_{700}/R_{670})$
	Normalized differential chlorophyll index (NDCI)	$(R_{680}-R_{460})/(R_{680}+R_{460})$
	Absorption depth at 671 nm ($Depth_{671}$)	Removing continuum of spectrum from 569 to 763 nm
Water	Water index (WI)	R_{870}/R_{950}
	Normalized differential water index (NDWI)	$(R_{860}-R_{1240})/(R_{860}+R_{1240})$
	Absorption depth at 983 nm ($Depth_{983}$)	Removing continuum of spectrum from 933 to 1094 nm
Cellular structure	Structural independent pigment index (SIPI)	$(R_{800}-R_{450})/(R_{800}-R_{680})$
	Photochemical reflectance index (PRI)	$(R_{570}-R_{531})/(R_{570}+R_{531})$
	Red-edge vegetation stress index (RVSI)	$((R_{712}+R_{752})/2)-R_{732}$
Plant healthy status	Red edge position (REP)	Band corresponding to the maximum value of a first derivative

Table 2. The calculation formula of existing vegetation indices.

to distinguish vegetation and non-vegetation, but the identification effect of different plant species needs to be verified [38, 39]. The second is the discrimination method based on the multi-temporal information, which uses to distinguish vegetation species with significant differences on the growth cycle [40, 41]. The third is the discrimination method based on machine learning algorithms such as neural network [42], expert decision classification [43] and so on. The knowledge representation and establishment of reasoning mechanism are the problems that need to be solved in the application.

Hyperspectral remote sensing provides more data sources for the discrimination of plant species. Previous studies have showed that the unsmooth spectral resolution of multi-spectrum images is a bottleneck to improve the recognition precision of plant species. The detailed diagnotic features of hyperspectral make up for the deficiency of multispectral and gradually form two typical discrimination method of plant species. One is mathematical statistics method based on the dimensionality reduction of hyperspectral image, such as principal component analysis (PCA), MNF transform, wavelet transform and so on. However, this method only uses limited spectral information that does not reflect the physical formation mechanism of vegetation spectra. The other one is, by comparing the spectral waveform difference of various plant species, extracting the spectral characteristic parameters to quantify the difference, such as spectral feature fitting (SFF) [44], spectral angle mapper (SAM) [45] and so on.

3.3. Methods for dynamic change analysis of vegetation landscape pattern

The precondition of change analysis of vegetation landscape pattern is to determine the spatial parameters of vegetation community such as area and position. The traditional classification methods of remote sensing include visual interpretation, supervised and unsupervised classification, expert decision classification, neural network, vegetation index and so on. Some literatures compare the ability of different classification methods to extract vegetation community information, and results indicate that (1) the maximum likelihood classification in supervised classification have high efficiency and strong robustness [46], (2) band combination method and multi-temporal linear transformation method can effectively improve classification accuracy [47], (3) the classification accuracy of intelligent learning algorithms is more robust for the complicated geomorphic features [42]. In addition, the object-oriented classification is a newly arising method which is more widely used to vegetation distribution mapping, and the classification accuracy is generally higher than the traditional image-element classification method [4]. However, it is necessary to carry out the classification accuracy evaluation and robustness test in the multi landform environment. The dynamic characteristics of landscape pattern can reflect the interaction of various contradictions and external forces of vegetation, which was mainly analyzed by using the vegetation landscape index. At present, the relevant study in the dynamic changes is mainly concentrated in mangrove wetland landscape. For example, on the basis of identifying the dynamic changes of mangrove in Vietnam, Seto and Fragkias selected the maximum plaque index, patch number, patch size, fractal dimension, landscape shape index, etc., to reveal the changes of mangrove health and landscape heterogeneity [48].

3.4. Methods for vulnerability assessment of coastal wetland vegetation

The studies on the vulnerability assessment of coastal ecosystem in respect to sea level rise have been carried out since the 1980s, which to form several models. The latest and relatively perfect SPRC model was developed by European Union, which can reflect the effect process of '*Consequence*' of '*Source*' with '*Pathway*' on the '*Receptor*' [49]. '*Source*' (*S*) represents the affect factors of coastal wetland ecosystem. '*Pathway*' (*P*) is the tie between source and receptor. '*Receptor*' (*R*) represents the coastal wetland ecosystem. '*Consequence*' (*C*) represents the results of receptor under the influence of source. However, there is no definite method to evaluate the vulnerability of coastal wetland vegetation. Thus, in this section, according the conceptual framework of SPRC model, we analyze the factors with respect to vegetation in four steps (*S*, *P*, *R*, *C*), and then build the vulnerability assessment model of coastal wetland vegetation (shown in **Figure 6**).

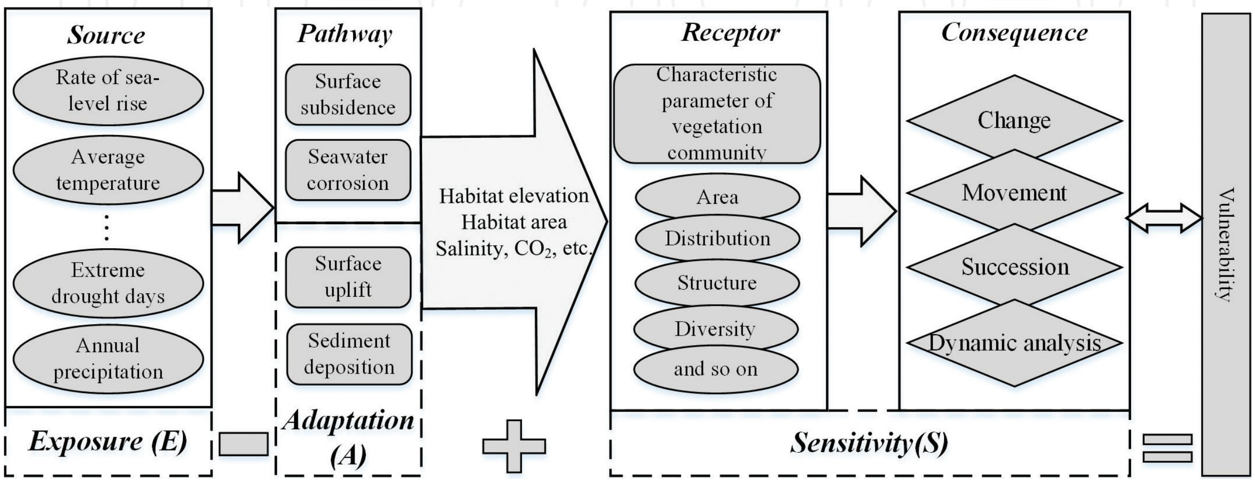

Figure 6. The SPEC model for vulnerability assessment on the coastal wetland vegetation.

(1) Analysis of '*Source*': sea level rise will change the water level of the intertidal zone and depositional dynamic condition and affect the submerge time of vegetation. In addition, extreme climate will also directly change the succession process of vegetation. **(2) Analysis of '*Pathway*':** the silt by the river to the sea, sediment moved by the waves, decaying organic matter from the dead branches and fallen leaves, soil subsidence induced by the artificial coastal engineering are the key factors affecting the rate of sea level rise. **(3) Analysis of '*Receptor*':** in this step, the landscape pattern indices will be analyzed, such as community structure, community area and distribution position of vegetation. **(4) Analysis of '*Consequence*':** vegetation will produce various response under the influence of climate change, such as the variation of community structure, movement of the distribution position, changes in the vegetation succession. However, the dynamic analysis of vegetation based on the multi-temporal image deserves more attention.

The index was classified into three groups for vulnerability evaluating, which including Exposure (E), Sensitivity (S) and Adaptation (A), and Vulnerability (V) and can be express in simple mathematical form: $V = E + S - A$. E refers to related climate change factors, mostly involved the index in '*Source*', such as rate of sea level rise, annual precipitation, etc. S represents the vegetation characteristic in response to climate change, mostly involved the index in '*Receptor*' and '*Consequence*', such as the change of community area and structure, landscape pattern indexes, etc. A represents the adapt ability of vegetation under the influence of climate change, mainly involved the index of analysis of '*Pathway*', such as sedimentation rate, annual sediment discharge, etc.

The evaluation indexes of E, S, A are digitized using the software platform of geographic information system (GIS), assign and store the indexes to the evaluation unit by combining the interpolation algorithm, and then building the geospatial quantization data of indexes in which spatial and attribute data are interrelated. Based on the above operation, the spatial overlay calculation of each vulnerability index layer was carried out, and then a composite layer with multiple index attributes was created, which is the ultimate vulnerability assessment index of vegetation.

4. Analysis of carbon sequestration characteristics of coastal wetland vegetation

4.1. Analysis of spatial distribution and temporal dynamic of vegetation sequestration

The spatial distribution of vegetation carbon storage is showing the trend of decreasing from high to low tidal flat, and the carbon storage increase gradually in the positive succession of vegetation [9, 50]. Growing in high-tidal flat and building a longer time of plant communities has become the main force of carbon sequestration. Invasive species have the absolute competitive advantage in the high salinity environment, because of its population density, carbon sequestration capacity is also higher. However, it is noteworthy that the strong reproductive and adaptive capacity of invasive species poses a great threat to indigenous plants, which makes their considerable carbon sequestration capacity lost its application value [51]. The temporal dynamic variation of vegetation carbon sequestration is similar to that of plant growth cycle, and the rapid accumulation of annual carbon sequestration occurs when the gradual enhancement of plant photosynthesis during April–July [51]. Aboveground biomass of vegetation is highest in summer and autumn, and then gradually falls down, which is allocated for breeding and root storage, so that the underground biomass is the highest in winter.

4.2. Analysis of spatial distribution and temporal dynamic of soil sequestration with respect to vegetation

The soil carbon stocks in the bare beach is lowest, which is because there is no higher plants distribution that organic carbon sources are limited [52]. In the middle-high-tidal flat, the carbon stocks of soil depend on the capture capacity of vegetation communities. Studies have shown that in the growth progress of plants, 10–40% of photosynthetic products migrate into the soil through root exudates, and most of the rest transform the organic carbon into soil through litter form, resulting in increased soil carbon stocks [53]. Therefore, soil carbon stocks reached the higher value in the dense area of plant root, which with the underground biomass of vegetation has a significant positive relationship. The soil carbon stocks in the wetland are the lowest in spring, and the plant residues in soil are decomposed rapidly with the increase of temperature, which forms the peak of carbon sequestration. In autumn and winter, the soil mineralization rate slows down with the temperature gradually decreases, the carbon accumulation rate is reduced, and the soil carbon stocks reach the highest value [52].

4.3. Extraction methods for carbon storage and carbon sequestration capacity of vegetation

The carbon storage and carbon sequestration capacity of wetland vegetation are two different concepts, which are calculated, respectively, based on the vegetation biomass and the net primary productivity. The carbon storage of vegetation refers to carbon stored in its existing biomass, while the carbon sequestration capacity refers to the fixed carbon capacity corresponding to the net primary productivity of vegetation [9, 52, 54].

1. Determination of vegetation biomass: in order to analyze the temporal characteristics of vegetation of carbon stocks, in all four seasons, setting up the sample plots in the survey area. A suitable number and area of parallel quadrats are set in each sample plot, after estimating the vegetation density in the quadrats, cutting the living part of plant by using the "W" or quincunx sampling method, bring back to the laboratory to calculated the aboveground biomass by multiplying the average weight by the density. After harvesting the ground parts of plant, dig out the corresponding roots, calculating the underground biomass by multiplying the average weight by the density.

2. Calculation of net primary productivity: the net primary productivity is the sum of biomass and ground litter of vegetation. The experiential proportion of allocation among aboveground and underground biomass was referenced in the relevant literature [9, 54], the ground litter is calculated from 5 to 10% of the existing biomass of aboveground part, and the net primary productivity of subsurface is calculated from 30 to 80% of the existing biomass of aboveground part.

3. Calculation of carbon storage and carbon sequestration capacity: the biomass of perennial herb and wood plants with more developed organs will increase every year, therefore their biomass and net primary productivity are different, which means that carbon stock and carbon sequestration capacity are different. However, the biomass and net primary productivity of wet shrubs, artificial cash crop, underwater plants and other annual wetland plants are the same. The carbon storage and carbon sequestration capacity are calculated based on the organic matter production process of vegetation (i.e. Photosynthesis). Every plant forming 1 g dry organic matter needs to assimilate 1.62 g CO_2 and fix 0.44 g carbon, and the carbon conversion coefficient can be determined to be 0.44. The calculating formula for the total carbon stock and total annual carbon fixation of wetland vegetation is:

$$C_i = pA_i Q_i \tag{1}$$

where A_i refers to the area of class *i* vegetation, hm^2. Q_i refers to the vegetation biomass (kg/m^2) or net primary productivity of class *i* vegetation ($kg/m^2 \cdot a$). *p* refers to the carbon conversion coefficient (0.44). C_i refers to the total carbon stock (*t*, when Q_i is the biomass of class *i* vegetation) or the total annual carbon fixation (*t/a*, when Q_i is net primary productivity of class *i* vegetation) of class *i* vegetation.

5. Summary and conclusions

The relative elevation drop and spatial loss of the habitat are the main driving factors of the coastal wetland vegetation succession under influence of climate change. The relationship between sea level rise rate and sediment accumulation rate determines the change of relative elevation, and then affects the flooding degree of plants. Landward movement of coastal wetland can avoid the habitat loss to a certain extent, but depends more on the terrain in the moving path. Long-term salt stress leads to the withdrawal of the low-salt-tolerant plant from the community competition, and ocean acidification caused by an increase in dissolved inorganic carbon concentrations cannot be neglected, which changed the photosynthetic activity of submerged plants. The dispersion of vegetation landscape patches increased high salinity or artificial crops will gradually erode the natural vegetation communities. Finally, the reverse or secondary succession of vegetation will be resulted, which accelerated the alien species invasion, and even worse, it will lead to the vegetation transformed into the bare flat.

Remote sensing technology provides a more effective method to analyze the change of coastal wetland vegetation under the climate change. The relationship between the stress factor and vegetation spectrum is established by using the vegetation index which often used to express the leaf biochemical substances (pigment, water, etc.). A mature method system based on multispectral image has established to extraction the spatial information of vegetation community, however hyperspectral show a better potential, which is needed to further develop the specially algorithm. Various landscape indices are used to reflect the dynamic change of landscape pattern, which can reveal the change of landscape heterogeneity. A fragility evaluation model of coastal wetland vegetation was established base on the conceptual framework of SPRC model.

The rapid accumulation of vegetation carbon sequestration occurs in the period of stronger photosynthesis. However, the invasive species with considerable carbon stock has lost its application value. The soil carbon storage has a significant linear relationship with the underground biomass of vegetation, and reached the highest value in winter. Carbon stock and carbon sequestration ability are calculated on the basis of biomass and net primary productivity, respectively. Unlike the annual plants, because of the biomass of perennial plants increased every year, its biomass and net primary productivity is different.

Combined with the above analysis results, the future research needs to be improved or expanded from the following aspects. (1) The reclamation of coastal wetland will accelerate the degradation of vegetation function. However, the relationship between the reclamation type and climate change, and the combined influence mechanism of various factors on the vegetation need to be further explored. (2) Remote sensing method shows the outstanding potential for vegetation stress analysis, while the field data collection is also an essential step. Therefore, the combination of the botany sampling method and remote sensing will help to improve the standardization of sampling data, so that the results of remote sensing survey from point to surface are more accurate. (3) Compared with other habitat environment, coastal wetlands are particularly special because of its periodically inundated with water. Therefore, it is very important to develop the remote sensing method considering the influence of seawater submergence, to extraction the information of vegetation community. In addition, the study on the landscape dynamics change of mangrove forest is relatively mature, but there are few researches on the other coastal wetland types, especially the typical river-sea interactive wetland. (4) Firstly, analyzing the distribution pattern of carbon source of vegetation by using "3S" detection method, and to realize the scale transformation from point to surface. Secondly, exploring vegetation carbon storage processes in response to climate change, especially seagrass beds. Finally, by combining the carbon storage process and remote sensing data, establishing a "coupling model of carbon process-remote sensing", to realize the scale conversion from process to region.

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