IMPACTS OF SPARTINA ALTERNIFLORA EXPANSION ON LANDSCAPE PATTERN AND HABITAT QUALITY: A CASE STUDY IN YANCHENG COASTAL WETLAND, CHINA

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Abstract. Yancheng National Nature Reserve (YNNR) in Jiangsu province is the largest wintering habitat for red-crowned cranes (*Grus japonensis*) in the world. However, the *Spartina alterniflora* (*S. alterniflora*) expansion had caused a series of ecological problems. In the paper, by using ETM + images as data source, GIS technology and the InVEST model were used to analyze the influence of *S. alterniflora* expansion on the landscape pattern and habitat quality through scenario simulation. We found that: from 2000 to 2020, under the current conditions, the percentage of landscape (PLAND) of *S. alterniflora* marsh would increase from 17.525% to 51.522%, which would result in a risk of extinction for the *Suaeda salsa* (*S. salsa*) marsh; the habitat quality index (Q) would be decreased from 0.8183 to 0.7074. Under the condition of removing *S. alterniflora*, the PLAND of *S. salsa* marsh would be restored to 43.8317%, and the Q would be increased to 0.9463. Under the condition of controlling *S. alterniflora* expansion, the PLAND of *S. alterniflora* marsh would be decreased to 8.678%, the PLAND of *S. salsa* marsh would be restored to 43.8653%, and the Q would be increased to 0.9198. The results would be beneficial to the management of the YNNR.
Keywords: *scenario simulation, habitat protection, species invasion, InVEST, the YNNR*

Introduction

The Yancheng coastal wetland is located in the middle of the Jiangsu coast. It is one of the most typical and representative distribution areas of muddy coastal wetlands integrating tidal flats, tides, rivers, salt marshes, *Phragmites australis* (*P. australis*) marshes, and *Spartina alterniflora* (*S. alterniflora*) marshes in China and in the world. It is the first world natural heritage site in Jiangsu province, the first natural heritage site of a coastal wetland in China, and the second such site in the world. Yancheng Coastal Wetland has basically maintained its natural ecological structure and function (Liu et al., 2003) with the Yancheng National Nature Reserve (YNNR) and Jiangsu Dafeng Elk National Nature Reserve. There are 17 species listed in the International Union for Conservation of Nature (IUCN) red list of species. It is an irreplaceable natural habitat that provides protection for rare and endangered migratory birds and has global value.

S. alterniflora is a perennial herb that is native to the west coast of the Atlantic and the Gulf of Mexico. It plays an important role in protecting coastal wetlands from wave erosion because of its rapid spread and great ability to promote silt deposition (Ayres et al., 2002). Therefore, *S. alterniflora* was successfully introduced in Yancheng coastal wetlands in the 1980s. In the 1990s, a large community was formed and rapidly expanded, and the species has become the dominant vegetation in the YNNR. The invasion of *S. alterniflora* has caused significant changes to the native ecosystems, including alteration of habitat structures, the extinction of native species, and altered

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ecosystem productivity (Vitousek et al., 1996; Pimentel et al., 2000; Neira et al., 2006; Liao et al., 2008; Wang et al., 2008). Invaders can have spatially variable effects on the ecosystem structure and function through their exploitation of different patches as they advance across landscapes (Sharp et al., 2019). The expansion of *S. alterniflora* has reduced the living space of other intertidal organisms and caused negative ecological effects (Liu et al., 2009). Cranes and other rare species primarily forage in *P. australis* marshes and *S. salsa* marshes in Yancheng Coastal Wetland (Wang et al., 2019). The landward expansion has led to the loss and fragmentation of *S. salsa* marshes, which is used as a wintering habitat for cranes.

The impact of the invasion of *S. alterniflora* on the coastal wetlands has become an important research topic in recent years (Liu et al., 2007; Schindler et al., 2013; Ayres et al., 2004). However, most studies focus on the population scale. *S. alterniflora* competes with native plants, and the habitat fragmentation of *P. australis* communities has led to the forced miniaturization of *Paradoxornis heudei*, which depends on these habitats (Dong et al., 2010). The invasion of *S. alterniflora* has resulted in the gradual shrinking of the habitat areas of *S. salsa*. This has led to significant changes in the spatial distribution pattern of the nesting sites of *Saunders's gull* during the breeding period, which has had a significant impact on the population (Liu et al., 2009). The invasion has also led to a large reduction of suitable wetland areas for red-crowned cranes to live and feed, which has had a certain impact on the dynamic distribution of their wintering population (Liu et al., 2016; Wang et al., 2019).

The mentioned study clarified the influence of *S. alterniflora* expansion on population dynamics, which could provide a scientific basis for the protection of specific population. With the extensive application of remote sensing technology, studies have been widely carried out on the impact of *S. alterniflora* expansion on the landscape pattern (Zhang et al., 2013; Wang et al., 2014; Fang et al., 2014). In this context, the InVEST model was used to analyze the impact of *S. alterniflora* expansion on habitat quality at the landscape scale. We examined how much the expansion could extend in the study area in the future and what it could look like. From the perspective of sustainable development of nature reserves, we also examined the possible trends of landscape change and habitat quality development of nature reserves in the future, which would provide reference for the sustainable construction and management of the research area.

Material and methods

Study area

The YNNR is located at 32°20' N - 34°37' N and 119°29' E - 121°16' E (*Fig. 1a*). It covers 4.533×10^5 hm2, and the length of the coastline is 582 km. The YNNR is located in a transition zone between a subtropical zone and a warm temperate zone. It was established in 1983 and upgraded to a national nature reserve in 1992. It is an important member of the World Biosphere Reserve, the Northeast Asia Crane Network, and the East Asia-Australia Wader Migration network and has been added to the list of Wetlands of International Importance.

The core zone of the YNNR has a total area of 1.92×10^4 hm^2 and reaches the Xinyang River in the north, the Doulong River in the south, the seawall road in the west, and the edge of mudflats in the east (*Fig. 1b*). It is a typical tidal muddy wetland. The core area of the YNNR is divided into north and south areas by Zhonglugang Road. In the north, a project was carried out for the artificial restoration of *P. australis*

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marshes in an area that covers about 0.52×10^4 hm^2. The southern part is weakly affected by human activities, and the evolution of the landscape pattern is mainly affected by natural factors such as climate, topography, hydrology, soil, and vegetation. It has become a typical area with natural conditions and covers about 1.11×10^4 hm^2. The southwest is an aquaculture pond with an area of 0.29×10^4 hm^2. In this study, the area of natural conditions was selected as the study area (*Fig. 1c*), in which the development of *S. alterniflora* is typical and well preserved.

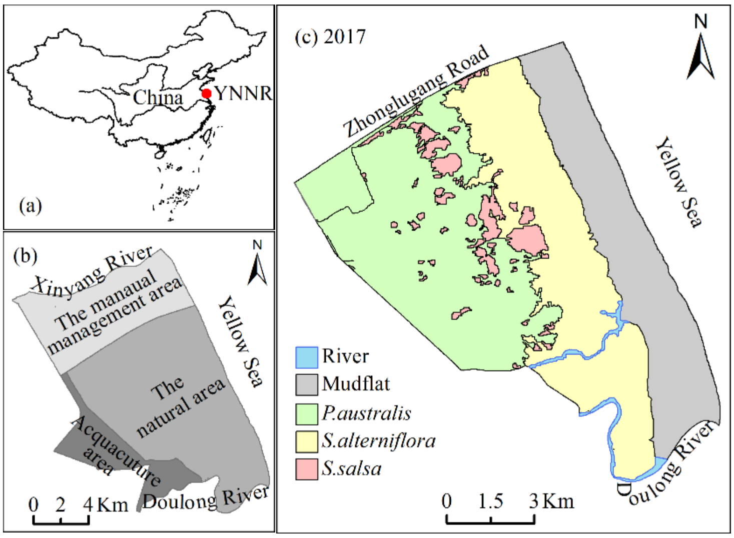

Figure 1. *The location and scope of the study area. (a) The Yancheng National Nature Reserve (YNNR) is located in the central east coast of China. (b) The scope of the core zone of the YNNR. (c) Landscape classification of the study area in 2017*

Data source and landscape type

The ETM + remote sensing images in May 4, 2000, May 21, 2006 and September 24, 2011 were used as data sources. The ETM + remote sensing image includes seven multispectral images and one panchromatic image, and the former has a resolution of 30 m while the latter has a resolution of 15 m. In ENVI 5.0, on the basis of atmospheric correction and geometric correction, the methods of the unsupervised classification and the decision tree classification were used to interpret the remote sensing images. In ArcGIS 10.0, the landscape type maps were completed, as shown in *Figure 2*. A coastal wetland is a complex natural complex between the land and sea with various types of ecosystems. The landscape in the core area of the YNNR is divided into three categories: natural wetland, artificial wetland and non-wetland. The division is based on the landscape characteristics of the study area and the definition of the Convention on Wetlands of International Importance as a Waterfowl Habitat. The natural wetland includes five types: *P. australis* marsh, *S. salsa* marsh, *S. alterniflora* marsh, mudflats, and rivers. The artificial wetland are aquaculture ponds, and the non-wetland area are dams.

Landscape pattern analysis

To analyze landscape pattern change, FRAGSTATS 4.2 was developed by the United States Department of Agriculture (USDA). Six landscape indices describe the characteristics of the landscape structure composition and spatial configuration of the

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Percentage of Landscape (PLAND): the Fractal Dimension Index (FRAC), Shannon's Diversity Index (SHDI), Landscape Dominance Index (LDI), Landscape Evenness Index (SHEI), and Aggregation Index (AI). The landscape transfer matrix can also help to explain how the composition and types of landscape change. It can also comprehensively and concretely describe the structural characteristics of the landscape and the changes of quantity and direction between landscape types.

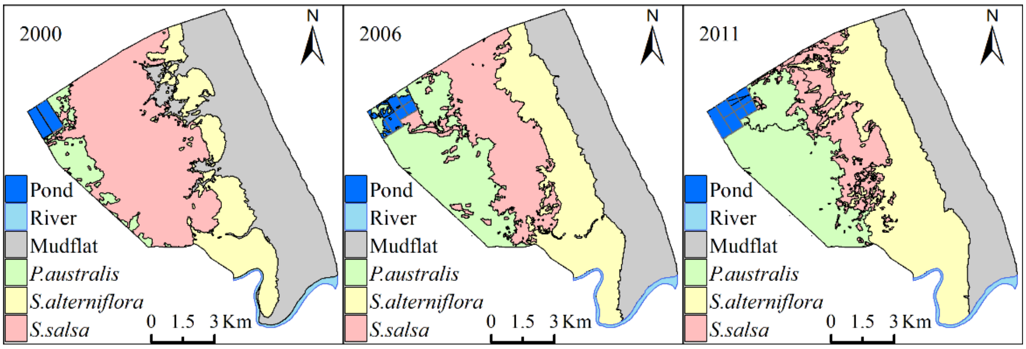

Figure 2. *Landscape type maps in 2000, 2006 and 2011*

Landscape change scenario simulation

A mechanism model (V 1.0) was developed for the landscape pattern of Yancheng coastal wetland based on the soil moisture and salinity processes (Software copyright: No.01678102, 2017). The model was designed by using the platforms ArcGIS 10.0 and MATLAB 2008. It can dynamically display the regional landscape changes and explain their mechanisms from the perspective of ecological processes (Zhang et al., 2014)

The system is composed of four parts. First, the main program reveals the relationship between landscape pattern change and ecological process. The second is that time function requires continuous changes in time and can realize the landscape simulation of any time (unlimited time interval) in the study area. The third part is visual expression, and the fourth part is used to call commands.

The model includes the threshold parameters of soil moisture and salinity of different types of landscapes and their annual change parameters, which are driven by different factors (Zhang, 2018). In this study, the soil moisture and salt parameters were adjusted based on the landscape types and soil moisture and salinity in 2011 to simulate the landscape pattern changes in 2020 under different scenarios. The change of the landscape pattern was simulated under three scenarios: the current situation (Scenario A), *S. alterniflora* would continue to expand in accordance with the present natural conditions and without any interference. Removal of *Spartina alterniflora* (Scenario B), *S. alterniflora* would be removed completely through certain artificial measures. Ecological restoration (Scenario C), *S. salsa* marsh would be restored and the expansion of *S. alterniflora* to *S. salsa* marsh would be controlled by techniques.

In the study, we used the images of 2017 to verify, and the overall accuracy of the simulation was 82.03%. The Kappa coefficient value was 0.72. When the Kappa coefficient was greater than 0.7, the consistency between the simulation result and the real value was considered to be quite satisfactory (Monserud and Leemans, 1992; Landis and Kochm,1997).

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Habitat quality assessment

The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model were developed by Stanford University, The Nature Conservancy (TNC), and World Wide Fund for Nature or World Wildlife Fund (WWF) to simulate the change of quality and value of ecosystem processes under different land cover scenarios. The biodiversity module in the InVEST model can assess changes in habitat quality in different times. In the model, habitat quality is generally affected by threat factors, habitat suitability, and ecological protection policies. Relevant parameters are shown in *Tables 1* and *2*.

Table 1. *Attribute table of ecological threat factors*

Threat factors	Maximum impact distance (km)	Weight	Linear correlation of regression
Aquaculture pond	1	0.6	0
River	3	0.4	1
Road	5	0.8	1
S. alterniflora	3	0.8	0

Table 2. *Habitat suitability and sensitivity to threat factors of different landscape types*

Landscape types	Habitat suitability	Aquaculture pond	River	Road	*S. alterniflora*
Aquaculture pond	0.5	0	0.5	0	0.5
River	0.5	0.5	0	0.8	0.5
Mudflat	0.8	0.5	0.3	0.3	0.8
Road	0	0	0	0	0
P. australis	1	0.3	0.6	0.6	0.5
S. alterniflora	0.5	0.5	0.5	0.7	0
S. salsa	1	0.5	0.8	0.5	0.8

The threat factors and habitat suitability are based on whether they are beneficial to the health of habitats of rare species, such as red-crowned cranes. The InVEST model can use either a linear or an exponential model depending on the particular relationship between the distance-decay rate of a threat and the maximum effective distance to a threat. The habitat quality index was calculated as follows (Sharp et al., 2017):

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r} \right) r_y \, i_{rxy} \beta_x s_{jr} \quad \text{(Eq.1)}$$

In this equation, D_{xj} is the habitat degradation index, which characterizes the degree of habitat degradation. R is the number of threat factors, y_r is the number of grid cells on the threat factor layer, w_r is the weight value of the threat factor, r_y is the number of raster unit threat factors in the layer, i_{rxy} represents the influence degree of threat factor r in grid y on habitat grid x, β_x is the degree of protection, and s_{jr} is the sensitivity of the threat factor, which refers to the degree of change of different landscape types under the influence of threat factors with a range of 0 to 1.

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \quad \text{(Eq.2)}$$

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In this equation, Q_{xj} is the habitat quality index, H_j is the habitat suitability, which refers to the suitability of different landscape types for reproduction, habitat and activities of organisms, ranging from 0 to 1. D_{xj} is the degree of habitat degradation, and *k* is the half-saturation coefficient, which is set to 15 (half of the grid resolution). z is generally set to 2.5.

Results

Landscape pattern changes

The landscape change in Yancheng Coastal Wetland is the result of human activities and natural conditions. Human activities mainly include building dams and roads, artificial breeding, and the introduction of exotic species. The natural conditions include hydrogeomorphic processes, vegetation processes, and soil processes. Natural conditions are a basic driving force for the change of coastal wetland landscapes. Human activities change the natural conditions of coastal wetlands, resulting in the change of the landscape.

The landscape structure of the study area in the YNNR is dominated by *P. australis* marsh, *S. salsa* marsh, *S. alterniflora* marsh, and mudflats (*Fig. 2*). The change of the landscape structure showed that the areas of *P. australis* marsh and *S. alterniflora* marsh were expanding constantly, and the area of the *S. salsa* marsh was obviously decreasing. From 2000 to 2011, the PLAND of the *P. australis* marsh increased from 5.042% to 23.601%, that of the *S. alterniflora* marsh increased from 17.525% to 34.466%, and that of the *S. salsa* marsh decreased from 36.910% to 14.414%.

In 2000, 2006, and 2011, the FRAC was 1.046, 1.038, and 1.035, respectively. The continuous decline of the FRAC indicated that the landscape patches in the study area had a trend of regular development. The AI in 2000, 2006, and 2011 was 95.453, 95.553, and 95.244 respectively, showing a slow trend of first rising and then falling with weak change overall. This indicated that the landscape changes in the study area were generally subject to less artificial interference and followed the laws of natural development with a high degree of aggregation among different landscape types. From 2000 to 2011, the SHDI first increased and then decreased. In contrast, the LDI first decreased and then increased. From 2000 to 2006, the proportion of different landscape types developed towards a relatively balanced situation, and the LDI declined due to the expansion of *P. australis* and *S. alterniflora* and the decrease of *S. salsa* marsh. From 2006 to 2011, the *S. salsa* marsh continued to decrease with the continuous expansion of *P. australis* and *S. alterniflora*, the proportion of different landscape types began to develop imbalance again, and LDI increased.

The expansion rate of the *S. alterniflora* marsh was first slow and then became faster. From 2000 to 2006, the annual expansion rate was 163.167 hm^2/a, which was significantly lower than the rate of 182.364 hm^2/a from 2006 to 2011. The variation trend of the FRAC and AI of the *S. alterniflora* marsh was not obvious from 2000 to 2011. The FRAC values in 2000, 2006, and 2011 were 1.031, 1.049, and 1.030, respectively, which indicated that the shape of the *S. alterniflora* marsh changed little in the natural state. The AI in 2000, 2006, and 2011 was 89.712, 94.605, and 94.336, respectively. The spatial aggregation of the *S. alterniflora* marsh showed consistent characteristics with the overall landscape.

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Habitat quality changes

From 2000 to 2011, the habitat quality in the study area showed an overall degradation trend (*Fig. 3*). The habitat quality index (Q) decreased from 0.8183 to 0.7569 (a decrease of 7.5034%). From 2000 to 2006, the Q decreased from 0.8183 to 0.7924 with an average annual decrease of 0.0043. From 2006 to 2011, the Q decreased to 0.7569 with an average annual decrease of 0.0071. Habitat quality declined more rapidly in the latter period than in the previous period. The decrease of habitat quality was closely related to the expansion speed of the *S. alterniflora* marsh.

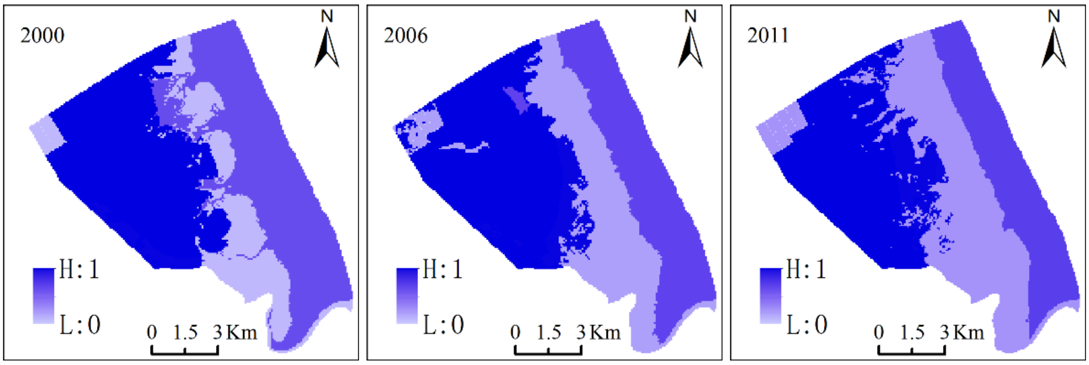

Figure 3. *Habitat quality maps in 2000, 2006 and 2011*

According to the classification method of equal intervals, the Q of the study area was divided into four intervals of 0–0.25, 0.25–0.5, 0.5–0.75, and 0.75–1, which indicate poor, general, good, and excellent habitat quality, respectively. As shown in *Table 3*, the overall habitat quality of the study area was relatively high and was rated as excellent in most areas, followed by general grades and poor grades with no distribution of good grades.

Table 3. *Habitat quality classification statistics from 2006 to 2011*

Grading ranges	**2000**		**2006**		**2011**	
	Area ($\times10^2$hm^2)	**Percentage (%)**	**Area ($\times10^2$hm^2)**	**Percentage (%)**	**Area ($\times10^2$hm^2)**	**Percentage (%)**
0-0.25	0.070	0.064	0.114	0.104	0.200	0.182
0.25-0.50	22.208	20.189	32.448	29.498	42.026	38.205
0.50-0.75	0	0	0	0	0	0
0.75-1.00	87.722	79.747	77.438	70.398	64.774	61.613

There was a trend of polarization in habitat quality in the study area. The changes of the proportion of the space area of the three grades were compared. The areas with excellent habitat quality showed a continuous decline, and the proportion of such areas dropped from 79.747% in 2000 to 61.613% in 2011 (a decrease of 22.739%). The areas with general and poor habitat quality increased. The proportion of areas with poor habitat quality increased from 0.064% in 2000 to 0.182% in 2011 (nearly double). Areas of general habitat quality increased from 20.189% in 2000 to 38.205% in 2011 (an increase of 89.237%).

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Discussion

Factors affecting the S. alterniflora expansion

Due to very strict environmental protection policies, human activities in the research area are weak, so the expansion of *S. alterniflora* is mainly driven by natural factors such as climate, hydrological dynamics, geomorphic processes, and vegetation. The main factors are coastal geomorphic processes and the change of plant-cover types. The process of landscape change is continuous and stable. The spatial gradient changes of geomorphic processes and hydrological processes result in the landscape of the study area having a parallel belt pattern extending from north to south and changing from land to sea (Zhang et al., 2013).

The climate in the Yancheng coastal area is basically similar to the east coast of the United States, and the broad intertidal zone is very suitable for the growth of *S. alterniflora* (Callawayet al., 1999; Liu et al., 2004). The coast of the study area is also a typical muddy coast. Under the action of tides and tideways, the average high-water line keeps advancing towards the sea. The subtidal zone and lower intertidal zone are flat, and a tidal creek has developed (Zhang et al., 2006). The fast silting and the wide and gentle beach surface provide a good sedimentary environment for the development of *S. alterniflora*. The tidal amphidromic system of the South Yellow Sea and the tidal advancing system of the East China Sea meet at the Yancheng coast, which makes it difficult for the seeds of *S. alterniflora* to drift with the tides, and they fall on the beach to germinate (Liu et al., 2004).

The geomorphic processes affect the hydrological processes and then affect the physical and chemical properties of the soil, especially the moisture and salinity. Soil is an important driving force of landscape change and has a direct impact on the development and succession of vegetation. A comparison was conducted using elevation data from land to sea in 2002 and 2011 in the study area (*Fig. 4*) (Hou et al., 2003). The elevation changes from 2002 to 2011 showed an increasing trend overall, and the increasing degree of elevation gradually increased from *P. australi* marsh and *S. salsa* marsh, to *S. alterniflora* marsh. In 2002, the elevation gradually decreased from the land to the sea, but in 2011, the strong ability of *S. alterniflora* to collect silt led to the elevation being significantly increased in *S. alterniflora* marsh. As a result, the elevation of the study area had a “U” shape (Hou et al., 2013).

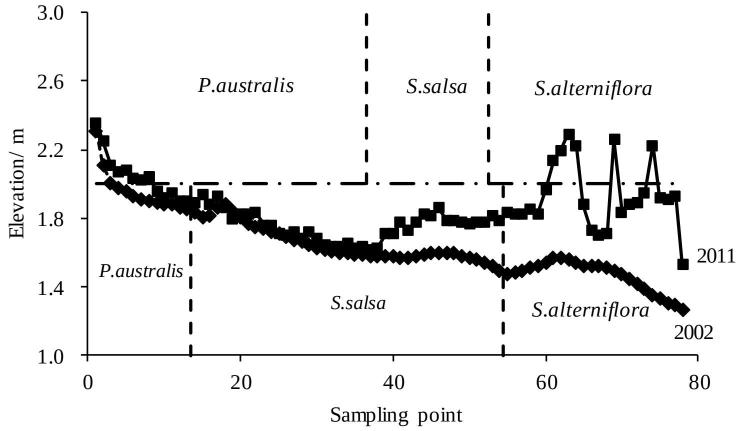

Figure 4. *Elevation changes from 2002 to 2011*

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Furthermore, the response of vegetation to hydrology and geomorphology promotes the expansion of *S. alterniflora*. *S. alterniflora* marshes are distributed in the upper of intertidal zone from the upper edge to the average high-tide level and to the lower edge to the average tide level. The frequency of tidal invasion is between 20% and 80%. The geomorphic processes provide a vast space and environmental conditions for the development of *S. alterniflora* (Zhang et al., 2004), forming an evolution pattern of a mudflat-*S. alterniflora* marsh. The native pioneer plant is *S. salsa*, which spreads and expands through seeds. Because of its short plants, a higher frequency of tidal invasion results in smaller plants and fewer branches, which seriously affect the expansion of *S. salsa* to the sea. Its niche cannot reach the tidal flat when the frequency of tidal invasion is more than 20%. Therefore, the expansion ability of *S. salsa* to the sea is far less than that of *S. alterniflora*, and it cannot match the expansion speed of the beach surface in a rapidly silted beach (Zhang et al., 2004; Hou et al., 2013).

As the elevation of the *S. alterniflora* marsh increased, a sharp decrease in the frequency of tides passed through it to reach the *S. salsa* marsh. This restricted the water and salinity conditions needed for the development of the *S. salsa* marsh and promoted the expansion of the *S. alterniflora* marsh to the lower edge of the *S. salsa* marsh. *S. alterniflora* has strong resistance to silting, wind, and waves, and it can grow in most areas of the intertidal zone (Yuan, et al., 2009). Therefore, the expansion of *S. alterniflora* is the fastest, leading to a change of the coastal wetland pioneer community from *S. salsa* to *S. alterniflora*.

S. alterniflora also has two ways of reproduction: sexual and asexual. Sexual reproduction has certain advantages in adapting to different environments. The genetic composition of progeny produced by asexual reproduction is always the same as that of the mother. However, *S. salsa* mainly depends on seed propagation and expansion. The plant is short and has a disadvantageous position in interspecific competition. Therefore, at the upper edge of the *S. alterniflora* marsh, the species can rapidly occupy the growth space when in competition with *S. salsa*, as well as absorb and utilize resources. Thus, it occupies more favorable habitat and forms the new evolution pattern of *S. salsa* marsh - *S. alterniflora* marsh in the study area.

S. alterniflora expansion affecting on landscape patterns

The spatial distribution, expansion characteristics, and pattern changes of *S. alterniflora* have a significant impact on the coastal wetland landscape. These factors change the composition of the landscape structure, the diversity, and the heterogeneity characteristics (Zhang et al., 2018). Diverse mechanisms of *S. alterniflora*, such as marginal expansion, external isolation expansion, and tidal creek expansion, have a profound impact on the landscape pattern changes (Wang et al., 2018). The introduction of *S. alterniflora* was successful, and the pioneer community and the dominant population in the coastal wetland gradually changed to S. alterniflora. The expansion of *S. alterniflora* changed the landscape succession sequence of the coastal wetland: the succession sequence of mudflat to *S. alterniflora* marsh appeared in the coastal wetland since the introduction of *S. alterniflora*, the succession sequence of mudflat to *S. salsa* marsh gradually disappeared after the formation of the ecotone between *S. alterniflora* and *S. salsa*, and the succession sequence of *S. salsa* marsh to *S. alterniflora* marsh appeared. From land to sea, the landscape spatial pattern changed from "*P. australis* marsh – *S. salsa* marsh – *S. alterniflora* marsh – mudflat" to "*P. australis* marsh – *S. alterniflora* marsh – mudflat."

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The landscape transfer matrix (*Fig. 5*) showed that from 2000 to 2006, in the source composition of *S. alterniflora* marsh, mudflats accounted for 34.331%, and *S. salsa* marsh accounted for 2.483%. From 2006 to 2011, the mudflat accounted for 10.591%, and *S. salsa* marsh accounted for 14.503%. Comparing the two periods, *S. alterniflora* dominated the expansion towards the sea in the earlier period, while in the later period, *S. alterniflora* expanded to both the ocean and the land. The expansion to the land is greater than the expansion to the sea. From 2000 to 2006, the average width of the *S. alterniflora* marsh increased by 767.393 m, and it pushed forward to the sea about 965 m. From 2006 to 2011, *S. alterniflora* marsh expanded toward both the sea and the land. It expanded about 325 m to the sea and 445 m to the land, and the average width increased by 771.410 m (*Fig. 6*).

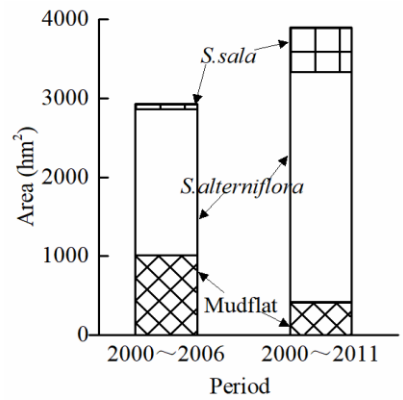

Figure 5. *Landscape composition transformed into S. alterniflora*

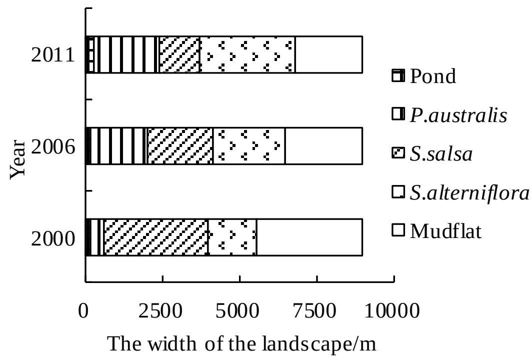

Figure 6. *Landscape pattern change of the study area*

According to the current development mode (Scenario A), by 2020, the PLAND of *S. alterniflora* marsh would increase to 51.522%, and the expansion rate would reach 210. 357 hm^2/a, while the PLAND of *S. salsa* marsh would decrease to 2.999% under two-way compression. In terms of the spatial pattern (*Fig. 7*), the *S. alterniflora* marsh would basically connect with the *P. australi*s marsh, and the competition between the *P. australi*s population and the *S. alterniflora* population for spatial resources would be the most intense in the middle tide wetland. Even in the local area of high-tide beaches, the *S. alterniflora* population could form small-scale patches and spread to the *P. australi*s population (Pan et al., 2012).

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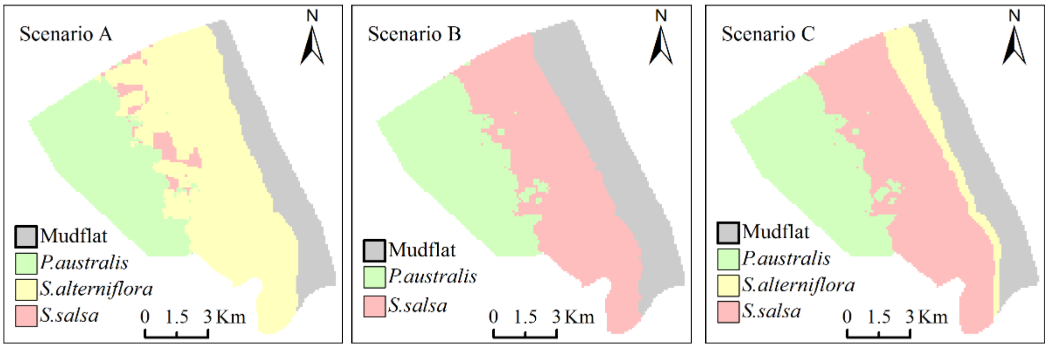

***Figure 7.** Simulation results of landscape pattern in different scenarios*

The expansion of *S. alterniflora* gradually formed a single plant community, which reduced the biodiversity of bird habitat and the number of suitable habitats (Wang et al., 2019). Furthermore, the structure of bird community tended to be simplified (Guntenspergen et al., 2006). The native species of *S. salsa* played an important role in the process of overwintering and reproduction for birds. Thus, it is necessary to take measures for the protection and restoration of the *S. salsa* marsh and to delay the expansion of *S. alterniflora* (Zhang et al., 2017). Scenario B examined the removal of *S. alterniflora*. By 2020, the PLAND of *S. salsa* marsh would be recovered to 43.832%, and *S. alterniflora* marsh would disappear (*Fig. 7*). In Scenario C, a certain scale of *S. alterniflora* would be reserved to protect the coast, and it would no longer expand to the direction of *S. salsa* marsh. Moreover, artificial measures would be taken to restore the evolution sequence from mudflat to *S. salsa* marsh. The results showed that by 2020, the PLAND of *S. salsa* marsh would be recovered to 43.865%, and the PLAND of *S. alterniflora* marsh would be controlled to 8.678% (*Fig. 7*). The landscape pattern index of the three models were compared, and the following results were obtained (*Fig. 8*): SHDI, scenario C > scenario A > scenario B; the difference of the FRAC was small, scenario A > scenario C > scenario B; SHEI, scenario B > scenario C > scenario A; AI: scenario B (98.0113) > scenario C (97.4472) > scenario A (97.0993).

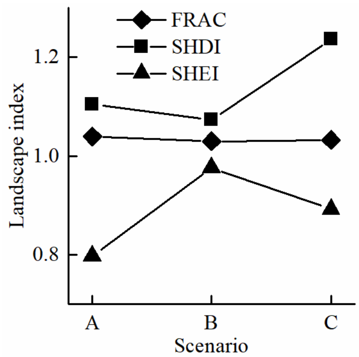

***Figure 8.** Landscape index scenario simulation results*

S. alterniflora expansion affecting habitat quality

The expansion of *S. alterniflora* changed the vegetation structure, geomorphic pattern, and hydrological processes in the study area, as well as the service function of

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the ecosystem. The benthos of *S. alterniflora* is rich, and the height of the vegetation on the surface is often more than 1.5 m. But the vegetation coverage of *S. alterniflora* is up to 90-100%, and there is no other vegetation among the plants after two or more years of growth. Consequently, *S. alterniflora* marsh is unsuitable for the habitat and reproduction of birds (Deng et al., 2009).

Furthermore, the blocking of *S. alterniflora* from the tide inhibited the growth of *S. salsa* (Shen et al., 2003) and had adverse effects on the birds that depend on the propagation and habitat of the *S. salsa* community, such as *Saunders's gull*, *Sternahirundo*, *S. albifrons*, and *Trigatotanus*. The results showed that with the expansion of *S. alterniflora,* the Q values of the study area showed a significant decline. Based on the remote sensing image analysis of YNNR from 1983 to 2017, it was found that the Q was negatively related to the expansion of *S. alterniflora*. Faster expansion of *S. alterniflora* correlated with a faster decline of habitat quality. In scenario A, *S. alterniflora* would continue to expand, and the Q would decrease to 0.7074. In scenario B, *S. alterniflora* would be removed, and the Q would increase to 0.9463. In scenario C, *S. alterniflora* would be controlled to a certain scale, and the Q would increase to 0.9198 (*Figs. 9* and *10*).

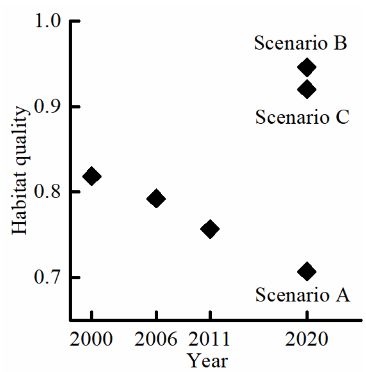

Figure 9. *The value changes of habitat quality*

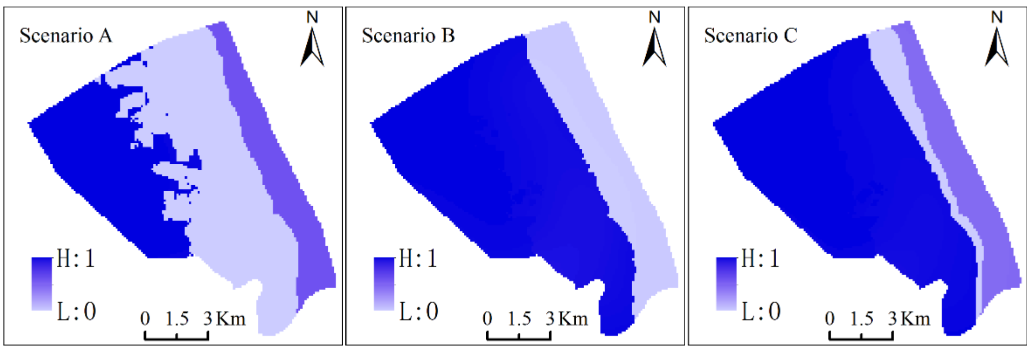

Figure 10. *Simulation results of habitat quality in different scenarios*

Based on the results, rich landscape diversity should be maintained along with the stability of the coast, and the wetland habitat quality should be improved. Scenario C would be a relatively ideal model for three reasons. First, it would help to retain a certain scale of *S. alterniflora* marsh, prevent erosion from tidal water on the coast, and

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promote the deposition of the beach surface, although further study is needed to determine the appropriate scale of *S. alterniflora*. Secondly, it would protect the local species *S. salsa* and improve the suitability of habitat areas for rare species such as the red crowned crane. Thirdly, it would maintain the landscape diversity; the SHDI of scenario C was the highest and reached 1.236.

Ecological engineering measures, physical engineering measures, and biological measures could be effective means to control the expansion of *S. alterniflora* based on maintaining the integrity and continuity of the coastal ecosystem. In addition, some research has shown that the changes in habitats caused by inventors could limit the inventors over time because the acquisition of habitat changes created certain habitat properties that exceeded the optimal range for inventors (Tang et al., 2012).

Conclusions

This study quantitatively evaluated the effects of the expansion of *S. alterniflora* on the landscape pattern and habitat quality in the YNNR. The results showed that the rapid expansion led to a sharp reduction of the local species of *S. salsa*, which has posed a serious threat to the biodiversity. The landscape pattern gradually changed from "*P. australi*s marsh – *S. salsa* marsh – *S. alterniflora* marsh – mudflat" to "*P. australi*s marsh – *S. alterniflora* marsh – mudflat." It affected the living environment of species that use the *S. salsa* community as a habitat and breeding ground. With the expansion of *S. alterniflora*, the habitat quality decreased significantly. Controlling the expansion of *S. alterniflora* and restoring the *S. salsa* marsh would be an ideal choice for the sustainable development of the YNNR. In the future, it will be an important task for the YNNR to control the *S. alterniflora* expansion and restore the *S. salsa* marsh. On one hand, we need to study the suitable scale of *S. alterniflora* in order to play its ecological function. On the other hand, we need to explore the approach of utilization for *S. alterniflora* and give full play to the comprehensive benefits.

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