



Article

Response of Landscape Evolution to Human Disturbances in the Coastal Wetlands in Northern Jiangsu Province, China

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Abstract: Human disturbance is one of the essential driving forces of landscape evolution. The quantitative evaluation of the spatial and temporal characteristics of landscape evolution and its relationship with human disturbance are of great significance to regional ecological protection and management and are crucial for achieving coordinated socioeconomic development and ecological–environmental protection. In this study, we took the coastal wetlands in northern Jiangsu province, China, as the research area, and proposed a quantitative evaluation method for directional landscape evolution. On this basis, the spatiotemporal characteristics of the landscape evolution from 1980 to 2020 and the relationship with human disturbance were quantitatively evaluated by combining a human disturbance index and statistical methods. The results showed that: (1) The area of the natural wetlands decreased significantly over the past 40 years, while the areas of artificial wetlands and non-wetlands increased significantly. (2) The landscape evolution process was dominated by the degradation process. The main types of degradation were natural wetland conversion to artificial wetland and non-wetland areas and *Spartina alterniflora* invasion. The restoration type was mainly restoration among artificial and natural wetlands. (3) The degradation of wetland landscapes demonstrated a southward shift trend and the spatial consistency with the change of the human disturbance index was high (the correlation coefficient was 0.89). (4) The human disturbance index was significantly and positively correlated with the rate of degradation, with a correlation coefficient of 0.43, and was not significantly and positively correlated with the restoration rate, with a correlation coefficient of 0.14. The findings in this paper provide additional information and theoretical guidance for the control of coastal wetland development and utilization, as well as for achieving coordinated wetland resource development together with utilization and ecological protection in the coastal wetlands of Jiangsu province, China.

Keywords: coastal wetlands; degradation; restoration; human disturbance; northern Jiangsu



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1. Introduction

A landscape is a heterogeneous geographical unit consisting of different ecosystem types over a certain extent of land [1]. The landscape pattern determines the form of the spatial distribution of its resources and environment and influences the regional ecological processes and functions. Coastal wetlands are important habitats and breeding grounds for offshore organisms and migration transit stations for birds, and are precious wetland resources with important ecological functions, such as water conservation, water purification, soil and water conservation, climate regulation and biodiversity protection functions [2,3]. They are also intersection areas for four major domains (the lithosphere, atmosphere, hydrosphere, and biosphere), with frequent material–energy exchange, as well as transition zones of sea–land ecosystems, with high degrees of vulnerability and sensitivity [2–4]. At the same time, coastal areas display active socioeconomic development,

strong human–land interactions, dramatic landscape changes, and prominent ecological and environmental problems. Under the influence of human activities, A large number of coastal wetland resources have been lost or degraded and coastal wetland landscapes have been transformed [5–7]. Compared to the first national wetland resources survey in China, the total area of coastal wetlands in the second national wetland resources survey decreased by 1,361,200 hectares (wetlands changed into uplands), with a reduction rate of 22.91%, which was higher than the average reduction rate of 8.82% for the national wetlands [7]. The loss or degradation of wetlands globally is currently a priority concern in many countries; therefore, quantitative assessment of the directional evolution characteristics of coastal landscapes (the term “directional” refers to wetlands loss, degradation, or recovery) and their relationship with human disturbance needs to be done to provide relevant information for the ecological conservation and management of coastal wetlands [8–11].

A large number of fruitful studies have been conducted by scholars on the spatial and temporal variation characteristics of wetland landscape evolution and its driving mechanisms (landscape evolution refers to the process of transformation of one landscape into another over time). The research methods are diverse, mainly including transfer matrices, landscape indices, and landscape models [11–16]. Transfer matrices are mostly used for parametric statistical analysis of the landscape evolution process, while landscape models are used for the prediction and evaluation of the landscape’s future evolution, and landscape indices are the most widely used in landscape evolution analysis, as these include highly condensed landscape pattern information and can reflect the landscape composition and spatial configuration characteristics. However, scale issues, ecological salience, and the connections with ecological processes still require further research [17]. Certain indicators (area, landscape index, etc.) are scalar indicators, which are static quantitative analysis methods that do not clearly characterize the direction of landscape evolution. In contrast, an ecosystem can be considered as a “self-organizing system limited by human activities” with multiple characteristics of self-organizing processes, some of which are directional in nature (e.g., landscape evolution) [18–23]. Cui et al. [2] and Müller et al. [23] combined landscape evolution sequences with directional discriminators for landscape degradation evaluation. The directionality of landscape evolution needs to focus on both degradation and restoration, which can reflect the direction of ecological environment (restoration or degradation), which is closely related to ecological security, conservation, and management. There is a need for relevant research in this field. This study will analyze the process and spatiotemporal characteristics of directional landscape evolution by introducing the landscape evolution model of coastal wetlands in northern Jiangsu constructed by Cui et al. [2] in 2015, combining the transfer matrix method to propose the evaluation index of directional landscape evolution (restoration or degradation).

Human disturbance refers to the influence of human activities on the natural environment or ecosystem [24], and was first used to describe the degree of influence of human activities on forest ecosystems [25,26]. The concept of the “degree of hemeroby” was proposed by the German ecologist Sukopp in 1969 [27] and was later translated by scholars as the “ecological disturbance degree” [28] and the “human disturbance degree” [29] and applied to landscape ecology research, particularly in the study of the influence of human disturbances on wetland evolution [7,8,30,31]. Generally, based on landscape data, disturbance levels are assigned to different landscapes, and a grid method is used to calculate the human disturbance index by area weighting. On the one hand, the integrity of natural geographic units and the attribution of administrative units are not considered in the grid division; on the other hand, the assignment of the degree of interference is mainly based on landscape data, which are highly subjective, meaning that different regions have different meanings for the same landscape and human activity intensity. Therefore, a method for assigning the degree of disturbance according to the regional characteristics is a key step in accurately and quantitatively evaluating the degree of disturbance and its relationship with landscape evolution, which is also a difficult research task.

In this paper, we chose the coastal wetlands in northern Jiangsu province, China, as the study area based on the eight-period remote sensing interpretation data from 1980 to 2020. We quantitatively evaluated the spatial and temporal characteristics of landscape evolution by introducing an improved directional landscape evolution model method and human disturbance index. We also revealed the relationship between landscape evolution and the human disturbance index and provided a scientific basis for the optimization of the wetland landscape pattern, ecological environmental protection, and management.

2. Data and Methods

2.1. Study Area

The coastal wetlands of northern Jiangsu, China, are located between the modern Yangtze River estuary and the abandoned Yellow River estuary and consist of three parts: the abandoned Yellow River delta alluvial plain, the Lixia River plain, and the northern flank of the Yangtze River delta, which is a typical silty plain coast (it is the most typical type of silty coastal are in not just China, but across the world) [32] (Figure 1). The area is home to the Yancheng National Rare Bird Nature Reserve and the Dafeng Elk National Nature Reserve, and also serves as an important transit point for approximately 3,000,000 seasonal birds in spring and autumn and nearly 200,000 waterfowl in winter, providing a critical habitat for rare threatened and endangered species that have an important position in the conservation of biodiversity in China [2]. In addition, the area is located at the intersection of the main axes of the productivity layout along the Yangtze River, along the Longhai Line, along the Shanghai–Nanjing Line, and along the coast, which has unique location conditions and an irreplaceable strategic position. After the founding of the People’s Republic of China, this area experienced sea salt development (salt field landscape), cotton cultivation (cotton field landscape), and reclamation for mariculture (mariculture landscape) and the harbor (harbor landscape). Human interference has strongly influenced the composition and structure of the landscape in the area, causing dramatic changes in the type of landscape, as well as significant regional differences, making it an ideal area for studying human interference and landscape evolution.

The study area spans 10 counties and cities, including Xiangshui county, Binhai county, Sheyang county, Dafeng city, Dongtai city, Hai’an city, Rudong county, Tongzhou district, Haimen city, and Qidong city. This paper defines coastal wetlands as supratidal wetlands, intertidal mudflats, and offshore potential mudflats. The ancient coastal dike built in the Song Dynasty, Fan Gong Dike, is roughly considered as the location of the high tide level, which is the western boundary of the mudflats; the multi-year average low tide level is the eastern boundary; the northernmost administrative boundary of Xiangshui county is the northern boundary; the southernmost administrative boundary of Qidong city is the southern boundary.

2.2. Landscape Data

Landsat MSS/TM/OLI data for 1980, 1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2020 were used in the study. This is mainly because these eight periods correspond well with China’s 5-year plan and the development stages of the study area, which is in line with the stages of coastal wetland development, which can highlight the stages of landscape evolution more. The landscape data were interpreted by researcher Guosheng Li and Dr. Linlin Cui from the Institute of Geographical Sciences and Resources, Chinese Academy of Sciences; associate researcher Jilong Chen from the Chongqing Institute of Green Intelligence, Chinese Academy of Sciences; and senior engineer Huajun Liao from SuperMap Software Co., Ltd., using a visual interpretation method based on Landsat data (a total of eight periods of landscape data). Based on the field survey data in 2015 and the 1:200,000 beach resource survey data in 1980s, the accuracy of the interpreted data in 2015 and 1980 was evaluated as being between 81.45 and 91.67%, respectively. Since the data for other years were applied with the same interpretation method as in 2015, the accuracy of the interpretation data was found to be relatively reliable and met our

application requirements. The specific method can be found in the literature [32], and some of the data have been used in the literature [2,18,32]. In addition, the landscape data showed that the mean patch area of the study area over the eight target years was 1.83–3.06 km², so 30 m Landsat pixels were sufficient for interpretation.

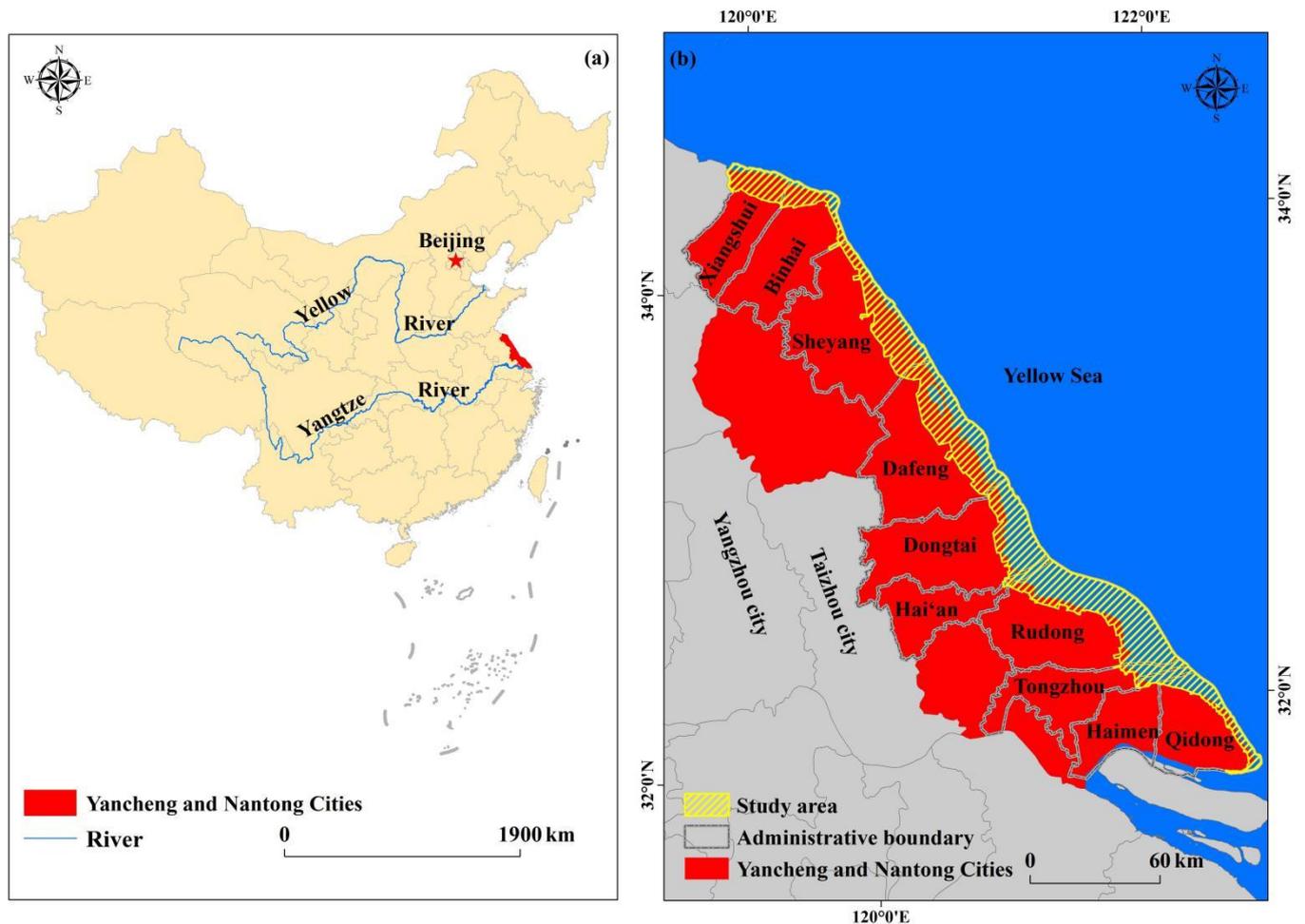


Figure 1. Location and extent of the research area, (a) locations of Yancheng and Nantong cities in China, (b) specific location of the study area in Yancheng and Nantong cities.

The landscapes included three major categories based on the National Wetland Resources Survey and Monitoring Technical Regulations (China): natural wetlands, artificial wetlands, and non-wetlands, among which the natural wetlands were divided into shallow marine waters, tidal flats, *Suaeda glauca*, *Phragmites australis*, grasslands, rivers, and *Spartina alterniflora*; the artificial wetlands were divided into pools, salt fields, aquafarms, and paddy fields; the non-wetlands were divided into drylands, woodlands, barelands, urban settlements, rural settlements, levees, and other construction lands (as shown in Figure 2).

2.3. Landscape Evolution Evaluation Method

The directional landscape evolution model was proposed in 2015 by Cui et al. [2,18], which combines landscape evolution with directional discrimination for the evaluation of the wetland landscape evolution directionality (Figure 3). In this study, the landscape evolution direction was divided into the restoration direction and the degradation direction, while the evolution within non-wetlands was not part of this study.

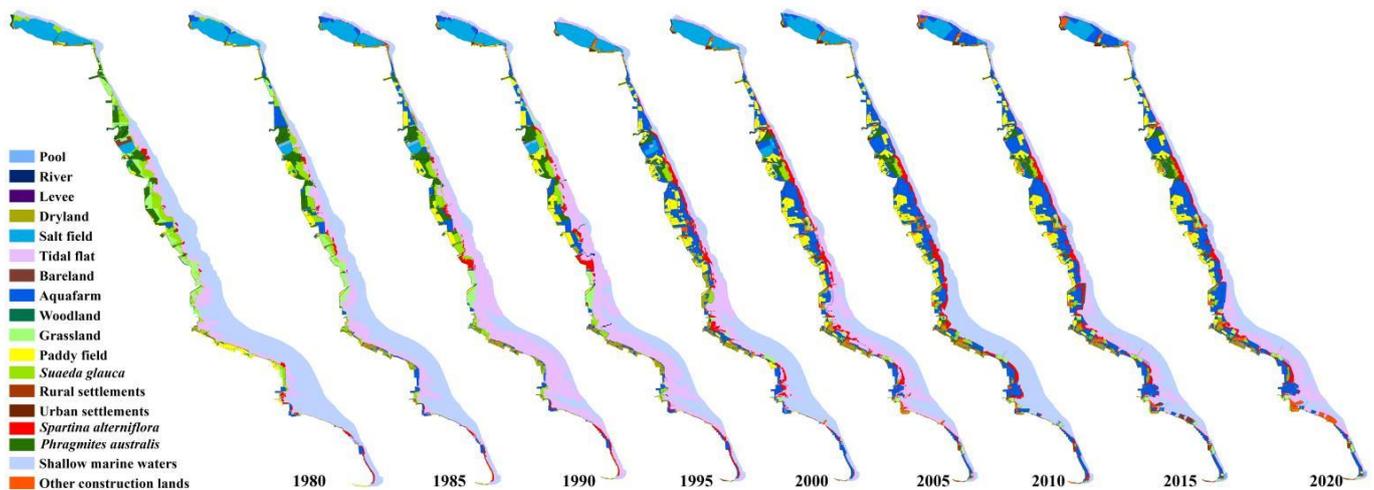


Figure 2. Landscape map of the coastal wetlands in Jiangsu, China, 1980–2020.

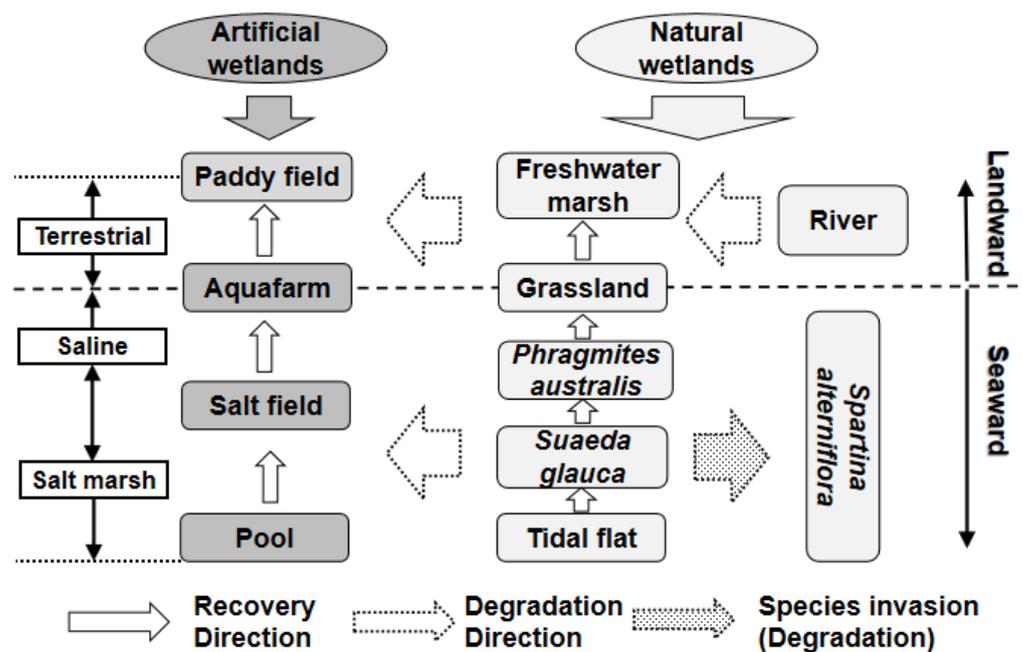


Figure 3. Directional succession model of the coastal wetland landscape in northern Jiangsu, China.

The direction of natural wetland landscape degradation includes the following changes: (1) natural wetlands converted into artificial wetlands or non-wetlands; (2) natural community succession involving soil dewatering; (3) natural community succession involving soil salinity accumulation; (4) the invasion of exotic species. Regarding the artificial wetlands, the direction of degradation moves as follows: paddy fields → aquafarms → salt fields → pools. The direction of wetland landscape recovery or restoration follows the inverse trend.

Based on the directional evolution model of the coastal wetland landscape in Figure 3, the degraded or restored evolved area was counted in combination with the transfer matrix method and the percentage of degraded or restored evolved area to the total area of the region was used as the evaluation index of wetland degradation or restoration.

$$K = \sum_{i=1}^n D_i / D \tag{1}$$

where K denotes the proportion of the area where degradation or restoration occurred in the region; D_i denotes the area where degradation or restoration occurred in the i -th landscape; D is the total area of the region.

The theoretical basis of the transition matrix is a quantitative calculation of the transformation between different landscapes. Usually the rows in the transfer matrix represent landscapes at the moment of T_1 and the columns represent landscapes at the moment of T_2 ; A_{ij} represents the total area of landscape i converted to landscape j during $T_1 - T_2$; A_{ii} represents the area where landscape i remained unchanged during $T_1 - T_2$.

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{bmatrix} \quad (2)$$

2.4. Human Disturbance Index

Previous studies used the grid method to calculate the human disturbance index, while the integrity of the natural geographic units and the attribution of administrative units were not considered in the grid division. To facilitate data management, we used administrative districts as the statistical unit to calculate the human disturbance index, which was calculated as follows [10,11].

$$HI = \sum_{i=1}^n (S_i/S) \times C_i \quad (3)$$

where HI is the human disturbance index of an administrative unit; n is the number of landscapes in an administrative unit; S_i is the area of type i landscape within an administrative unit; S is the total area of an administrative unit; C_i is the human disturbance coefficient corresponding to the type i landscape.

The human disturbance coefficient is a quantitative characterization of the degree of disturbance of human activities with the natural property characteristics of the regional landscape. As the forms and objects of human activities in different regions are different, the size of the disturbance coefficient should be determined according to the purposes of human activities and the characteristics of the object (landscape), and a targeted quantitative setting should be made. Under the scenario of no human activity interference at all, the study area was considered a typical salt marsh wetland landscape. Therefore, the definition and setting of the degree of human disturbance in the region in this paper mainly considered the degree of the disturbance level of human activity on the regional wetland landscape and wetland function. Based on the results of previous research [7,8,33–37], and combined with the directional landscape evolution model, the greater the deviation of the current landscape from the natural wetland landscape (and function; non-wetland deviation was the largest, followed by artificial wetland), the greater the defined disturbance coefficient, and conversely the smaller the defined disturbance coefficient.

According to the above ideas, the deviation of the non-wetland landscape from the natural wetland landscape (and function) was the largest in the current landscape, and the artificial wetland landscape was the second largest. Therefore, for the convenience of the study, the human disturbance coefficient of the study area was set to six levels (from 0 to 5) in this paper (Table 1). Among them, shallow marine waters and *Spartina alterniflora* communities are the least affected by human activities due to their inherent properties and geographic distribution characteristics; thus, their disturbance coefficient was set to 0. The tidal flats, *Suaeda glauca*, *Phragmites australis*, grasslands, and rivers are natural wetlands, which are less affected by human activities, so the human disturbance coefficient was set to 1. Most of the woodlands in the study area were planted forests and most of the barelands were perennially unexploited lands. Although these are non-wetland in nature, the actual degree of human disturbance is greater than that of natural wetlands and less than that of artificial wetlands; therefore, they were set to 2. Most of the pools were artificially

excavated, and thus the disturbance coefficient was set to 3. Paddy fields, aquafarms, salt fields, and drylands are the most significant types of landscapes with planting and farming activities in this study area, and the degree of human disturbance is large; therefore, the disturbance coefficient was set to 4. Urban settlements, rural settlements, levees, and other construction lands are the non-wetland landscapes most affected by human development and construction activities, with the strongest interference coefficient, which was set to 5.

Table 1. The human disturbance coefficients of the different landscapes in the study area.

Disturbance Coefficient	Landscape Class
0	Shallow marine waters and <i>Spartina alterniflora</i>
1	Tidal flats, <i>Suaeda glauca</i> , <i>Phragmites australis</i> , grassland, and rivers
2	Woodlands and barelands
3	Pools
4	Paddy fields, aquafarms, salt fields, and dryland
5	Urban settlements, rural settlements, levees, and other construction lands

2.5. Statistical Analysis

To analyze the trends in the area of landscape evolution and the anthropogenic disturbance index, regression analysis was applied in this study. It is an important method to study the trends of variables in time series, based on the time variable x and the landscape area y , which can be described as follows [38]:

$$y = ax + b + \varepsilon \quad (4)$$

where a is the slope, b is the intercept, and ε is the random error. The linear equation is obtained by least squares linear fitting and the slope a indicates the trend of landscape area y values. The goodness of fit (R^2) test and F-test were used to test the effectiveness of the regression analysis. R^2 is the degree of fit of the regression line to the observations. The closer the value of R^2 is to 1, the better the fit of the regression line to the observed values; conversely, the smaller the value of R^2 is, the worse the fit of the regression line to the observed values. Statistical significance was set at the 0.05 level.

The Pearson correlation coefficients between the human disturbance index and the rate of landscape evolution, the landscape evolution area, and the change quantity of the landscape index were calculated in order to analyze the effects of human disturbance on landscape evolution and evaluate the reliability of the landscape evolution analysis method.

2.6. Landscape Indices

To evaluate the reliability of the landscape evolution analysis method, on the basis of previous studies [11,39,40], considering the structural characteristics of the coastal wetland landscape in the study area and the ecological significance of the landscape index, the mean patch area (Area-MN) and aggregation index (AI) were used in this study at the landscape level. The specific calculation formula is as follows:

- (1) Area-MN is commonly used for landscape fragmentation evaluation. Smaller Area-MN values represent a more fragmented landscape:

$$\text{Area_MN} = \frac{PA}{PN} \quad (5)$$

where PA is the total area of patches (km^2) and PN is the number of patches.

- (2) AI is used to characterize the degree of aggregation and non-randomness. Larger AI values represent higher landscape aggregation and better connectivity:

$$\text{AI} = 100 \times \left[\sum_{i=1}^m \left(\frac{g_{ii}}{\max(g_{ii})} \right) \times p_i \right] \quad (6)$$

where m is the total number of patch types; g_{ii} is the number of nodes between pixels of patch type i based on the single-fold method; p_i is the area ratio of the landscape comprised of patch type i .

3. Results

3.1. Analysis of Area Change

In the past 40 years, the decrease in wetlands in the study area was 529.87 km², with a rate of decrease of 13.25 km²/year. The natural wetlands showed a significant decreasing trend ($R^2 = 0.94$, $p < 0.05$), while artificial wetlands ($R^2 = 0.93$, $p < 0.05$) and non-wetlands ($R^2 = 0.97$, $p < 0.05$) showed significant increasing trends (Figure 4). The natural wetlands decreased by 2344.83 km², accounting for 33.18% of the total study area (7068.22 km²), with an average annual decrease rate of 58.62 km²/year (Table 2). The main types of natural wetlands that decreased were tidal flats (1637.08 km²), *Suaeda glauca* (476.94 km²), grasslands (342.92 km²), and *Phragmites australis* (136.96 km²), accounting for 63.11%, 18.39%, 13.22%, and 5.28% of the net decrease in area of the above four types of natural wetlands, respectively. The total increase in artificial wetlands was 1814.96 km², accounting for 25.68% of the total study area, with an average annual increase rate of 45.37 km²/year. The main increase was 1699.10 km² in aquafarms, followed by 402.55 km² in paddy fields and 9.88 km² in pools, accounting for 93.62%, 22.18%, and 0.54% of the net increase in the area of artificial wetlands, respectively (the area of salt paddies decreased by 296.57 km², accounting for 16.34%).

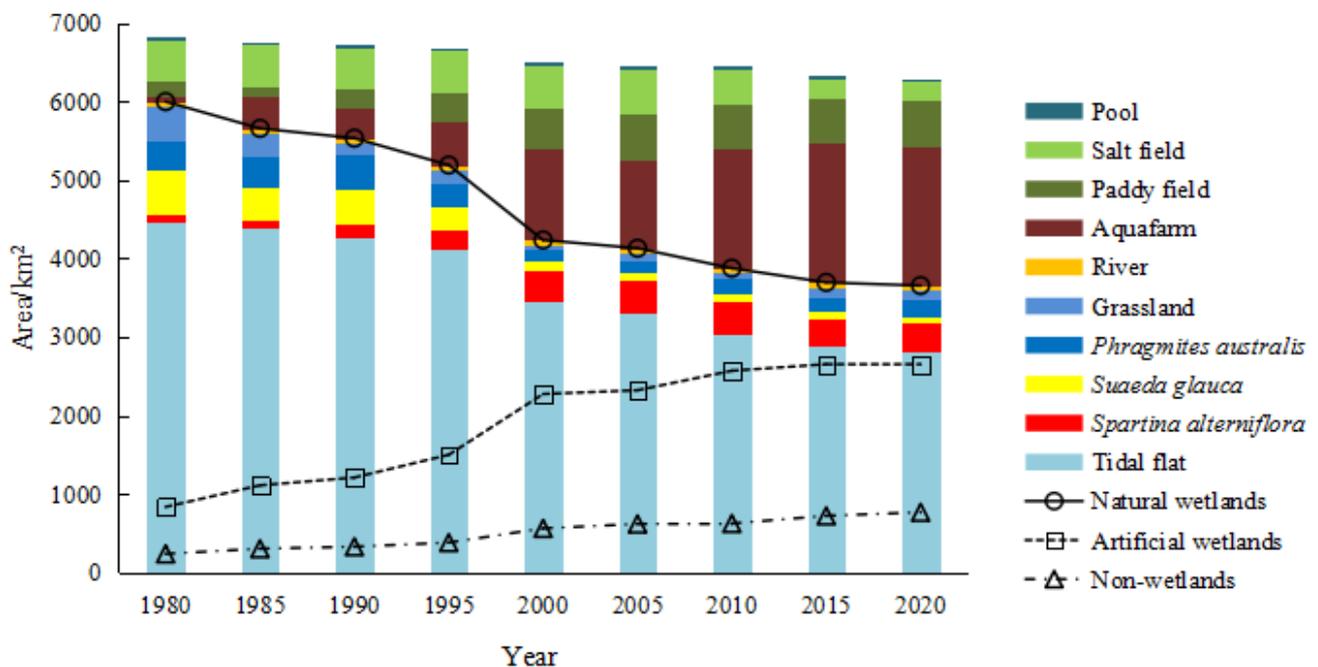


Figure 4. Changes in the area of different wetland landscapes in North Jiangsu during 1980–2020.

The area of coastal wetlands in the study area accounted for 23.98% of the 10 coastal administrative districts (Xiangshui county, Binhai county, Sheyang county, Dafeng city, Dongtai city, Hai'an city, Rudong county, Tongzhou district, Haimen city, and Qidong city); however, the changes in the natural and artificial wetlands accounted for 86.96% and 70.30% of the changes in the natural and artificial wetland areas in the 10 coastal administrative districts, respectively. The loss of natural wetland area and the increase in artificial wetland area in the coastal area of Jiangsu province, China, in the past 40 years mainly occurred in the coastal wetland area, while the rate of natural wetland loss was higher than the rate of artificial wetland increase. In addition, *Spartina alterniflora* was the

only natural wetland landscape with an increasing trend in area. This area increased by 238.45 km² in the past 40 years, accounting for 3.37% of the total study area of 7068.22 km², with an average annual rate of increase of 5.96 km².

Table 2. The area change statistics of the coastal wetland in northern Jiangsu during 1980–2020.

Item		1980	2020	Area Change (km ²)	Change Rate (km ² /year)
Natural wetlands	Area (km ²)	5999.99	3655.16	−2344.83	
	Percentage of total area of the region (%)	84.89	51.71	−33.18	−58.62
	Percentage of total wetland area (%)	87.80	57.99	−29.81	
Artificial wetlands	Area (km ²)	833.33	2648.29	1814.96	
	Percentage of total area of the region (%)	11.79	37.47	25.68	45.37
	Percentage of total wetland area (%)	12.20	42.01	29.81	
Wetlands (including Natural and Artificial wetlands)	Area (km ²)	6833.32	6303.45	−529.87	−13.25
	Percentage of total area of the region (%)	96.68	89.18	−7.50	
Total area of the region (km ²)				7068.22	

3.2. Analysis of the Landscape Evolution Process

The change area of natural wetlands was the largest (3111.76 km²), accounting for 82.44% of the total change area (3774.50 km²), while the change area of artificial wetlands accounted for only 13.99% (Table 3). Among the transformation processes of natural wetlands, the internal conversion among natural wetlands, and the conversion of natural wetlands to artificial wetlands and non-wetlands accounted for 23.00%, 62.76%, and 14.24% of the total conversion area of natural wetlands, respectively. The transformation of natural wetlands in the study area was the most significant change in the past 40 years. In particular, the conversion of natural wetlands to artificial wetlands was the most obvious.

Table 3. Statistics of the landscape evolution over the last 40 years.

Degradation Type	Degradation Area (km ²)	Percentage of Total Degradation Area (%)	Restoration Type	Restoration Area (km ²)	Percentage of Total Restoration Area (%)
Natural wetlands → non-wetlands	443.07	14.56	Non-wetlands → natural wetlands	13.14	1.88
Artificial wetlands → non-wetlands	186.86	6.14	Non-wetlands → artificial wetlands	86.91	12.45
Natural wetland inter-degradation	93.48	3.07	Natural wetland inter-restoration	293.09	41.99
Artificial wetland inter-degradation	36.50	1.20	Artificial wetland inter-restoration	266.61	38.20
Natural wetlands → artificial wetlands	1953.07	64.20	Artificial wetlands → natural wetlands	38.17	5.47
<i>Spartina alterniflora</i> invasion	329.05	10.82	Total restoration area	697.92	
Total degradation area	3042.03		Percentage of regional area (%)	9.87	
Percentage of regional area (%)	43.04		Percentage of pre-existing wetland area (%)	10.21	
Percentage of pre-existing wetland area (%)	44.52		Percentage of degradation area (%)	22.94	

Note: A → B represents A conversion to B.

During 1980–2020, the total area of landscape transformation was 3774.50 km², accounting for 53.40% of the total area of the study area. The area of landscape degradation reached 3042.03 km², accounting for 43.04% of the total area of coastal wetlands and 44.52% of the area of the wetlands in the previous period (1980). The area of landscape restoration reached 697.92 km², accounting for 9.87% of the total area of coastal wetlands, 10.21% of the area of wetlands in the previous period (1980), and accounting for 22.94% of the degradation (Table 3). The sum of the degraded and restored evolved area of the landscape accounted for 99.08% of the total evolved area of the landscape. The evolution of modern wetland systems in the study area is still dominated by the degradation process, and the degree of restoration and wetland restoration is relatively low. The areas of natural wetlands → artificial wetlands, natural wetlands → non-wetlands, and *Spartina alterniflora* invasion equaled 1953.07, 443.07, and 329.05 km², respectively accounting for 64.20%, 14.56%, and 10.82% of the total degraded area. The degradation of wetlands in the study area over the past 40 years—mainly the transition type of natural wetlands to artificial wetlands and non-wetlands, as well as the invasion of *Spartina alterniflora*—also requires attention. The degradation of artificial wetlands (artificial wetlands → non-wetlands and the degradation within artificial wetlands) covered 223.36 km², accounting for 7.34% of the total degraded

area. This indicates that the degradation of artificial wetlands was weak. Among the types of restoration, those among natural and artificial wetlands accounted for the highest proportions, covering 293.09 and 266.61 km², respectively, and accounting for 41.99% and 38.20% of the restoration area in the region, respectively. This indicates that the evolution of wetland landscape restoration in the study area in the past 40 years was mainly based on the gradual restoration of natural wetlands, such as soil desalination, while the conversion of salt fields into aquafarms under the intervention of human activities was also one of the important reasons for the structural restoration of wetland systems in the study area.

The landscape degradation area in the study area from 1980 to 2020 showed a non-significant decreasing trend as a whole and had obvious phasing characteristics. There was a non-significant increasing trend in the degradation area from 1980 to 2000 and a non-significant decreasing trend in the degradation area from 2000 to 2020 (Figure 5). Except for the degradation among natural wetlands, which showed a significant monotonic decline, all other types showed a non-significant increasing trend, followed by a decreasing trend, and the inflection points were all in the 1995–2000 period.

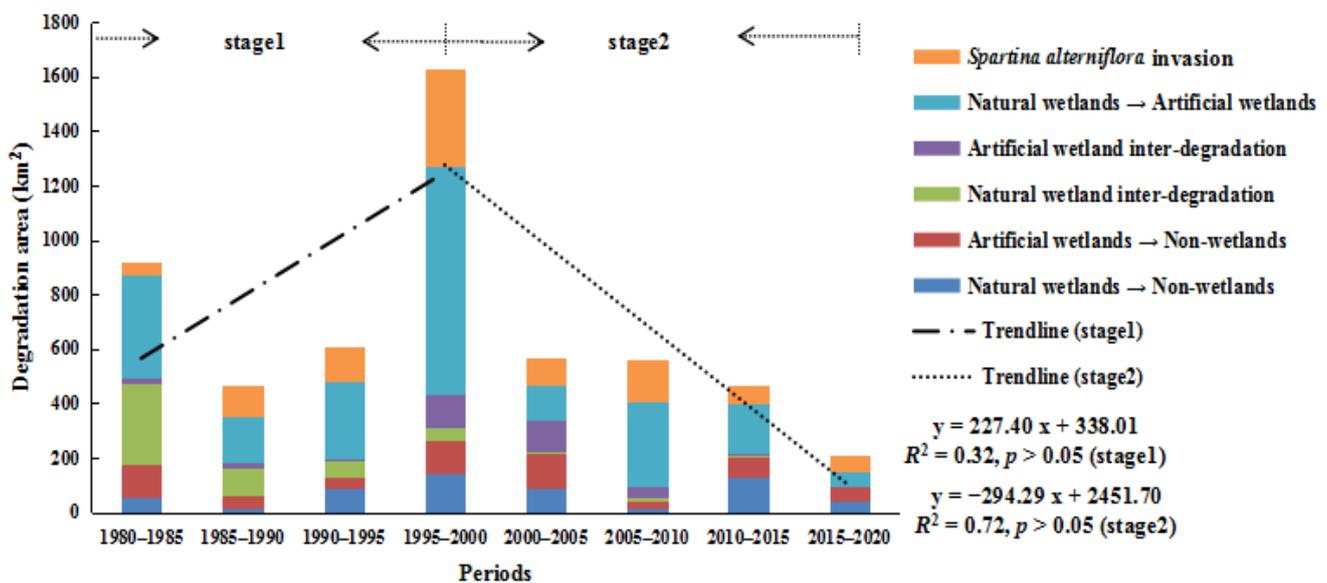


Figure 5. Degradation types of the coastal wetlands in different periods in northern Jiangsu, China.

The main degradation types differed in the different time periods; however, the proportion of natural wetlands → artificial wetlands, natural wetlands → non-wetlands, and *Spartina alterniflora* invasion to the total degraded area ranged from 51.53% to 85.16%. This indicates that these three types were the main wetland degradation types in the study area. In response to the landscape restoration, the sudden decrease in the area of restoration in the 2015–2020 time period may be related to the reduction in wetland restoration under human disturbance from strengthening of the wetland protection in recent years.

The 1980–2015 landscape restoration in the study area showed an overall non-significant upward trend and also had segmental characteristics. The inflection point was also located in the 1995–2000 time period (Figure 6). The main types of restoration were natural and artificial wetland inter-restoration, both accounting for more than 58% of the restoration, except for the 2000–2005 and 2015–2020 time periods.

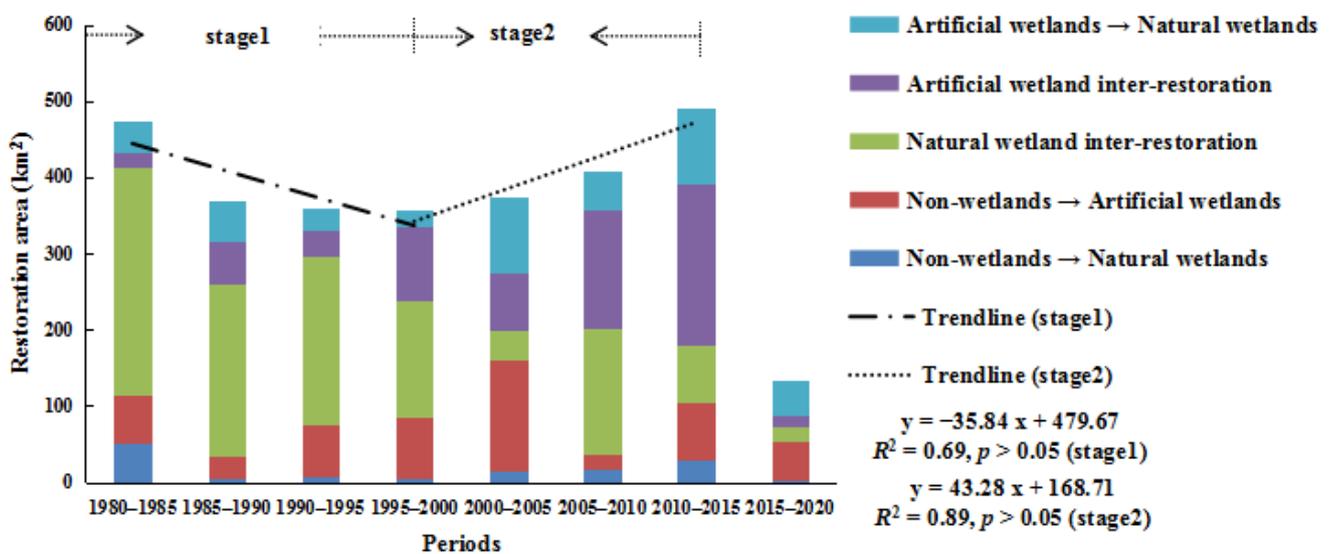


Figure 6. Restoration types of coastal wetlands in different periods in northern Jiangsu, China.

Combined with the results in Table 3, although the evolution of modern wetland systems in the study area from 1980 to 2020 was still dominated by degradation processes and the degree of restoration and wetland restoration was relatively low, the degradation was on a decreasing trend and the restoration was on an increasing trend; thus, the wetland ecosystem in the study area as a whole was on a restoration trend.

3.3. Spatial–Temporal Characteristics in Landscape Evolution

From Figure 7, the degradation of the coastal wetland landscape in northern Jiangsu, China, in the past 40 years mainly occurred in Sheyang county, Dafeng city, Dongtai city, and Rudong county, where the degraded area accounted for 84.37% of the total degraded area in the region. The degradation types were mainly natural wetlands > artificial wetlands, natural wetlands > non-wetlands, and *Spartina alterniflora* invasion. The proportions of degraded areas in each administrative district from largest to smallest were Dafeng city (67.14%) > Sheyang county (54.63%) > Dongtai city (52.30%) > Hai'an city (42.10%) > Qidong city (38.05%) > Rudong county (28.70%) > Haimen city (25.46%) > Binhai county (22.49%) > Tongzhou district (20.59%) > Xiangshui county (19.04%). The landscape restoration in the study area mainly occurred in Sheyang county, Binhai county, Dafeng city, Rudong county, and Ringshui county. The restoration area accounted for 84.98% of the total restoration area in the region, while the restoration types were mainly the restoration among artificial wetlands and the restoration among natural wetlands. The proportions of restored areas in each administrative district were Binhai county (35.21%) > Sheyang county (18.77%) > Xiangshui county (16.05%) > Tongzhou district (10.70%) > Dafeng city (7.86%) > Qidong city (7.78%) > Hai'an city (7.38%) > Rudong county (4.21%) > Dongtai city (3.73%) > Haimen city (3.63%).

Tables 4 and 5 display the rates of degradation and recovery evolution of the coastal wetland landscape areas for eight periods in each county and city, respectively. The rates of degradation from Xiangshui county to Dafeng city in the north showed a decreasing trend, while those from Dongtai city to Qidong city (except Rudong county) in the south showed an increasing trend, indicating a southward trend of coastal wetland landscape degradation in northern Jiangsu, China.

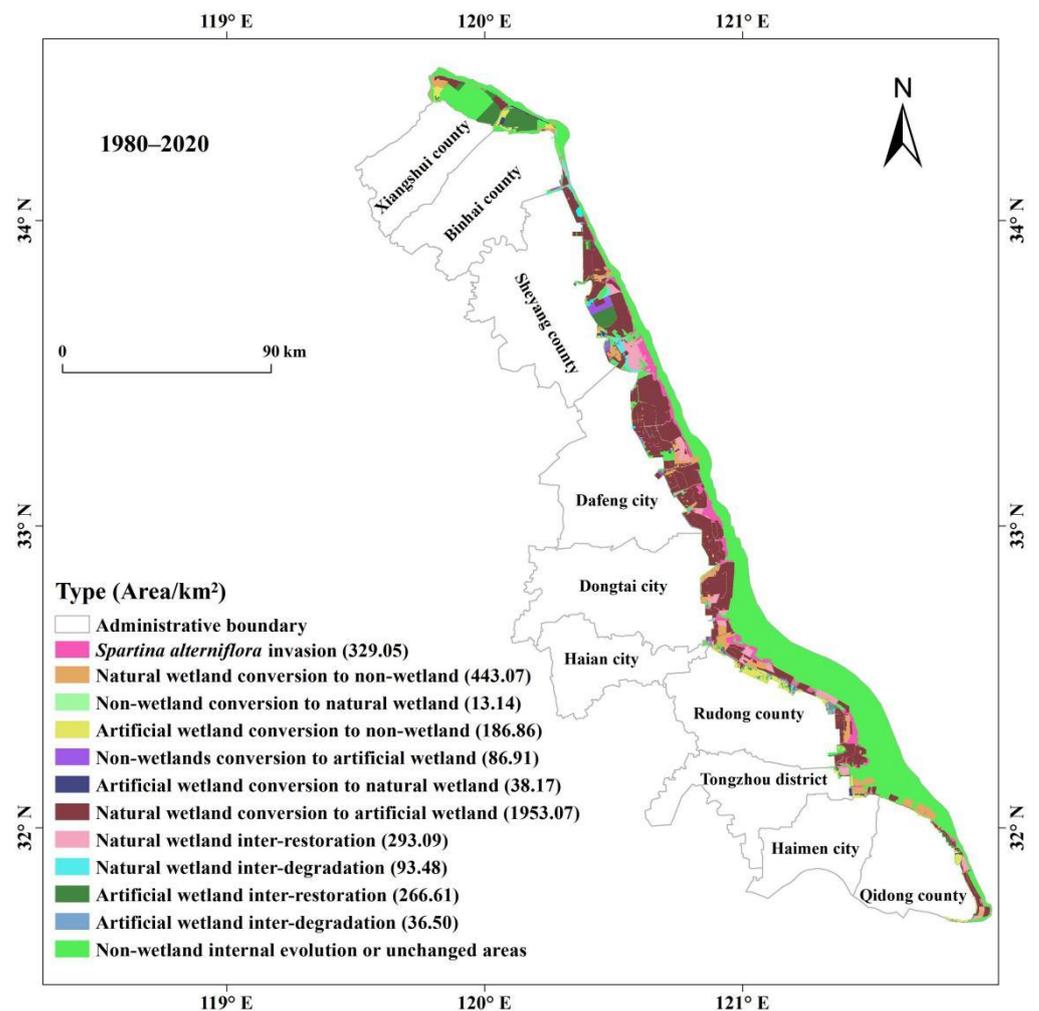


Figure 7. The spatial distribution pattern and types of wetland landscape evolution in the past 40 years.

Considering the trends for the rates of degradation and recovery evolution in the eight periods, the 10 counties and cities were classified into four categories: decreasing–decreasing trend (rate of degradation with a decreasing trend and recovery evolution with a decreasing trend), decreasing–increasing trend (rate of degradation with a decreasing trend and recovery evolution with an increasing trend), increasing–increasing trend (rate of degradation with an increasing trend and recovery evolution with an increasing trend), and increasing–decreasing trend (rate of degradation with an increasing trend and recovery evolution with a decreasing trend). Three counties and cities in the study area had a decreasing–decreasing trend for the rate of degradation and restoration of coastal wetlands in the last 40 years. The absolute value of the slope of the rate of degradation was larger than that of the rate of restoration and the coasts of the three counties are all siltation coasts, which indicates that the ecological conditions of these counties and cities were slowly improving and that more attention should be paid to them in the future. Two counties and cities showed a decreasing–increasing trend, for which the recovery evolution rates in the latter periods were greater than the rates of degradation, indicating that the ecological condition of these two counties and cities was improving faster. However, since the shorelines of Xiangshui and Binhai counties are of the erosion type, the coastal wetlands of these two counties and cities should also receive continuous attention. There were three counties and cities with increasing–increasing trends, where the shorelines of Haimen and Qidong were relatively stable. The slopes of their rates of degradation and recovery evolution were close and the average rate of degradation was larger than the rate of recovery evolution, which indicates that the ecology of coastal wetlands in

Haimen and Qidong will continue to deteriorate. The slope of the rate of degradation in Dongtai city, which is located on a siltation-type coast, was five times that of the slope of the recovery evolution, while the average rate of degradation was two times that of the recovery evolution, which indicates that the coastal wetlands in this city were experiencing accelerated degradation.

Table 4. Changes of the coastal wetland areas' rates of degradation in 10 counties and cities in the study area over eight periods.

Region	1980–1985	1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	Average	Trendline	Trend
Xiangshui county	10.20	5.53	2.10	12.57	1.39	0.55	5.55	4.09	5.25		Decrease with fluctuations
Bin Hai county	11.30	5.42	3.66	9.61	1.62	2.17	0.97	2.79	4.69		
Sheyang county	52.39	23.53	27.14	60.99	17.44	16.16	13.97	6.33	27.25		
Dafeng city	54.10	37.56	58.21	132.59	27.92	22.09	10.98	2.47	43.24		
Rudong county	35.67	6.94	11.84	41.22	28.00	27.78	20.48	7.27	22.40		
Dongtai city	10.03	8.86	8.24	49.17	19.76	23.87	23.43	11.17	19.32		Increase with fluctuations
Hai'an city	0.12	1.02	2.71	4.83	4.07	1.85	1.77	1.64	2.25		
Tongzhou district	2.04	0.54	1.02	2.80	2.78	1.86	4.24	0.83	2.01		
Haimen city	1.61	0.67	0.49	1.57	2.94	3.96	0.68	2.57	1.81		
Qidong city	6.10	4.04	6.12	10.67	7.36	11.52	11.01	2.67	7.43		

Table 5. Changes of the coastal wetland areas' rates of restoration in 10 counties and cities in the study area over eight periods.

Region	1980–1985	1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	Average	Trendline	Trend
Sheyang county	32.17	19.87	23.80	18.40	16.91	30.52	9.23	7.78	19.84		Decrease with fluctuations
Dafeng city	24.48	28.06	22.38	16.79	24.08	7.81	18.26	6.90	18.60		
Hai'an city	3.28	1.66	1.16	0.35	1.00	1.09	0.61	0.00	1.14		
Rudong county	11.38	10.12	7.11	17.82	3.36	14.03	13.74	0.00	9.70		
Tongzhou district	2.32	0.25	1.22	2.85	2.30	1.51	2.37	0.00	1.60		
Dongtai city	9.39	7.68	4.34	8.92	17.89	8.66	5.55	10.97	9.18		Increase with fluctuations
Xiangshui county	3.84	0.36	1.82	0.64	1.15	12.46	15.26	0.03	4.44		
Bin Hai county	4.81	4.84	7.02	2.56	4.11	0.79	23.11	0.52	5.97		
Haimen city	0.43	0.21	0.72	0.73	0.72	1.65	2.13	0.00	0.82		
Qidong city	2.52	0.93	2.48	2.31	3.09	2.93	7.69	0.61	2.82		

In the future, more resources should be invested in these three counties and cities, and effective measures should be taken to control the degradation and to promote the evolution of the restoration. Although the area of coastal wetlands in these two counties is relatively small, policymakers should pay greater attention to them due to the accelerated degradation of the coastal wetland landscape in this region.

3.4. Correlation Analysis of the Human Disturbance Index and the Rate of Landscape Evolution

The human disturbance index of the coastal wetlands in the study area showed a significant monotonic increasing trend ($p < 0.05$) from 0.91 in 1980 to 2.25 in 2020 (Figure 8a). The trends of human disturbance in Yancheng city and Nantong city were the same as those in the study area, while the values and rates of change of human disturbance index in Yancheng city were greater than those in Nantong City.

The changes of the human disturbance index in all 10 counties and cities in the study area showed a significant upward trend and were ranked in order of the mean value of the human disturbance index: Xiangshui county > Binhai county > Sheyang county > Dafeng city > Dongtai city > Hai'an city > Qidong city > Rudong county > Tongzhou district > Haimen city (Figure 8b).

The amount of variation in the human disturbance index in Xiangshui county, Binhai county, Sheyang county, Dafeng city, and Rudong county showed a decreasing trend. The amount of variation in the human disturbance index in Dongtai city, Hai'an city, Tongzhou district, Haimen city, and Qidong city showed an increasing trend (Figure 8c).

Although the human disturbance index in the study area showed a significant increasing trend, due to the differences in the size of the human disturbance base in each county and city, the base in the northern counties and cities was large and the human disturbance gradually stabilized with a decreasing trend, while the human disturbance base in the southern counties and cities was small and showed a faster growth trend. This indicates a southward trend of human disturbance.

In terms of the amount of change, the human disturbance index was significantly and positively correlated with the rate of degradation throughout the study area, with a correlation coefficient of 0.43 ($p < 0.05$). The human disturbance index was not significantly and positively correlated with the rate of restoration, with a correlation coefficient of 0.14 ($p > 0.05$) (Figure 8d). There was a strong correlation between wetland landscape degradation and human activities in the study area, while the correlation between restoration and human activities was weak.

For each county and city, except for Rudong county, Haimen city, and Qidong city, the human disturbance and the rate of wetland landscape degradation in the rest of the counties and cities were positively correlated. In particular, Sheyang county and Dafeng city were highly significantly correlated. The human disturbance index and the rate of wetland restoration in each county and city were insignificantly correlated; Sheyang county and Dafeng city were positively correlated, while the rest of the counties and cities were negatively correlated.

From the spatial pattern of change, the human disturbance had a strong spatial consistency with the degradation and restoration—the slope of change of the human disturbance factor was significantly and positively correlated with the rate of degradation and the rate of restoration for all counties and cities, with correlation coefficients of 0.89 ($p < 0.05$) and 0.68 ($p < 0.05$), respectively.

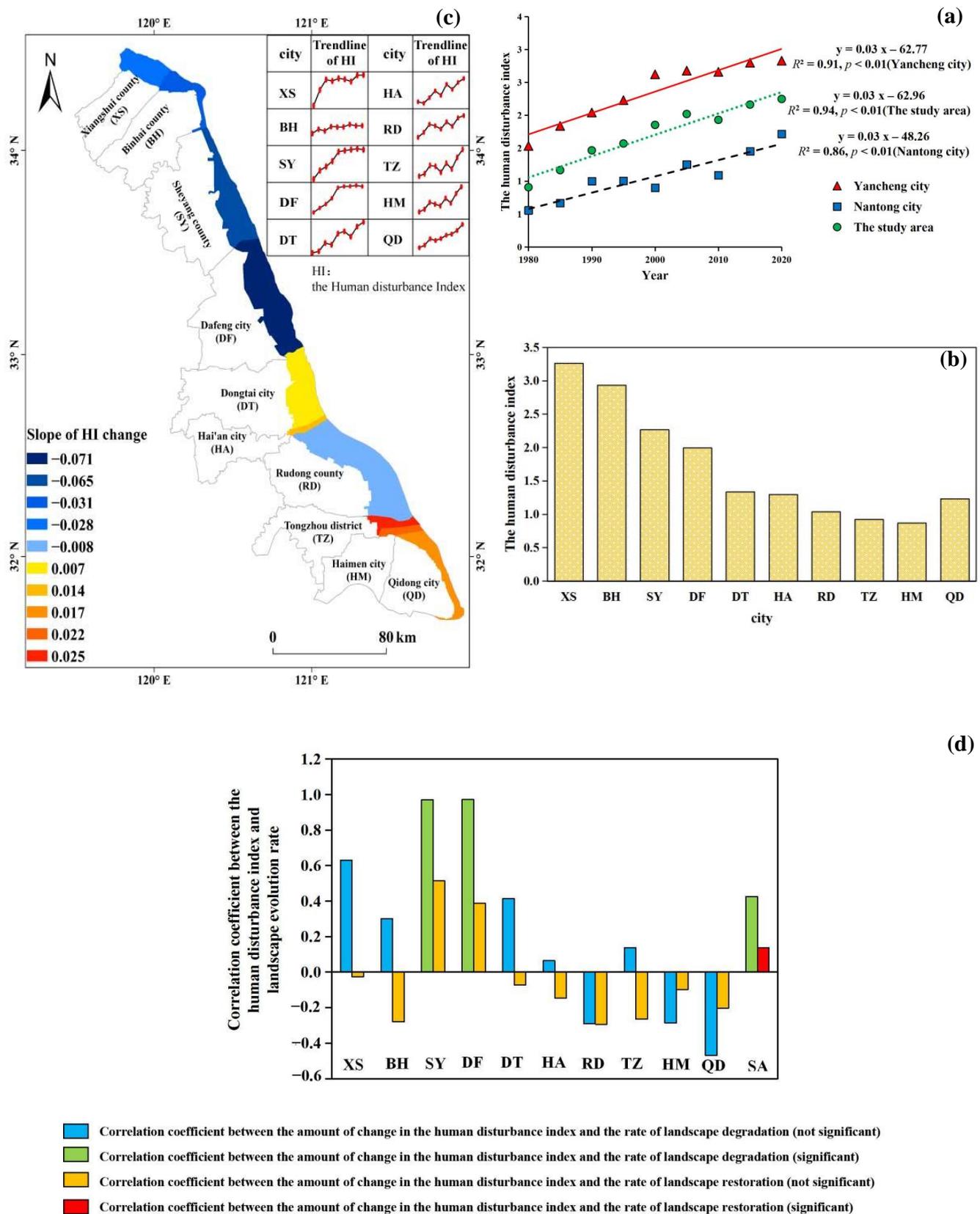


Figure 8. The variation trend for the human disturbance index and the correlation with landscape evolution, (a) trends of the human disturbance index in Yancheng city, Nantong city and the whole study area, (b) the average value of the human disturbance index in each county and city from 1980–2020, (c) trends of the human disturbance index by counties and cities during 1980–2020, (d) correlation between the human disturbance index and landscape evolution rate in counties, cities and study areas.

4. Discussion

4.1. Human Distribution, Natural Change, and Landscape Evolution

Disturbance is an important ecological process that includes both natural and human disturbances. Human disturbance mainly affects the landscape structure, function, and diversity by changing landscapes (e.g., evolving from low-disturbance natural or semi-natural landscapes to high-disturbance anthropogenic landscapes) and the spatial distribution and configuration of their components [11,41–43]. The history of landscape evolution in the coastal wetlands in northern Jiangsu, China, comprises coastal wetland resource development driven by natural geographical features (natural conditions) plus socioeconomic development, with prominent stage and spatial variability characteristics. The coastal wetland is a good land reserve resource and Jiangsu province has abundant coastal wetland resources with a long history of polder reclamation, which can be traced back to the construction of the Fan Gong dike [33]. Since 1980, the development and utilization of coastal wetlands has changed from sea salt development, demolishing salt-making stoves and cultivation land, to land reclamation and cotton cultivation to the comprehensive development and utilization of land for agriculture, forestry, animal husbandry, fisheries, and salt [44,45]. The study area has gone through several stages of development—from the development strategy of “Marine Sudong” in the Ninth Five-Year Plan to establish a new grain and cotton base; to the development of millions of mu (1 mu = 1/15 hectare) of mudflats in the 10th Five-Year Plan; to the development of “ports, towns, and coastal harbor industry” in the 11th Five-Year Plan; to the construction of a “new port industrial zone, modern agricultural base, new energy base, and coastal new city” in the 12th Five-Year Plan; and finally to the integrated development of a “port, industry, and town” in the 13th Five-Year Plan. This series of economic development initiatives has led to dramatic changes in land use patterns, and the intensity of human disturbance has gradually increased, eventually leading to the evolution of regional landscapes—a large number of natural landscapes (such as tidal flats, *Suaeda glauca*, and *Phragmites australis*) have been developed and utilized as aquafarms, salt fields, arable land (paddy fields and drylands), settlements, etc.

The preliminary results of this paper are discussed below.

First, there was a southward trend of landscape degradation in the coastal wetlands in the study area (Table 4), while the changes in the human disturbance index also showed a decreasing trend to the north of Dongtai City and an increasing trend to the south (Figure 8). The reasons for the southward landscape degradation trend of the coastal wetlands may be related to the variability of regional physical geographic characteristics (natural conditions) and socioeconomic development. Xiangshui county, Binhai county, and the northern part of Sheyang county (the mouth of the Guanhe River to the mouth of the Sheyang River) are located near the mouth of the abandoned Yellow River and belong to the erosive coast, where the reclamation potential is small. Therefore, the internal evolution of the anthropogenic landscape occurred mainly in this region. From the southern part of Sheyang county to Haimen city (from the mouth of Sheyang River to Dongzao Port), the old Yellow River’s submerged deltaic sediment and Yangtze River’s inlet sediment (under the joint action of the north–south tidal wave system and the off-shore radiating sandbar) form a siltation environment with less wind and waves. The siltation is strong, which is of typical siltation along the coast. The Qidong city section is part of the stable coastal section [46].

Second, the development of human disturbance intensity demonstrated an obvious stage development process, closely related to the economic development stage in the region; thereby, the coastal wetland landscape degradation produced significant stage characteristics. For 1980–1990, the intensity of the human disturbance in the coastal wetland region was low. Coupled with the emphasis on the polder approach and not utilization, the regional economic development level was low, which made the rate of landscape degradation generally decrease in all counties and cities (Table 4). After 1990, with the population growth and economic development, the urbanization process for coastal Jiangsu accelerated, while the development of coastal wetlands was an important

initiative to reduce the economic differences between the north and the south, enhancing the intensity of the reclamation development of coastal wetlands [45]. The rate of landscape degradation from Xiangshui county to Hai'an city reached a maximum in 1995–2000 (Table 4). After 2015, the government strengthened the protection of coastal wetlands by strictly controlling reclamation, while Jiangsu province also introduced a national ecological protection red line plan to further protect coastal wetlands. This led to a rapid decrease in the rate of landscape evolution in the study area from 2015 to 2020.

The above preliminary research results indicate that the northern part of the Jiangsu coast needs to further optimize the landscape, while the southern part needs to strengthen the protection of coastal wetlands to achieve coordination of the coastal wetland development and utilization with ecological protection as far as possible.

Third, the rate of landscape degradation in the study area was significantly positively correlated with the changes in the human disturbance index. This, on the one hand, also supports the judgment that human disturbance may be the driving force of landscape evolution in the study area. On the other hand, it also indicates that landscape evolution may be influenced by certain other factors such as climate change. In estuarine coastal areas, changes in water exchange at the land–sea interface; changes in groundwater levels; and sensitive habitat factors such as soil salinity caused by beach exploitation, global climate change, and sea level changes control the development and evolutionary processes of coastal wetland ecosystems [47]. Global climate change affects the runoff from the estuaries, coastal hydrodynamic conditions, and regional evapotranspiration. The increase in salinity of tidal flats under conditions of reduced inlet runoff inevitably leads to changes in coastal ecological conditions, which affects the growth and development processes of various plants and animals in the soil and water bodies. Under conditions of relatively low precipitation, changing the coastal surface water or groundwater by a few centimeters may degrade the wetland ecology [48]. Sea level increases not only reduce tidal flats and coastal wetlands due to erosion or inundation [49], but can also affect the process of landscape evolution of coastal wetlands by altering the composition and salinity of sediments and the hydrological pattern of coastal wetlands [50,51]. At the same time, sea level increases may also increase the frequency and intensity of natural disasters, such as storm surges, salt water intrusion, and flooding, which indirectly interfere with the ecological processes such as nutrient cycling and primary production of coastal wetland systems, undermine the stability and balance of coastal wetland systems, lead to increased ecosystem vulnerability, and ultimately lead to the degradation of the landscape ecology of coastal wetland systems.

In addition, landscape evolution and human disturbance intensity are scale-dependent, and this paper was directly based on the statistics of 30 m resolution data without considering the influence of different scales on the landscape evolution and human disturbance intensity.

4.2. Reliability of the Landscape Evolution Analysis Method

In this paper, we used the directional landscape evolution model to study the landscape evolution of coastal wetlands. To verify the reliability of the method, based on the results of previous studies, we selected Area-MN and AI at the landscape scale to perform a correlation analysis with the landscape evolution area. The results showed that the amount of Area-MN change in Yancheng city, Nantong city, and the whole study area showed a weak negative correlation with the corresponding landscape degradation and restoration areas. The amount of AI change showed a negative correlation with the landscape evolution area in Yancheng city and the study area, and a weak positive correlation with the landscape evolution area in Nantong city. In particular, AI showed a significant negative correlation with the area of landscape degradation in Yancheng city and the study area (Table 6).

Table 6. Correlation coefficients between the landscape evolution area and change quantity of the landscape index. Mean patch area (Area-MN) and landscape aggregation index (AI).

Type	Yancheng City		Nantong City		Study Area	
	Degradation Area	Restoration Area	Degradation Area	Restoration Area	Degradation Area	Restoration Area
Change amount of Area-MN	−0.12	−0.09	−0.30	−0.14	−0.14	−0.08
Change amount of AI	−0.60 **	−0.28	0.01	0.00	−0.27 *	−0.04

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

From 1980 to 2020, many natural landscapes changed from continuous large patches of natural landscapes with low human disturbance to a series of relatively small patches of anthropogenic landscapes with high human disturbance. The results of previous studies have shown that wetland degradation increases landscape fragmentation and decreases the connectivity of the same landscapes [52–54]. The results of the correlation analysis showed that landscape degradation was negatively correlated with Area-MN and AI, which indicates that landscape degradation increased the landscape fragmentation and decreased the landscape connectivity. The results of this paper also corroborate the findings of previous studies, which to a certain extent also proves the reliability of the method proposed in this paper. In addition, the landscape evolution demonstrated a non-significant weak negative correlation with Area-MN, especially in Nantong, which showed a non-significant weak positive correlation with AI, which also indicates that the landscape index needs to be chosen carefully.

In addition, it should be noted that the landscape evolution model, which is the core of the directional landscape evolution evaluation method proposed in this paper, has no way to be directly applied in other regions due to the regional variability of landscapes in different regions. However, the framework of this method and the construction method of the evolution model are universal.

4.3. Uncertainty of the Human Disturbance Index

Zhou et al. (2018) analyzed the spatial and temporal changes of human disturbances in the Jiangsu coastal zone, China, based on 1.5 km × 1.5 km grids, and the results showed that the human disturbance index had an upward trend from 1995 to 2013 [11]. The increments of the human disturbance index were larger in Sheyang County, Dafeng City and Dongtai City in 1995–2002, while the regions with larger increments in 2002–2013 were Qidong City and Haimen City. This indicates a southward trend of the human disturbance. These findings are consistent with the results of the current study. The administrative unit was chosen as the evaluation unit for the human disturbance index in this study. Compared with the standard grid unit, the areas of administrative units presumably vary, which can lead to larger index values for administrative units, with smaller areas when the area of a given landscape is the same. The human disturbance within administrative units is not uniform, and the closer the area to a settlement, the more serious the human disturbance is. This study uses the average disturbance level within administrative units instead of disturbance within counties and cities, which may be different from the actual situation. The human disturbance index based a standard-sized grid unit may be more reasonable for studying its spatial distribution characteristics. At the same time, we are not clear about the influence of different spatial scales on the relationship between human disturbance and landscape evolution. Therefore, the scale effects of human disturbance and landscape evolution should be further explored to reduce uncertainty through the integration of multi-scale information, with a view to better supporting coastal wetland restoration, conservation, and management.

The disturbance coefficient is a key parameter for calculating the human disturbance index, and its assignment is based on landscape data, which are highly subjective. The

magnitude of the disturbance coefficient only characterizes the relative degree of deviation of different landscapes in the region from the natural wetland landscape and has only relative significance. Therefore, the same landscape in different areas may represent different intensities of human activities or a certain landscape in the same area with different patch characteristics (area, size, density and shape, etc) may also represent different intensities of human activities. Therefore, further research is still needed on how to assess the human disturbance coefficient more scientifically and objectively in a quantitative manner.

5. Conclusions

In this paper, we quantitatively analyzed the spatial and temporal characteristics of landscape evolution and its response to human disturbance in the coastal wetlands in northern Jiangsu, China, from 1980 to 2020 through a directional landscape evolution model and localized human disturbance coefficients.

The results of the study showed that from 1980 to 2020, landscape degradation was the main feature of regional landscape evolution. In 1980–1990, due to the emphasis on the polder approach and not utilization, the economic efficiency was not high, which resulted in a reduced rate of landscape degradation for this period. From 1990 to 2005, the rate of landscape degradation reached its maximum value due to the accelerated urbanization process and the increased economic benefits of reclamation development and utilization. After this, the rate of landscape degradation gradually decreased as the difficulty and cost of polder reclamation increased and the awareness of conservation increased. After 2015, the protection of coastal wetlands was strengthened at the national level and polder reclamation was strictly controlled, while Jiangsu province also introduced the “national ecological protection red line plan”, which resulted in the rate of landscape degradation in the study area from 2015 to 2020 decreasing rapidly. At the same time, due to the obvious southward trend of landscape degradation and human disturbance, the southern part of the study area needs to further increase its control over coastal wetland development and utilization, so that the development and utilization of coastal wetlands can be carried out in a coordinated manner with ecological protection.

In this paper, we applied a method to quantitatively evaluate the evolution of the coastal wetland landscape, and through a comparative analysis with the traditional landscape index, we found that this method had a certain degree of reliability. However, we cannot ignore the shortcomings of this study, which are mainly reflected by two aspects. First, the directional landscape evolution model only considered landscape degradation and restoration, ignoring the transformation of land types (transformation between non-wetland types) beyond the directional discrimination of the method. Second, landscape evolution and human disturbance intensity are scale-dependent, and this paper was directly based on the statistics of 30 m resolution data without considering the influence of different scales on the landscape evolution and human disturbance intensity. Third, inconsistencies in the interpretation accuracy of the landscape data may also add to the uncertainty of the results. The above shortcomings should be further explored in future studies to reduce the uncertainty of research conclusions and to better support the promotion of the coordinated development of coastal wetland exploitation and ecological protection.

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