remote sensing

Article

Remote Sensing of Coastal Wetland Degradation Using the Landscape Directional Succession Model

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Abstract: In recent decades, human activities have impaired the structure, function, and diversity of coastal wetland ecosystems, and there is a need for the rational planning of ecological restoration to curb wetland degradation. However, the challenge remains to quickly and accurately identify degraded wetland areas and their degradation levels. In this study, we used remote sensing interpretation data from 1980 to 2020 and the wetland degradation evaluation method based on a landscape directional succession model to quantify the spatial and temporal characteristics of wetland degradation in Jiangsu Province, China. The key findings showed that 3020.67 km^2 of wetlands became degraded over the 40 years of this study, accounting for 42.74% of the total area of coastal wetlands, and that the overall degradation was mild. This degradation presented significant spatial differences, with the wetland degradation in Yancheng City observed to be more serious than that in Nantong City. Degradation mainly occurred in Sheyang County, Dafeng District, Dongtai City, and Rudong County, and the spatial distribution pattern of severe and moderate degradation, mild degradation, and non-degradation was observed from land to sea in that order. The degradation of wetlands was observed to have obvious stages, and the degradation of coastal wetlands in the study area from 1980 to 2020 showed a significant increasing trend. The comprehensive score of wetland degradation in 2020 (1.67) was 3.70 times that in 1985 (0.45), and the turning point occurred in 2000. The types of wetland degradation were dominated by the transformation of natural wetlands into construction land (coastal industry), fish farming, and arable land, as well as the invasion of exotic species. Although great efforts have been made in recent years to protect and restore coastal wetlands, the development and utilization of coastal wetland resources should be strictly controlled to achieve the goal of sustainable development in coastal areas.

Keywords: coastal wetlands; degradation; remote sensing; Jiangsu

Citation: Cui, L.; Li, G.; Liao, H.; Ouyang, N.; Li, X.; Liu, D. Remote Sensing of Coastal Wetland Degradation Using the Landscape Directional Succession Model. *Remote Sens.* **2022**, *14*, 5273. https://doi.org/10.3390/rs14205273

Academic Editors: Cristina Tarantino, Maria Adamo and Valeria Tomaselli

Received: 14 September 2022
Accepted: 19 October 2022
Published: 21 October 2022

1. Introduction

Wetland degradation refers to the relative deviation of a wetland's ecosystem structure, functions, and services from its natural state at a certain spatio-temporal scale due to geographical environmental changes and the transitional use of wetland resources by humans [1–3]. As a transition zone of water–land ecosystems, wetlands have several important ecological functions, such as water purification, coastal protection, and biodiversity maintenance. However, the combined effect of geographical changes and human activities has caused a decrease in the area of natural wetlands, leading to prominent ecological and environmental problems and serious degradation of wetlands [4–6], which poses a serious threat to regional socio-economic development and ecological security. Therefore, wetland degradation and restoration has received widespread attention from scholars at home and abroad and become a research hotspot of global concern [7,8].

Evaluation methods for coastal wetlands mainly include the single-factor evaluation method, multi-factor integrated evaluation method, and landscape ecology method. The single-factor evaluation method determines whether a wetland is degraded by comparing the changes in a single indicator value (e.g., area, productivity, or diversity) before and after wetland degradation [9,10]. In this method, the selection of evaluation indicators is very important, as the opposite conclusions may be obtained if such indicators are not selected properly. Multi-factor integrated evaluation is mainly used to determine whether and to what extent wetlands are degraded by comparing changes in the weighted sum of multiple factors before and after wetland degradation. Such methods include the rapid evaluation method [11], the biological integrity index [12], the hydrogeomorphic classification method [13], the integrated matrix analysis method [14], and the integrated index method [15]. Each of these methods, however, has its own shortcomings. The rapid evaluation method is not yet universally applicable due to different wetland types and stresses. The biological integrity index method offers intuitive results, but field sampling requires significant human, material, and financial resources and is difficult to apply on a large regional scale. The advantage of the hydrogeomorphic method is that the evaluation results are reproducible, but the disadvantage is that the results are not comparable between different wetland types. The integrated matrix analysis method and integrated index method have the advantages of simple calculations and easy comparisons, but the disadvantage is that the relationship between indicators at the same level (structure, process, function, and service) or different levels is not clear, which means that the indicators may be redundant or function in opposite directions (in terms of the directionality of system change), leading to problems in the reliability of the conclusions.

The landscape ecology method mainly uses landscape indices to study the degradation process of wetlands and their spatial and temporal characteristics. The landscape index is a quantitative index that can highly condense landscape pattern information and reflect its landscape structural composition and spatial configuration characteristics [16]. This method is mainly used to analyze the processes, trends, and spatial and temporal characteristics of wetland degradation by comparing the changes in landscape indices in different time periods. Although a large number of studies have applied landscape indices to the evaluation of wetland degradation, and fruitful results have been achieved, such methods still have the following shortcomings: (1) landscape indices only provide a description of the overall characteristics of the landscape based on simple mathematical statistics or topological calculation formulas and a lack of spatial location meaning, and many indices do not have a clear ecological meaning and cannot reflect the specific ecological processes and landscape functions; (2) there are duplication and scale problems between landscape indices. Ecosystems can be viewed as a "self-organizing system limited by human activities" with multiple characteristics related to self-organizing processes, some of which are directional in nature (e.g., landscape evolution) [17–19]. Cui et al. (2015) and Müller et al. (2006) combined landscape evolution with directional discrimination for degradation evaluation. While the current method based on landscape directional succession is not yet able to evaluate the degree of wetland degradation, the present study improves the method proposed by Cui et al. (2015) and applies it to evaluate the degree of wetland degradation and analyze the spatial and temporal characteristics of coastal wetland degradation. In addition, wetland degradation is the result of a combination of natural and human factors. There are significant stages and regional differences in wetland degradation due to differences in natural geographic conditions, socio-economic development levels, the degree of policy improvement, and citizens' awareness of ecological and environmental protection [20–23].

The modern coastal plain of Jiangsu developed on the basis of three geomorphic systems: the modern Yangtze River Delta, the Lixia River Plain, and the abandoned Yellow River Delta [24]. Before 1855, the three geomorphic systems had long influenced the spatial pattern of the evolution of the coastal plain of Jiangsu and its coastal wetland system. The Yellow River was diverted from the plains of Jiangsu to the modern Yellow River Delta in Bohai Bay to enter the sea in 1855. Since then, the evolution of the coastal plain and its coastal wetland system in Jiangsu has been profoundly changed. The modern abandoned Yellow River delta area has changed from a large amount of runoff and sediment transport to the Yellow Sea before 1855 to an abandoned estuarine delta, and the coastal plain has changed from a silty estuary to an erosion-receding one. Since then nearly 160 years ago, the spatial pattern of the evolution of the coastal plain and its coastal wetland system in Jiangsu has changed dramatically [25]. At the same time, the region has undergone anthropogenic modifications (reclamation and construction of seawalls) over the past 1000 years, which have served as coastal protection to some extent. The erosion in the region mainly originates from coastal dynamics (erosion due to waves and tides) and western Pacific typhoon landfalls (about seven–eight times per year), resulting in a predominantly erosive north and predominantly silting south [26], but with relatively small rates of natural erosion and accretion [27]. After human modification, coastal wetlands have become semi-natural ecosystems. The spatial variability of the physical geographic context and the stage of human disturbance activities in the region may make it possible for the evolution of Jiangsu coastal wetlands to be characterized by spatial and temporal differentiation. Therefore, in this study, the spatial and temporal evolution characteristics of coastal wetland degradation in Jiangsu Province were quantitatively evaluated using Landsat images and the improved landscape directional evolution model. This study will help researchers better understand the degradation of coastal wetlands in Jiangsu Province, and thus, promote the planning and conservation of coastal wetlands.

2. Data and Methods

2.1. Study Area

The Jiangsu coastal zone is located between the estuaries of Guan River and Yangtze River and consists of the abandoned Yellow River Delta, the Lixia River Plain, and the Yangtze River Delta, including Xiangshui County, Binhai County, Sheyang County, Dafeng District, and Dongtai City in Yancheng City and Haian City, Rudong County, Tongzhou District, Haimen District, and Qidong City in Nantong City (Figure 1). After the founding of New China, the region has experienced sea salt development (salt field landscape), cotton cultivation (cotton field landscape), mariculture (mariculture landscape), harbor construction (harbor landscape), and the invasion of exotic species. Natural and anthropogenic disturbances have strongly changed the structure and function of the regional ecosystem, resulting in dramatic landscape changes and severe wetland degradation [28–30]. Referring to the definition of coastal wetlands, and taking into account the actual situation of the distribution of coastal mudflats in Jiangsu Province, the spatial scope of the study area is defined as "the coastal road adjacent to the ancient Fan Gong Dike as the western boundary, the multi-year mean low tide level as the eastern boundary, the northern boundary of Xiangshui County as the northern boundary, and the southern boundary of Qidong City as the southern boundary".

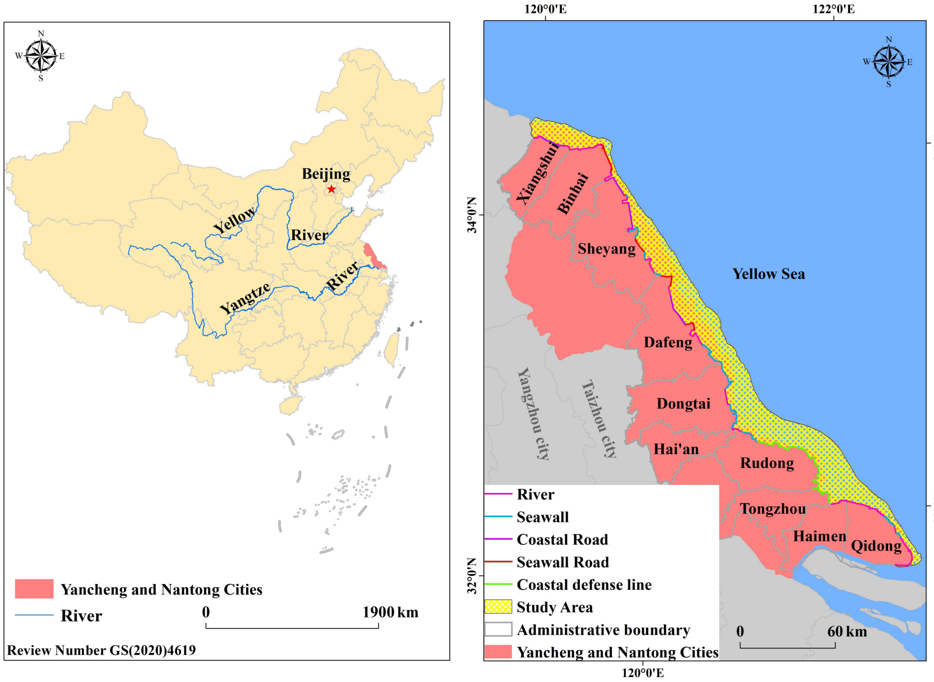


Figure 1. Location of the study area.

2.2. Landscape Interpretation

2.2.1. Remote Sensing and Ancillary Data

Open-access Landsat data, with a high resolution and long time span, are ideal for monitoring the structure of a wetland and its evolution at the landscape level [31–33]. For this study, a total of 27 scenes (3 scenes per year) from Landsat 3 MSS (Multispectral Scanner) C1 Level-1, Landsat 5 TM (Thematic Mapper) C1 Level-1, and Landsat 8 OLI (Operational Land Imager) C1 Level-1 products between 1980 and 2020 were collected from the United States Geological Survey EarthExplorer website (https://earthexplorer.usgs.gov/ (accessed on 26 June 2021)). Data with less than 20% cloud cover were selected. The selected Landsat data information is shown in Table 1. The images of each year were first stitched together, and then all images were registered to Albers equal area projection using ground control points and nearest neighbor interpolation. The root mean square error of registration was less than 0.5 pixels. Then, these images were clipped using the study area boundary.

In addition, the following groups of digital elevation model (DEM), beach resource survey, geographic vector, and field survey datasets were collected to support the visual interpretation of the landscape and its accuracy evaluation. DEM data with a 30 m spatial resolution were downloaded from the Geospatial Data Cloud website (http://www.gscloud.cn/ (accessed on 26 June 2021)); beach resource survey data were obtained from the library of the Institute of Geographic Sciences and Resources, Chinese Academy of Sciences; geographic vector data were acquired from the Standard Map Service website (http://bzdt.ch.mnr.gov.cn/index.html (accessed on 26 June 2021)); and field survey data were obtained from a 2015 field investigation.

Table 1. The list of Landsat images in this study between 1980 and 2020.

Year	Date	Sensor	Cloud Cover (%)	Path/Row	Year	Date	Sensor	Cloud Cover (%)	Path/Row
1980	14/04/1980 1/05/1980 5/11/1980	MSS	0 0 0	129/36 128/37 127/38	2005	2/06/2005 24/04/2005 4/06/2005	TM	0.05 4.28 0.43	120/36 119/37 118/38
1985	23/03/1985 24/09/1985 20/11/1985	TM	0 7 0	120/36 119/37 118/38	2010	13/04/2010 31/10/2010 9/11/2010	TM	1 2 9	120/36 119/37 118/38
1990	8/05/1990 15/04/1990 13/07/1990	TM	0 0 6	120/36 119/37 118/38	2015	13/05/2015 30/11/2015 3/08/2015	OLI	15.87 7.03 6.81	120/36 119/37 118/38
1995	22/05/1995 3/08/1995 12/08/1995	TM	0 0.41 0	120/36 119/37 118/38	2020	26/05/2020 19/05/2020 12/05/2020	OLI	4.47 0.21 2.74	120/36 119/37 118/38
2000	17/04/2000 10/04/2000 21/05/2000	TM	0 0 0	120/36 119/37 118/38					

2.2.2. Landscape Classification System

To better understand the distribution of coastal wetlands in Jiangsu, a landscape classification system was established according to the Ramsar Convention and the National Wetland Resources Survey and Monitoring Technical Regulations (China) [30], as shown in Table 2.

Table 2. Landscape classification system.

Level I	Level II	Level III	Description
Wetlands	Natural wetlands	Grassland	The supratidal zone with grasses (*Imperata cylindrica*, *Aeluropus sinensis*, *Apocynum venetum*, etc.) growing
		River	Permanent river, stream, or creek
		Phragmites australis	*Phragmites australis* marsh
		Suaeda glauca	*Suaeda glauca* marsh (*Suaeda salsa*, *Salicornia europaea*)
		Spartina alterniflora	*Spartina alterniflora* marsh (*Sporobolus anglicus*, *Spartina alterniflora*)
		Tidal flat	Intertidal mudflats
		Shallow marine water	Marginal or inland extensions of ocean with maximum depths of approximately 6 m
	Artificial wetlands	Paddy field	Farmland where rice is grown
		Pool	Artificially dug pools or low-lying catchment areas
		Salt field	Site for salt production by evaporation
		Aquafarm	Site for aquaculture
Non-wetland area	Non-wetland	Dryland, woodland, urban settlements, rural settlements, bare land, levee, other construction lands	

2.2.3. Accuracy Evaluation

Although there are many image interpretation methods that have been successfully applied to landscape classification [34], visual interpretation is still the most reliable method.

After detailed indoor interpretation, the accuracy of visual interpretation results was evaluated by field verification or by using the beach resource survey data as reference data, and at least 25 validation samples were selected for each class. Overall accuracy, Kappa coefficient, producer accuracy, user accuracy [32], and classification accuracy [35] were calculated. Where the classification accuracy is calculated as follows.

(1) Define the confidence level (α) and find out the corresponding value from the normal distribution table (Z_α);
(2) Determine the number of validation samples (N);
(3) Calculate the overall sample accuracy (P);
(4) Determine the classification accuracy using the following inequality.

$$\left(-Z_\alpha^2 - N\right) \times x^2 + \left(Z_\alpha^2 + 2NP\right) \times x - N \times P^2 > 0 \quad (1)$$

where $\alpha = 99\%$, $Z_\alpha = 2.326$, and x is the classification accuracy. After the accuracy evaluation, the problems found were interpreted again to form the final interpreted data.

2.3. Evaluation Method of Coastal Wetland Degradation

2.3.1. A Method for Identifying Wetland Degradation Based on Landscape Directional Succession Model

The wetland degradation identification method, based on the landscape directional succession model, was proposed by Cui et al. in 2015. This method combines the landscape succession model with directional discrimination for wetland degradation diagnosis at the landscape level (Figure 2). The direction of natural wetland degradation includes (1) the conversion of natural wetlands to artificial wetlands or non-wetlands due to wetland development and utilization, (2) natural community succession involving soil dewatering, (3) natural community succession involving soil salt accumulation, (4) the invasion of exotic species, and (5) the opposite direction of settlement of pioneer species. The degradation directions of artificial wetlands include (1) the conversion of artificial wetlands into non-wetlands and (2) the direction of the ecological service value reduction: paddy field → aquafarm → salt field → pool (paddy field → aquafarm indicates the conversion from paddy fields to aquafarms.) [18,30].

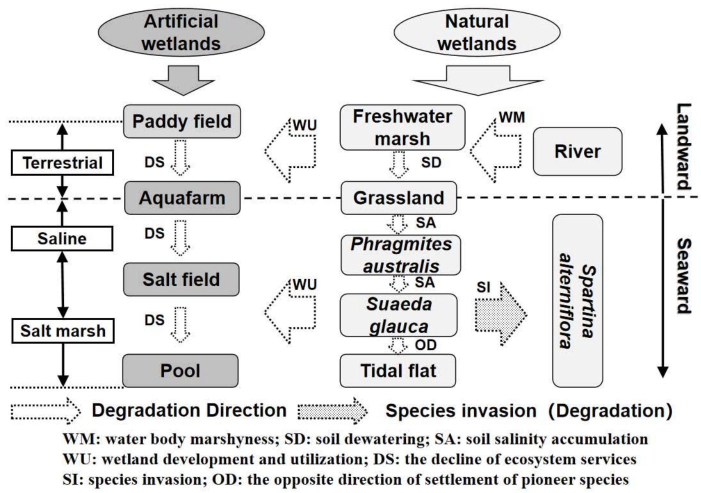


Figure 2. Directional succession model of coastal wetland landscape in Jiangsu Province, China.

Based on the directional succession model of coastal wetland landscapes shown in Figure 2, the degraded area was counted in combination with the transfer matrix method, and its percentage compared to the total area of the region or the total area of the wetland was taken as the evaluation index of wetland degradation using Equation (2):

$$K = \sum_{i=1}^{n} D_i / D \quad (2)$$

where K indicates the proportion of area where degradation occurred in the region; D_i indicates the area where degradation occurred in the ith landscape type; and D is the total area of the region or the total area of wetlands.

2.3.2. Diagnostic Method for the Degree of Wetland Degradation

According to the wetland succession model and process, each succession process is assigned a value; then, a comprehensive score is calculated and classified into degradation levels. Taking the natural wetland succession sequence "Imperata cylindrica → Phragmites australis → Suaeda glauca → Tidal flat" as an example, the reverse succession of neighboring types (e.g., Imperata cylindrica → Phragmites australis) indicates weak degradation and is assigned a value of 1. If Imperata cylindrica → Suaeda glauca, there is one type (Phragmites australis) in between, and a value of 2 is assigned. If Imperata cylindrica → Tidal flat, there are two types (Phragmites australis and Suaeda glauca) in between, and a value of 3 is assigned, etc. A value of 3 is assigned if the reed and salt artemisia are separated by two types (reed and salt artemisia). On this basis, the proportion of degraded area corresponding to each reverse succession process (e.g., if the original area of Imperata cylindrica is 100 km^2, and the succession area of Imperata cylindrica → Suaeda glauca is 20 km^2, the proportion of the degraded area of this reverse succession process is 20/100 = 0.2) is multiplied by its weight (for Imperata cylindrica → Suaeda glauca, the value is 2) and then summed, as in Equations (3) and (4):

$$S_i = \sum_{j=1}^{N}\left(\frac{A_{ij}}{A_i}w_{ij}\right) \tag{3}$$

$$S = \sum_{i=1}^{M} S_i \tag{4}$$

where A_{ij} denotes the area of succession from the ith landscape type to the jth landscape type; A_i is the initial area of the ith landscape type; w_{ij} is the weight of the succession of the ith landscape type to the jth landscape type; N is the number of the ith landscape type that can be transformed into other types; S_i is the composite score of retrogressive succession (degradation) of the ith landscape type; M is the total number of landscape types where retrogressive succession occurred; and S is the composite score of total retrogressive succession. The maximum score for the retrogressive succession of the major natural and artificial wetlands in the study area was 3. Therefore, this paper classifies wetland degradation levels as follows: non-degradation (S = 0), mild degradation (0 < $S \leq 3$), moderate degradation (3 < $S \leq 6$), and severe degradation (S > 6).

2.3.3. Methodology for Analyzing the Evolution of Wetland Degradation Grades

In order to further investigate the spatiotemporal distribution characteristics for the evolution of the degradation level of coastal wetlands in Jiangsu over the past 40 years, the non-degradation, mild, moderate, and severe degradation were first assigned numbers of 1, 2, 3, and 4, respectively. Then, the wetland degradation level in the period of 1980–1985 was used as the benchmark, and the data of other periods were calculated as the difference compared to this benchmark. Here, Dif represents this difference. If Dif ≤ -2, wetland degradation decreased by two or more levels, which means that the wetland degradation status improved significantly (Significantly improved). If Dif = -1, wetland degradation decreased, which means that the wetland degradation status improved (Improved). If Dif = 0, there was no change in the wetland degradation level, which means that the wetland degradation status is stable (Stable). If Dif = 1, the wetland degradation level is increasing, which means that the wetland degradation status deteriorated (Deteriorated). If Dif $\geq$ 2, then wetland degradation is increasing by two or more levels, which means that the wetland degradation status is severely deteriorated (Severely deteriorated).

3. Results

3.1. Time-Series Mapping and Area Statistics

Time-series landscape classification maps from 1980 to 2020, obtained with the visual interpretation method, are illustrated in Figure 3. Based on field survey data from 2015 and the 1:200,000 beach resource survey data from the 1980s, the classification accuracy of the landscape-interpreted data in 1980 and 2015, at 99% confidence level and a sampling overall accuracy of 91.67% and 81.45%, were 88.65%~93.93% and 77.55%~84.81%, respectively, with kappa coefficients of 0.88 and 0.80 (Table 3), which were greater than 0.75, indicating a reasonable agreement between the interpreted data and the reference data [36]. Since the same interpretation method used in 2015 was applied to the data of other years, the accuracy of the interpreted data was relatively reliable and met our application requirements. The area of each class (Level II) in the study area is shown in Figure 4. The area of natural wetlands showed a significant decreasing trend from 5999.99 km^2 in 1980 to 3655.16 km^2 in 2020, with a total decrease of 2344.83 km^2 (-58.62 km^2 yr^{-1}). The area of artificial wetlands and non-wetlands showed an increasing trend, with areas increasing by 1814.96 and 529.87 km^2 from 1980 to 2020, respectively. Meanwhile, the change in area was phased. The turning point was 2000, as the slope of the trend line of natural wetlands from 1980 to 2000 (-79.90 km^2 yr^{-1}) is more than twice that of the slope from 2000 to 2020 (-31.95 km^2 yr^{-1}). The slope of the trend line of artificial wetlands from 1980 to 2000 (65.36 km^2 yr^{-1}) was more than three times the slope from 2000 to 2020 (21.66 km^2 yr^{-1}). The slope of the trend line of non-wetlands was found to be relatively stable.

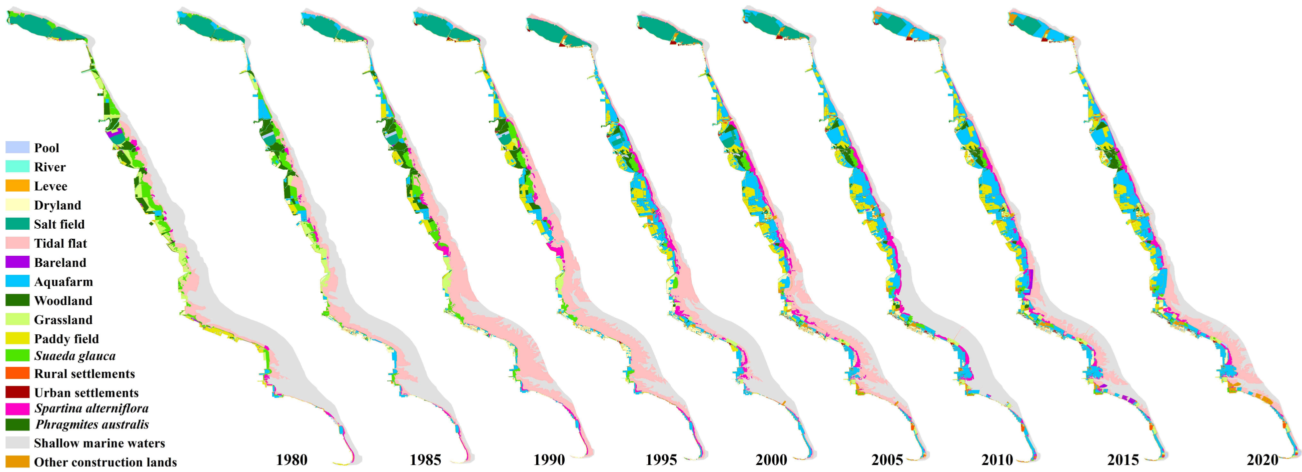


Figure 3. Time-series classification maps from 1980 to 2020.

Table 3. Accuracy of landscape classification results (%).

Landscape Type	1980		2015	
	User Accuracy	Producer Accuracy	User Accuracy	Producer Accuracy
Tidal flat and shallow marine water	91.18	96.88	90.00	90.00
Suaeda glauca	88.24	90.91	73.68	84.85
Phragmites australis	93.75	88.24	83.33	81.08
Grassland	95.12	95.12	94.74	87.80
River	96.43	90.00	90.00	90.00
Paddy field	88.24	93.75	69.44	78.13
Aquafarm	91.67	91.67	78.43	80.00
Salt field	89.47	87.18	82.50	75.00
Pool	91.89	94.44	74.36	80.56
Spartina alterniflora	96.15	94.34	86.27	83.02
Urban settlememts	96.77	96.77	90.00	87.10
Levee	96.55	93.33	92.00	76.67
Rural settlements	90.00	90.00	60.00	80.00
Bareland	82.35	93.33	81.82	90.00
Woodland	93.75	90.91	92.00	69.70
Dryland	88.89	86.96	73.33	71.74
Other construction lands	87.88	85.29	87.88	85.29
Overall accuracy	91.67		81.45	
Kappa coefficient	0.88		0.80	
Classification accuracy	88.65~93.93		77.55~84.81	

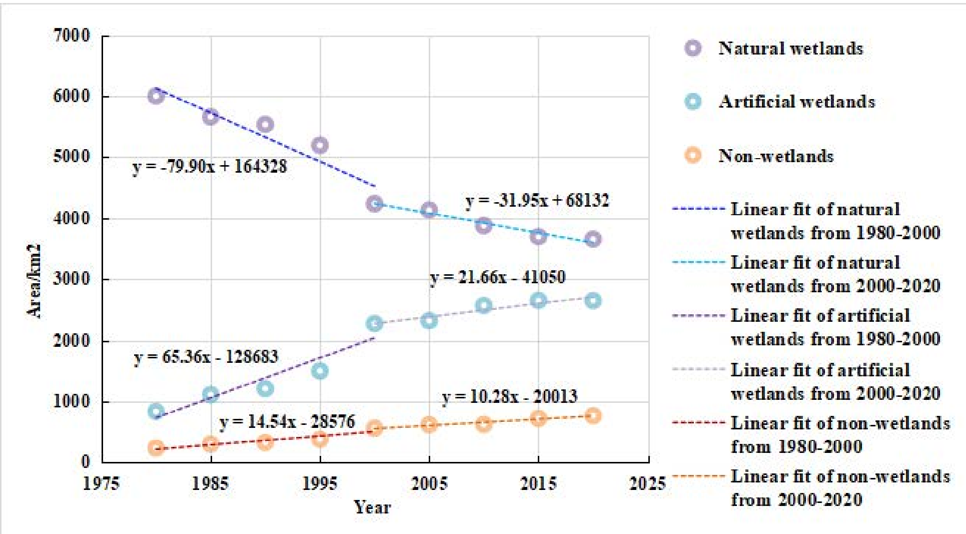


Figure 4. Areas of different landscape types from 1980 to 2020 (unit: km^2).

3.2. Spatial Distribution Characteristics of Degraded Areas

The area of wetland degradation in the study area from 1980 to 2020 was 3020.67 km^2, accounting for 42.74% of the total area of coastal wetlands (Figure 5). The areal percentages of natural wetland → artificial wetland, natural wetland → non-wetland, invasion of exotic species, artificial wetland → non-wetland, retrogressive succession within natural wetlands, and retrogressive succession within artificial wetlands were 64.67%, 14.67%, 10.89%, 6.19%, 2.37%, and 1.21%, respectively. This result indicates that the degradation processes of wetlands during this period were mainly dominated by natural wetland → artificial wetland and natural wetland → non-wetland; the invasion of exotic species also requires greater attention. In addition, the spatial distribution of wetland degradation was found to be uneven, with distribution mainly in Sheyang County, Dafeng District, Dongtai City, and Rudong County, totaling 2546.93 km^2 of wetlands degraded and accounting for 84.32% of the total degraded area (Table 4). The main types of wetland degradation in different counties and cities were also different. The main types of degradation in Sheyang County, Dafeng District, and Dongtai City were the same as those in the study area, while the main types of degradation in Rudong County included natural wetland → artificial wetland, natural wetland → non-wetland, and invasion of exotic species, in addition to artificial wetland → non-wetland. In terms of the proportion of degraded area in administrative districts, Dafeng District (66.57%) > Sheyang County (54.62%) > Dongtai City (51.64%) > Hai'an City (42.10%) > Qidong City (37.91%) > Rudong County (28.43%) > Haimen District (24.36%) > Binhai County (22.49%) > Tongzhou District (20.54%) > Xiangshui County (19.04%).

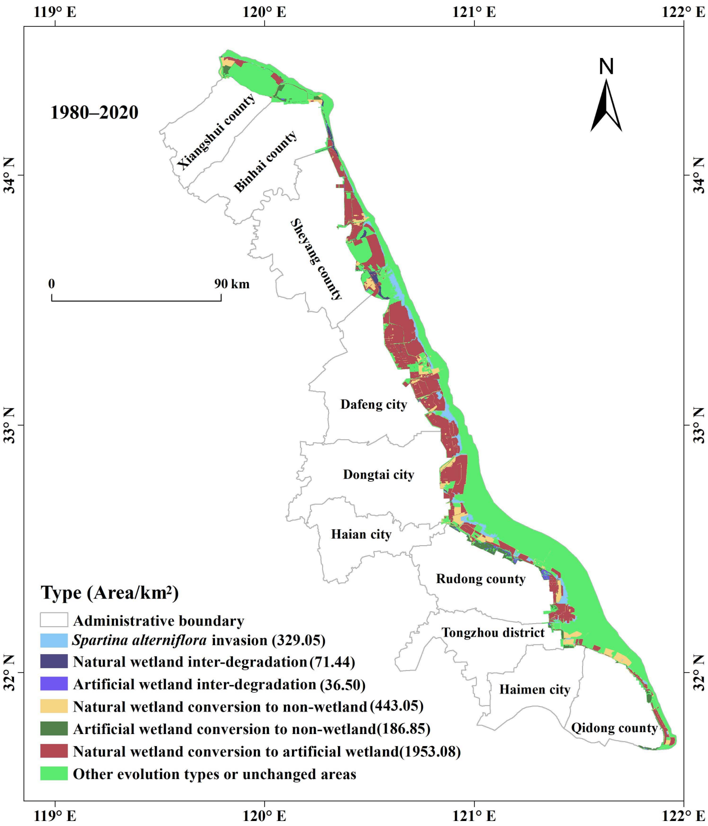


Figure 5. Spatial distribution of coastal wetland degradation types from 1980 to 2020.

Table 4. Degradation in different administrative regions of the study area in 1980–2020.

Type	Xiangshui County		Binhai County		Sheyang County		Dafeng District		Dongtai City		Hai'an City		Rudong County		Tongzhou District		Haimen District		Qidong City	
	Area/km^2	APDA	Area/km^2	APDA	Area/km^2	APDA	Area/km^2	APDA	Area/km^2	APDA	Area/km^2	APDA	Area/km^2	APDA	Area/km^2	APDA	Area/km^2	APDA	Area/km^2	APDA
NWs to NoWs	26.04	27.88	13.37	16.32	52.76	9.53	77.55	7.89	60.80	12.88	23.33	53.72	79.25	14.57	26.43	65.01	14.67	42.90	68.85	38.38
AWs to NoWs	17.58	18.82	31.08	37.93	7.55	1.36	1.46	0.15	1.83	0.39	0.00	0.00	84.42	15.52	7.95	19.56	6.36	18.59	28.62	15.95
NWID	1.26	1.35	18.95	23.12	34.79	6.29	13.70	1.39	2.37	0.50	0.00	0.00	0.35	1.04	0.00	0.00	0.02	0.05	0.00	0.00
AWID	0.46	0.49	1.94	2.37	2.90	0.52	0.64	0.06	0.00	0.00	0.00	0.00	28.47	5.23	1.03	2.53	0.02	0.06	1.04	0.58
NWs to AWs	44.87	48.04	14.87	18.14	410.18	74.11	765.58	77.91	367.98	77.93	8.06	18.55	253.69	46.64	2.51	6.18	10.79	31.55	74.55	41.55
SA invasion	3.19	3.42	1.74	2.12	45.26	8.18	123.70	12.59	39.20	8.30	12.04	27.73	92.49	17.00	2.73	6.71	2.35	6.86	6.35	3.54
Total area(km^2)	93.40		81.95		553.45		982.63		472.18		43.43		538.67		40.66		34.20		180.10	
APCA	19.04		22.49		54.62		66.57		51.64		42.10		28.43		20.54		24.36		37.91	
ADAPP	19.38		26.08		59.34		67.99		52.18		46.58		28.86		20.91		24.52		38.93	

Note: Areal percentage over the degradation area (APDA), areal percentage over the corresponding area within the administrative district (APCA), areal percentage over the degradation area of the previous period (ADAPP), natural wetland inter-degradation (NWID), artificial wetland interdegradation (AWID), natural wetlands (NWs), artificial wetlands (AWs), non-wetlands (NoWs); NWs to NoWs indicates the conversions of NWs to NoWs; AWs to NoWs indicates the conversions of AWs to NoWs; NWs to AWs indicates the conversions of NWs to AWs.

3.3. Analysis of Spatio-Temporal Changes in Wetland Degradation Grades

3.3.1. Analysis of Spatial Variation in Wetland Degradation Grades

In the past 40 years, 3020.67 km^2 of coastal wetlands in Jiangsu was degraded, with a degradation rate of 75.52 km^2 yr^{-1}. The degraded area accounted for 44.20% of the wetland area (6833.33 km^2) in 1980, and the distribution pattern of severe and moderate degradation, mild degradation, and non-degradation was observed from land to sea, in that order (Figure 6a). In terms of degradation degree, the whole study area was in a mildly degraded state. Additionally, non-degraded land was dominant within the region (55.81%), and the proportions of mildly, moderately, and severely degraded areas totaled 23.06%, 18.39%, and 2.74%, respectively. Severe degradation was dominated by the conversion of natural wetlands to non-wetlands (94.30%), moderate degradation was dominated by the conversion of natural wetlands to artificial wetlands (69.47%) and natural wetlands to non-wetlands (21.19%), and mild degradation was dominated by the conversion of natural wetlands to artificial wetlands (67.86%) and Spartina alterniflora invasion (20.69%) (Figure 6b). In terms of landscape types, natural wetlands (moderately degraded) were more severely degraded than artificial wetlands (mildly degraded), with grassland, Suaeda glauca, and Phragmites australis observed to be moderately degraded among natural wetlands and the remaining natural wetland types mildly degraded. The spatial variability of degradation was found to be significant. The proportion of the degraded area of coastal wetlands in Yancheng City reached 63.12%, and the areal proportions of non-degradation, mild degradation, moderate degradation, and severe degradation were 36.88%, 32.77%, 25.53%, and 4.82%, respectively, with a combined degradation score of 2.41. The proportion of degraded area of coastal wetlands in Nantong City was only about half of that in Yancheng City, accounting for about 32.98%, and the proportions of non-degradation, mild degradation, moderate degradation, and severe degradation areas were 67.08%, 17.43%, 14.69%, and 0.81%, respectively, with an overall degradation score of 1.20 (Figure 6c).

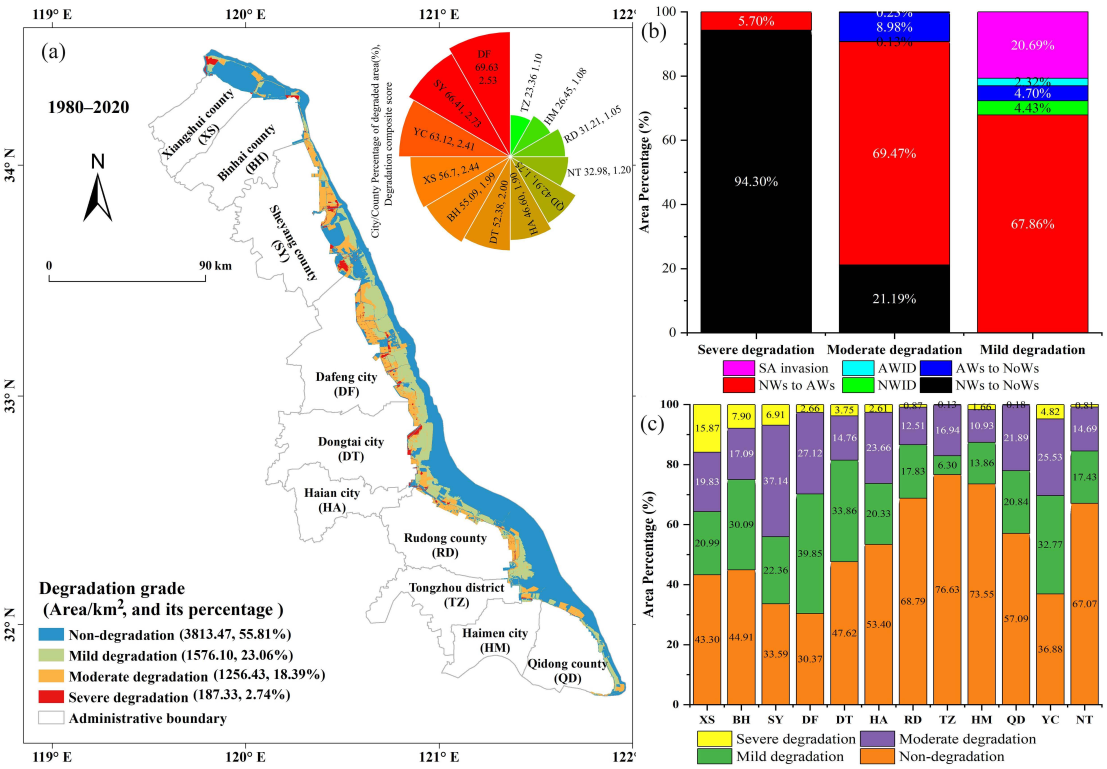


Figure 6. Degradation levels of coastal wetlands in different administrative units in Jiangsu during 1980–2020. (**a**) Spatial distribution of degradation grades; (**b**) Percentage of area occupied by each landscape transformation type in different degradation grades; (**c**) Percentage of area of different degradation grades in each region.

In addition, the degradation of coastal wetlands mainly occurred in Sheyang County, Dafeng District, Dongtai City, and Rudong County (84.34% of the total degraded area in the region, and the proportions of mildly degraded, moderately degraded, and severely degraded areas to the total area of each grade were 86.41%, 82.87%, and 76.80%, respectively). Notably, the proportion of degraded coastal wetland area in Sheyang County was 66.41%, and the proportions of mildly degraded, moderately degraded and severely degraded areas were 22.36%, 37.14%, and 6.91%, respectively; the proportion of degraded coastal wetland area in Dafeng District was 69.63%, and the proportions of mildly degraded, moderately degraded, and severely degraded areas were 39.85%, 27.12%, and 2.66%, respectively. It can be seen that the degraded area was larger in the region as a whole, but the degradation degree was mild, and the degraded area and degree in the northern counties and cities were higher than those in the southern cities and counties, with significant regional differences.

3.3.2. Analysis of Temporal Variation in Wetland Degradation Grades

The degradation composite score of the study area in all time periods was less than 3 and showed a significant increasing trend. The greatest change occurred in 2000 (Figure 7). The proportion of mild, moderate, and severe degradation also showed a significant increasing trend, and 2000 was the turning point of this change. The proportion of mild, moderate, and severe degradation showed a significant increasing trend before 2000, and the change rate of mild degradation after 2000 was half of that before 2000. The proportion of moderate degradation showed a non-significant increasing trend, and the proportion of severe degradation showed a non-significant decreasing trend. It can be seen that, over the past 40 years, although the coastal wetlands in the study area experienced a mild degradation state as a whole, and the rate of change in the degradation degree after 2000 was alleviated, degradation continues to aggravate the environment. The degradation composite score of coastal wetlands in Yancheng City (0.65–2.41) was larger than that of Nantong City (0.33–1.20) in all time periods, and the change rates of the degradation composite score and degradation areal proportion (all grades) were also larger in Yancheng City than in Nantong City. However, only the rate of change in the proportion of mildly degraded area (0.32) was somewhat smaller than that of Yancheng (0.43) after 2000. Meanwhile, the proportion of moderately and severely degraded areas in Yancheng City and the proportion of severely degraded areas in Nantong City both showed a non-significant decreasing trend. This result indicates, on the one hand, that the degradation of coastal wetlands in Yancheng City is more serious than that in Nantong City. On the other hand, this result indicates that although the degradation of coastal wetlands in both cities was alleviated to different degrees, the coastal wetlands in Nantong City should be given more attention and protection in the future.

The degradation composite scores of the ten counties and cities in the study area were all between 0 and 3, and all of them were mildly degraded. The composite scores of coastal wetland degradation in Xiangshui County (2.44), Sheyang County (2.73), and Dafeng District (2.53) were close to 3. Decision makers should pay more attention to this factor and take appropriate measures to control the further aggravation of wetland degradation. The turning point of the five counties and cities in the northern part of the study area, except for Xiangshui County, occurred in 2000, and the composite score of degradation was stable in the region after 2000. The proportion of the severely degraded area in 2015 and 2020 increased in Xiangshui County, mainly because the construction of the industrial park led to the conversion of natural wetlands into construction land. The degradation composite score of the five counties and cities in the south was significantly smaller than that of the five counties and cities in the north, and the degradation composite score of coastal wetlands in all counties and cities showed a significant increasing trend. However, there were differences in the turning points. Tongzhou District and Qidong City showed stabilized degradation composite scores after 2015, while Hai'an District, Rudong County, and Haimen District did not yet indicate a significant turning point during this period. This result indicates that, on the one hand, there are obvious stage-based characteristics of wetland degradation. On the other hand, this result shows that the wetland degradation in the five counties and cities in the north was controlled, to some extent, but still needs continuous attention and protection in the future, while the coastal wetlands in the five counties and cities in the south may continue to deteriorate and will require even more protection in the future.

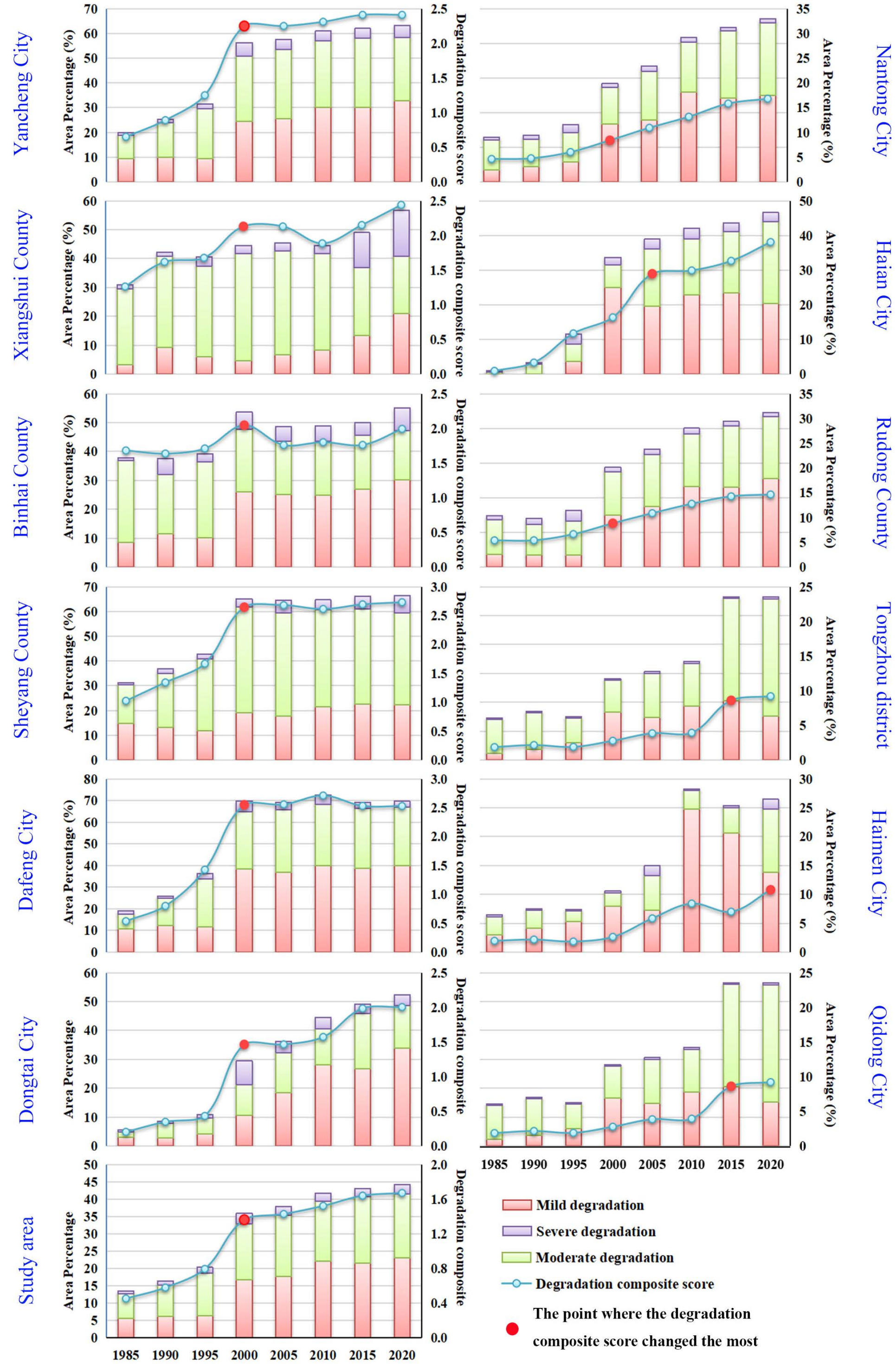


Figure 7. Changes in the overall degradation score and areal proportion of each degradation class of coastal wetlands.

3.3.3. Pattern Analysis of the Evolution of Wetland Degradation Grades

The proportions of areas with significantly improved, improved, stable, deteriorated, and severely deteriorated results in the study area during 1985–2020 were 0.26%, 1.38%, 63.76%, 23.38%, and 11.22%, respectively (Figure 8). The proportion of areas with improved and significantly improved results showed a non-significant increasing trend, and the maximum value appeared in the period of 2000–2005 (Table 5). The proportion of areas with deteriorated and severely deteriorated results changed more, indicating a decreasing trend, and had an obvious turning point; the maximum value appeared in the period of 1995–2000 (Table 6), indicating that the ecological conditions in the study area improved. The change trends in Yancheng City and Nantong City, however, were exactly the opposite. The proportion of areas with deteriorated and severely deteriorated land in Yancheng City showed a fluctuating downward trend, and the proportion of area with improved and significantly improved land experienced an upward trend. Conversely, the proportion of area with deteriorated and severely deteriorated land in Nantong City showed a fluctuating upward trend, and the proportion of area with improved and significantly improved results experienced a downward trend. These results indicate that the wetland degradation in Yancheng City has improved and should be given continuous attention and protection in the future, while the wetland degradation in Nantong City is relatively intensifying, and more resources need to be invested to take more effective measures to control the wetland degradation and improve ecological conditions.

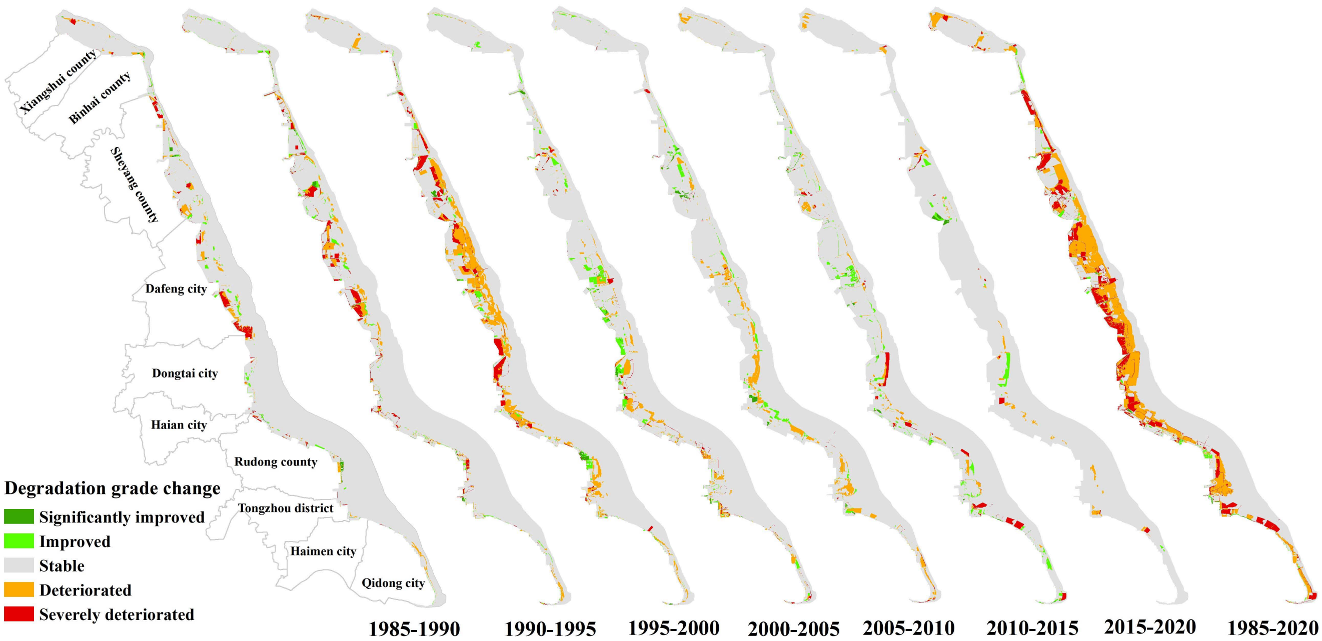


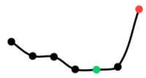
Figure 8. Spatial distribution of coastal wetland degradation grade changes in the study area.

Table 5. Proportion of improved coastal wetland degradation grade in each county and city compared to the total improved area in the study area.

Region	1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	Average	Trendline	Trend
Xiangshui County	0.90	4.88	1.12	1.73	4.27	0.79	0.15	1.98		Decrease with fluctuations
Binhai County	9.64	9.52	5.55	5.70	0.71	1.49	0.53	4.73		
Sheyang County	18.41	32.78	19.09	14.50	35.31	12.65	20.81	21.94		
Dafeng District	34.75	28.81	26.91	35.07	10.09	32.86	29.58	28.29		
Dongtai City	9.67	3.32	4.88	27.78	18.20	10.21	46.35	17.20		Increase with fluctuations
Hai'an City	0.03	0.91	0.58	1.54	2.83	0.75	0.00	0.95		
Rudong County	23.09	8.74	33.91	5.67	22.59	20.50	0.00	16.36		Decrease with fluctuations
Tongzhou District	0.35	3.25	0.94	2.71	1.24	3.18	0.00	1.67		
Haimen District	0.35	2.26	1.89	0.60	4.22	2.85	0.00	1.74		Increase with fluctuations
Qidong City	2.81	5.53	5.13	4.71	0.54	14.72	2.59	5.15		
Yancheng City	73.37	79.31	57.54	84.78	68.59	58.01	97.41	74.15		
Nantong City	26.63	20.69	42.46	15.22	31.41	41.99	2.59	25.85		Decrease with fluctuations
Study Area	1.57	1.95	2.06	3.84	2.73	3.24	1.50	2.41		Increase with fluctuations

Note: The last row of values indicates the proportion of area with an improving degradation level compared to the total area of the study area.

Table 6. Proportion of deteriorated coastal wetland degradation grade in each county and city compared to the total deteriorated area in the study area.

Region	1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020	Average	Trendline	Trend
Xiangshui County	5.22	1.16	0.96	1.09	0.60	7.21	10.85	3.87		Increase with fluctuations
Binhai County	3.96	2.22	2.13	0.61	0.56	0.91	7.90	2.61		
Sheyang County	28.36	21.93	18.51	11.01	9.37	16.83	17.05	17.58		Decrease with fluctuations
Dafeng District	37.52	50.90	44.28	18.14	18.28	7.59	4.66	25.91		
Dongtai City	11.05	6.04	14.37	22.54	24.50	21.80	19.94	17.18		Increase with fluctuations
Hai'an City	0.59	1.69	1.67	4.95	1.96	1.23	4.65	2.39		
Rudong County	7.20	9.73	14.19	26.63	27.16	22.47	18.39	17.97		
Tongzhou District	0.56	0.68	0.81	3.29	1.13	6.22	2.36	2.15		
Haimen District	0.53	0.36	0.54	3.52	4.43	0.96	7.08	2.49		
Qidong City	5.01	5.28	2.54	8.23	12.02	14.79	7.12	7.85		
Yancheng City	86.11	82.25	80.26	53.38	53.30	54.34	60.40	67.15		Decrease with fluctuations
Nantong City	13.89	17.75	19.74	46.62	46.70	45.66	39.60	32.85		Increase with fluctuations
Study Area	5.24	6.98	18.47	5.58	6.22	4.73	2.49	7.10		Decrease with fluctuations

Note: The last row of values indicates the proportion of area with deteriorating degradation level compared to the total area of the study area.

Patterns of change in wetland degradation grades also show spatial heterogeneity. Two of the 10 counties and cities (Sheyang County and Dafeng District) showed a decreasing–decreasing trend (both deterioration and improvement were decreasing), and the rate of deterioration was much larger than the rate of improvement, indicating that the ecological conditions of these two counties were slowly improving. Four counties and cities (Xiangshui County, Binhai County, Rudong County, and Tongzhou District) showed an increasing–decreasing trend (deterioration was on the rise and improvement was on the decline). The rate of deterioration was also greater than the rate of improvement, indicating that the ecological conditions in these four cities and counties were deteriorating at an accelerated rate; thus, policy makers should pay more attention to these cities. The remaining four cities and counties showed an increasing–increasing trend (both deterioration and improvement were on the rise). The rate of deterioration was still greater than the rate of improvement, indicating that the ecological conditions of these four counties and cities were deteriorating continuously and should be given more attention and protection in the future.

4. Discussion

4.1. Regional Variability in Wetland Degradation

The present study showed significant regional variability in wetland degradation in the study area. The proportion of degraded area and the composite score of degradation in Yancheng City were higher than those in Nantong City (63.12% > 32.98%, 2.41 > 1.20). This result may be related to the geographical location and socio-economic development of the city. Compared to Yancheng City, Nantong City is closer to Shanghai City, receives stronger economic radiation, has a higher GDP per capita (the GDP per capita in 2020 was 18.75 thousand dollars in Nantong City and 12.81 thousand dollars in Yancheng City), and focuses more on the development of traditional industries such as textiles and construction inland. Wetland degradation mainly occurred in Sheyang County, Dafeng District, Dongtai City, and Rudong County. This result may be related to the physical geography of the region. After the diversion of the Yellow River into the Bohai Sea in 1855, the abandoned Yellow River delta coast changed from siltation to erosion due to the loss of sediment sources [37–39]. The area encompasses the coast from the estuary of Guan River to the estuary of Sheyang River (including Xiangshui County, Binhai County, and the northern part of Sheyang County). The coast of Qidong City, which is located at the southernmost end, is the most stable, while the coast between the estuary of Sheyang River and Dongzao port (southern Sheyang County to Haimen District) is a typical siltation longshore. The coastal wetland resources between the estuary of Sheyang River and Dongzao port are rich, where a large area of coastal wetlands has been reclaimed and exploited to alleviate human–land conflicts and promote social and economic development. This is consistent with the findings of Gu et al. (2012) [26].

The distribution pattern from land to sea showed severe and moderate degradation, mild degradation, and non-degradation in that order. This is similar to the spatial distribution pattern of reclamation boundary changes and the main evolutionary directions of ecologically critical areas from 1977–2014 obtained by Li et al. (2015) in central Jiangsu [40]. Severe degradation was dominated by the conversion of natural wetland into non-wetland, mainly natural wetland into construction land (45.75%), dryland (34.84%), and settlements (7.98%). Moderate degradation was dominated by the conversion of natural wetland into artificial wetland, mainly natural wetland into aquafarm (41.05%) and paddy fields (26.24%). Mild degradation was dominated by the conversion of natural wetland into artificial wetlands and spartina alterniflora invasion, mainly natural wetland into aquafarm (57.52%) and spartina alterniflora invasion (20.69%). Under the background of rapid socio-economic development, the loss of high-quality arable land due to population growth and construction land expansion has exacerbated human–land conflict and affected national food security. Coastal wetlands are important reserve land resources for regional development [41]. Coastal wetland reclamation has alleviated human–land conflict to a certain extent. The reclamation area is mainly used for coastal industries, arable land, and aquaculture, consistent with the findings of Wang et al. (2020) [42], Chen et al. (2022) [43] and Hu et al. (2020) [32].

4.2. Stages of Wetland Degradation

The present study showed that the degradation of coastal wetlands in Jiangsu has obvious stage-based characteristics, mainly related to the policy of each socio-economic development stage. The Jiangsu Polder Command Department was established in 1980–1995, and the coastal wetland development and utilization modes of grain and cotton production and aquaculture were set. During this period, the economic development level was low, and although the degradation score was slowly increasing, the observed degradation was mainly mild and moderate.

The development strategy of "Marine Sudong" was proposed in 1995–2000. The policy of "who invests, who develops, who obtains the right to use the land" made a variety of economic components participate in the development and utilization of coastal wetlands. As the mechanization level of reclamation improved, the enthusiasm for developing and utilizing coastal wetlands was stimulated, which made the degradation area and score of coastal wetlands in this period rise rapidly, which is the reason why the maximum changes in the degradation scores of wetlands appeared in 1995–2000. Although the government planned to develop millions of mu (1 mu = 1/15 hectare) of mudflats in 2001–2005; develop "ports, towns, and coastal harbor industry" in 2006–2010, and construct a "new port industrial zone, modern agricultural base, energy base, and coastal new city" in 2011–2015, the rate of change in degradation was eased due to the increase in ecological and environmental awareness. The government promoted the integrated development of "port, industry and town" from 2016 to 2020 and has since started to strictly control the reclamation of coastal wetlands. The government also introduced the national ecological protection red line plan to strengthen the protection and restoration of coastal wetlands. The conversion of natural wetlands to aquafarms was the main type of wetland degradation observed in each stage, mainly because the high salt content of coastal wetland soils is not suitable for direct development as arable land [44], whereas the cost of aquaculture is relatively small and can bring great economic benefits [45].

Both the degraded area and degradation composite score of coastal wetlands in Yancheng City were larger than those in Nantong City, but the change rate of the degradation composite score and degraded areal proportion in Nantong City after 2000 were larger than those in Yancheng City. This result is mainly because, on the one hand, compared to Nantong City, Yancheng City has a larger reclamation area, and many reclamation areas have been close to or below the average seawater surface, making reclamation more difficult and costly [46]. Ecological protection awareness has also increased, while the intensity of reclamation has decreased [47]. On the other hand, before 2000, Nantong City's reclamation was less intense, the shoreline was in a siltation state, and the reclamation potential was greater [47,48].

4.3. Implications for Coastal Wetland Conservation Policies and Initiatives

Human activities remain the dominant factor in the degradation of modern coastal wetlands [6,49,50], which suggests that we should rethink the conservation policies of coastal wetlands. The "Ecological Civilization" strategy implemented in 2012 and the "National Marine Functional Zoning Plan (2011–2020)" have strengthened the management of the development and utilization of coastal wetlands. Additionally, the "Implementation Plan for Wetland Protection and Restoration System in Jiangsu Province" issued in 2017 explicitly mandated the protection of natural wetlands, including strengthening the restoration of degraded wetlands and enhancing the ecological functions of wetlands. Subsequently, the reclamation project has been effectively curbed [51]. The "Wetland Protection Law of the People's Republic of China" implemented in 2022 has strictly controlled the occupation of wetlands, strengthened the management and protection of coastal wetlands at the policy and institutional levels, and protected and maintained the stability of the ecological functions of wetlands [33]. Although coastal wetland reclamation has a positive impact on alleviating human–land conflicts and increasing people's incomes, reclamation will inevitably lead to wetland degradation (e.g., natural wetlands $\rightarrow$ artificial wetlands or non-wetlands), which adversely affects the ecological functions of coastal wetlands such as water purification, carbon sequestration, and biodiversity [52,53]: the natural wetland value is on average 31 times higher than the value of artificial wetlands and non-wetlands [54], thus jeopardizing regional ecological security and sustainable socio-economic development.

Evaluating wetland degradation is the foundation and prerequisite for optimizing wetland conservation and restoration [55]. The present study shows that there are significant stages and regional differences in the degradation of coastal wetlands in Jiangsu, which are dominated by the loss of natural wetlands and spartina alterniflora invasion. Therefore, minimizing the loss of natural wetlands should be fully considered when developing and implementing policies and initiatives for arable land conservation and urbanization development [56]. Meanwhile, spartina alterniflora is crowding the growing spaces of native species such as seagrass bed, suaeda glauca, and scirpus triqueter, thereby threatening the food sources and habitats of migrating birds [57]. However, this species also has the function of beach preservation and siltation promotion. For erosive shores (e.g., Xiangshui and Binhai Counties), the growth scale of spartina alterniflora can be appropriately controlled; for silty shores, strategies such as the preferential removal of fast-growing low-density subpopulations [58] could also be considered to remove spartina alterniflora.

4.4. Shortcomings and Prospects

A limitation of our study is that the diagnostic approach of wetland degradation based on the habitat succession model only considers the retrogression succession between different landscape types and should be explored in conjunction with changes in the same landscape type to assess wetland degradation in an integrated manner. Given the scale dependence among landscape patterns [59], wetland degradation at the landscape level is also scale-dependent. In contrast, this paper provided a statistical analysis based on 30 m resolution landscape interpretation data and did not consider the influence of different scales on the evaluation results of wetland degradation at the landscape level. Therefore, these shortcomings will be further investigated in future studies to better diagnose wetland degradation and reduce the uncertainty of research conclusions in order to better promote the innovative development of wetland degradation evaluation methods, provide technical support for coastal wetland ecosystem restoration and conservation, and guarantee the sustainable socio-economic development of coastal areas.

5. Conclusions

This study explored the spatial and temporal evolution characteristics of coastal wetland degradation in Jiangsu based on visually interpreted landscape data from 1980 to 2020 and wetland degradation diagnosis methods. Our study revealed obvious stages and regional differences in the degradation of coastal wetlands in Jiangsu. In total, 3020.67 km^2 of coastal wetlands in Jiangsu became degraded from 1980 to 2020, with most areas becoming mildly and moderately degraded. Yancheng City was confirmed to have more serious wetland degradation than Nantong City. The regions with the largest proportion of degraded wetland in the study area were identified as Sheyang County, Dafeng District, Dongtai City, and Rudong County. Among all wetland degradation types, the natural wetland was the most severely degraded by development; use for aquafarm, cropland, and construction land; and spartina alterniflora invasion. After 2000, the pressure of wetland degradation in Nantong City was even greater. Despite the great efforts made in recent years in wetland conservation and restoration, more coastal wetlands must be prevented from degradation due to human activities in order to achieve green and high-quality socio-economic development. In view of China's "ecological civilization" strategy, effective policies and regulations must be implemented to protect and manage coastal wetland resources and incorporate them into social development decisions to promote green, high-quality socio-economic development and build a sustainable development pattern in coastal areas.

Author Contributions: Conceptualization, G.L. and L.C.; methodology L.C.; analysis, L.C.; writing—original draft preparation, L.C.; writing—review and editing, G.L. and L.C.; funding acquisition, L.C.; Data curation, H.L., N.O., X.L., and D.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key R&D Program of China (Grant No. 2022YFC3200069) and China Postdoctoral Science Foundation (Grant No. 2019M660780).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We thank three anonymous reviewers and the Editors for their crucial comments that improved the quality of this paper. We acknowledge the use of the Landsat data from the United States Geological Survey EarthExplorer website (https://earthexplorer.usgs.gov/, accessed on 1 September 2022), the DEM data from the Geospatial Data Cloud website (http://www.gscloud.cn, accessed on 1 September 2022), the geographic vector data from the Standard Map Service website (http://bzdt.ch.mnr.gov.cn/index.html, accessed on 1 September 2022) and the beach resource survey data from the library of the Institute of Geographical Sciences and Resources, Chinese Academy of Sciences.

Conflicts of Interest: The authors declare no conflict of interest.

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