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Dynamic Changes in Landscape Pattern of Mangrove Wetland in Estuary Area Driven by Rapid Urbanization and Ecological Restoration: A Case Study of Luoyangjiang River Estuary in Fujian Province, China

Yuxin Yang [1], Xiang Ye [1,2] and Aijun Wang [1,2,*]

[1] Third Institute of Oceanography, Ministry of Natural Resources, Xiamen 361005, China; yuxinyyang@163.com (Y.Y.); yexiang@tio.org.cn (X.Y.)
[2] Fujian Provincial Key Laboratory of Marine Physical and Geological Processes, Xiamen 361005, China
* Correspondence: wangaijun@tio.org.cn

Abstract: Coastal wetlands are natural complexes situated between terrestrial and marine ecosystems and are one of the most productive ecosystems in terms of global biomass production. However, under the influence of intensive human activity, global coastal wetlands have undergone rapid degradation. In this study, RS technology, landscape ecology, and object-oriented methods were used to interpret remote sensing images from different periods and analyze the dynamic changes in landscape patterns and their driving mechanisms in coastal wetlands in the Luoyangjiang River estuary from 1983 to 2021 by considering changes in the landscape pattern index. The results show that the patch areas of all the types of wetland landscapes in the Luoyangjiang River estuary changed, and the patch areas of mangroves and *Spartina alterniflora* increased. The patch density of the coastal wetlands increased significantly, the index of mangrove aggregation increased, and the index of separation decreased. From the perspective of the overall characteristic value of the landscape pattern, the landscape diversity index and the evenness index of the study area gradually increased, and the difference in the proportion of different types of landscape was reduced. Additionally, the patch number and patch diversity significantly increased, the maximum patch index and the spread index decreased, and the landscape separation index significantly increased. Rapid urbanization and the implementation of many ecological restoration projects were shown to be the main factors driving changes in the landscape indices of coastal wetlands in the Luoyangjiang River estuary. In the study period, rapid urbanization significantly reduced the area of coastal wetlands, and the implementation of ecological restoration projects increased the fragmentation, heterogeneity, and dispersion of wetland landscapes in the study area and decreased the aggregation of wetland landscapes. Moreover, the distribution of all the types of landscapes gradually became more uniform.

Keywords: landscape pattern; coastal wetland; rapid urbanization; ecological restoration; Luoyangjiang River estuary

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Citation: Yang, Y.; Ye, X.; Wang, A. Dynamic Changes in Landscape Pattern of Mangrove Wetland in Estuary Area Driven by Rapid Urbanization and Ecological Restoration: A Case Study of Luoyangjiang River Estuary in Fujian Province, China. *Water* **2023**, *15*, 1715. https://doi.org/10.3390/w15091715

Academic Editor: Bommanna Krishnappan

Received: 11 March 2023
Revised: 24 April 2023
Accepted: 25 April 2023
Published: 28 April 2023

1. Introduction

Coastal wetlands are complicated natural complexes situated between terrestrial and marine ecosystems. They are one of the most productive ecosystems in terms of global biomass production, playing a critical role in coastal protection, water purification, biodiversity conservation, and carbon sequestration [1–4]. However, with the intensification of human activities, global wetland areas have experienced a net loss of 21% over the past 300 years [5], and global coastal wetland areas were reduced by more than 50% in the 20th century [3]. Mangrove wetlands are important coastal wetland ecosystems composed of mangrove plant communities, bare intertidal flats, tidal creeks, and water bodies, with depths not exceeding 6 m at low tide. They grow on tropical and subtropical coasts and are experiencing serious degradation problems, with approximately 35% of mangrove forests having disappeared globally in the past half century [6]. According to the FAO's 2015 Assessment Report, the global mangrove area was approximately 1.5×10^5 hm^2 in 2015, which was 4% less than in 2010 [7]. In China, the mangrove area rapidly decreased from 42,000 hm^2 in the 1950s to 22,000 hm^2 in 2000, owing to the large-scale reclamation of sea areas, deforestation, and pond cultivation, which is a rate of decrease far greater than the global average [8]. The role of mangrove wetlands in disaster prevention and reduction has been highlighted [9–11]. Coastal blue carbon research has further highlighted the strong carbon sequestration function of mangrove wetlands [12–14], and attention to mangrove wetlands has significantly increased, with mangrove ecological restoration projects being conducted globally [15–17]. Although the global mangrove area is declining annually, it is increasing in certain regions owing to increasing afforestation activities [18,19]. In China, the mangrove area has been gradually increasing since 2000 and significantly increasing since 2016, owing to the comprehensive implementation of ecological restoration projects such as "Blue Bay" and "South Red North Willow" [20]. Thus, China is one of a few countries with a net increase in mangrove area. It was projected that, by 2021, the mangrove wetland area in China would have increased to 27,100 hm^2 [21].

Landscape patterns are the spatial arrangement of landscape patches of different sizes and shapes and are the result of various ecological processes at different scales [22]. Changes in wetland landscape patterns form the basis for studying wetland function and implementing wetland protection [23]. By studying the evolution of mangrove wetland landscapes and analyzing the shape, size, number, and spatial combination of mangrove wetland landscape components and their changing processes, the ecological environment of mangrove wetlands can be analyzed and evaluated, and the influence of natural factors and human activities on the landscape patterns and dynamic processes of mangrove wetlands can be revealed. This study provides a basis for the protection and sustainable utilization of mangrove wetlands and will help in formulating mangrove ecosystem restoration and restoration programs in the future [24–26].

The mangrove wetland in the Luoyangjiang River estuary is in Quanzhou Bay: a typical semi-enclosed bay on the southeastern coast of China. Mangrove wetlands are diverse, and their biodiversity is very high; thus, they are an important component of international wetlands. In recent years, large-scale ecological restoration projects have attempted to significantly slow the degradation of mangrove wetlands in the Luoyangjiang River estuary around Quanzhou Bay caused by increasingly intense and destructive human activities [27–29]; thus, the landscape pattern of wetlands has changed significantly [30]. However, despite the implementation of many mangrove ecological restoration projects, our understanding of how these projects affect the landscape pattern of wetlands and of the driving mechanisms of landscape pattern change after the implementation of the projects remains unclear.

Therefore, this paper uses the mangrove wetland in the estuary of Luoyangjiang River as the research object. We collected field survey and remote sensing image data in different periods and used remote sensing technology and geographic information system technology (GIS) to analyze the landscape pattern change process from 1983 to 2021. The results reveal the landscape pattern change and the driving mechanism of mangrove wetlands in the estuary, providing a scientific basis for the protection and ecological restoration of mangrove wetlands.

2. Study Area

Quanzhou Bay is on the southeastern coast of China (Figure 1A). The wetland of Quanzhou Bay nature reserve is 6846.71 hm^2 and is rich in marine biological resources and rare and endangered species; thus, it is an important breeding ground for local water birds, including rare bird species such as the yellow billed egret and black billed gull, fish, shrimp, shellfish, etc., and is one of the most important bays on the southeast coast of China [27,31]. Quanzhou Bay has a subtropical marine monsoon climate with regular semi-diurnal tides, an average tidal range of 4.52 m, and a relatively small wave action [29]. The salinity of the water in the upper reaches of the Luoyangjiang River estuary is about 21.42 PSU–21.48 PSU during low tide and 25.78 PSU–26.36 PSU during high tide. The salinity of the water in the lower reaches of the Luoyangjiang River estuary is about 22.35 PSU–24.46 PSU during low tide and 32.80 PSU–33.00 PSU during high tide (unpublished data). Overall, under the same tidal level conditions, the salinity of the water in the lower reaches of the Luoyangjiang River estuary is higher than that in the upper reaches. Quanzhou Bay is fed by the Jinjiang and Luoyangjiang Rivers (Figure 1B,C), which form large intertidal wetlands in the bay [32]. Wetland plants in the Luoyangjiang River estuary are distributed on a muddy tidal flat. The intertidal zone comprises mangrove plant communities composed of *Aegiceras corniculatum*, *Kandelia obovata*, and *Avicennia marina* and other communities composed of *Spartina alterniflora* and reeds [33].

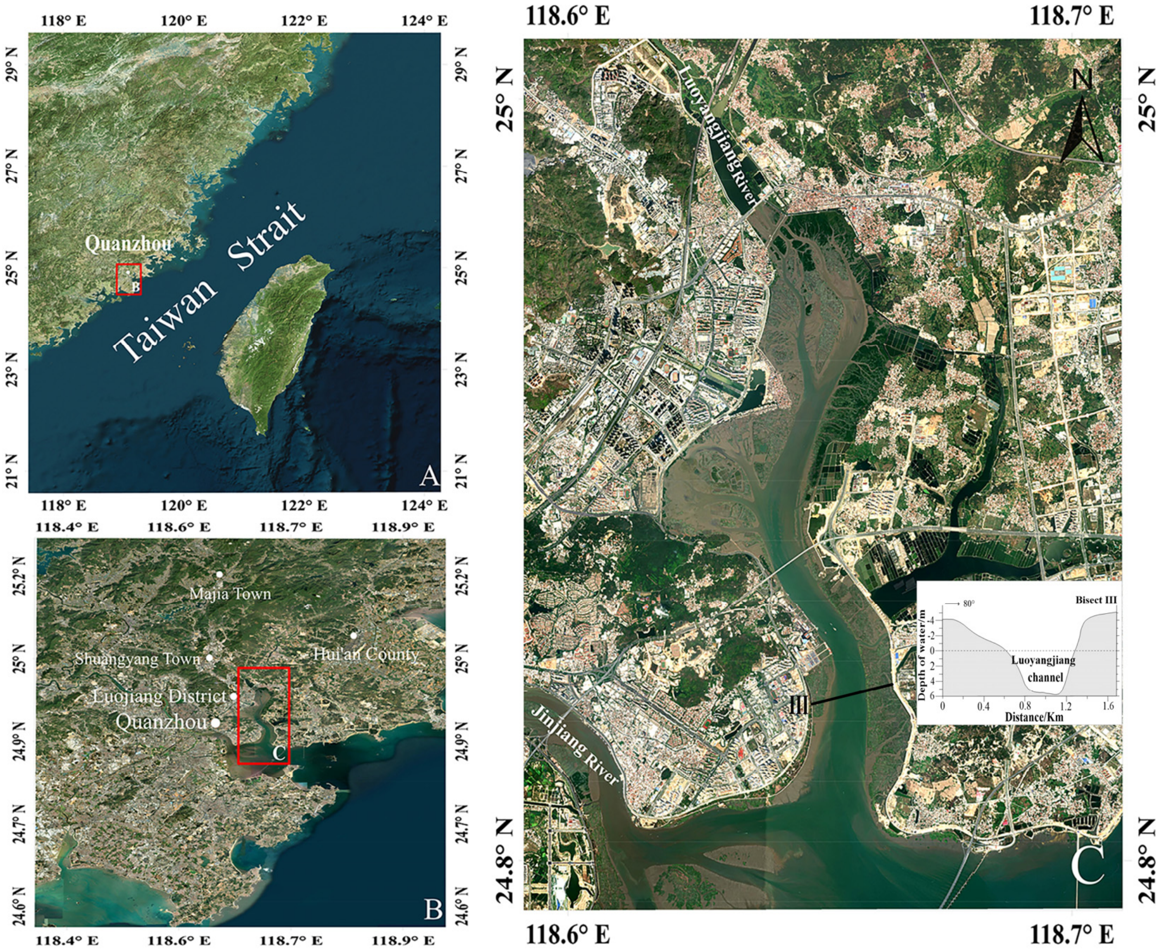


Figure 1. Satellite orthophotos of the study area. (Image is a Google Earth high-resolution image taken on 19 May 2021. The river section diagram is redraw from [34].)

3. Data Sources and Processing

3.1. Data Source and Preprocessing

The remote sensing image data used in this study were accessed from the Geospatial Data Cloud (https://www.gscloud.cn) accessed on 26 July 2021, and the processing level used for satellite images is L1TP. According to the research requirements and the quality of the remote sensing images, images from 1983, 1990, 1996, 2002, 2008, 2015, and 2021 were selected as data sources. Detailed information on these images is presented in Table 1. According to the topography profile across the river channel, as shown in Figure 1, the early stages of flooding, the end of the ebb tide, and the variation in the tidal level only occur in the channel, and there is no obvious influence on the variation in the intertidal area. Therefore, we believe that the images selected in this paper basically reflect all the information of the intertidal wetlands at that time.

Table 1. Remote sensing image details.

Period	Sensor Category	Imaging Time	Cloud Cover (%)	Tidal Information
1983	MSS	9–27 12:27:07	0	1 h after Low tide
1990	TM	7–20 06:46:45	0	1 h after low tide
1996	TM	12–11 14:36:25	0	Low tide
2002	TM	1–10 14:29:17	0	Low tide
2008	ETM	12–20 15:29:04	0	Low tide
2015	ETM	8–2 21:10:41	0.2	2 h after low tide
2021	OLI	2–15 07:01:38	0.2	2 h after low tide

A UTM-WGS84 projection was used, and the spatial resolution of the satellite was 30 m. Remote sensing images with a cloud cover of less than 1% were selected to reduce errors. ARCGIS 10.2, Envi 5.1, eCognition Developer 64, and FragStats were used for data processing and analysis. First, the image was preprocessed using Envi. This involved clipping and atmospheric correction, among other techniques, to reduce the errors caused by the atmosphere, lens, illumination, etc. Next, the required remote sensing data were obtained. Object-oriented classification and visual interpretation, combined with high-resolution image data from the related literature and other methods, were used to conduct a comprehensive classification of the study area. On the basis of the "Convention on wetlands" [35], a classification system encompassing mangroves, *Spartina alterniflora*, mudflats, water areas, and artificial surfaces was established.

3.2. Information Extraction of Object-Oriented Taxonomy

On the basis of spectral information features, object-oriented classification synthesizes texture information, geometric features, semantics, spatial location, and correlation information between adjacent pixels in remote sensing images [36]. The traditional remote sensing image classification method is based on pixel classification, and the object-oriented method uses a segmentation algorithm to segment the object using feature recognition to complete the final classification, which is more efficient and accurate than the traditional classification method. This method overcomes the limitations of traditional pixel-based classification, efficiently classifies remote sensing images, and effectively avoids severe issues related to the "Salt-and-pepper phenomenon" [27]. After repeated debugging, we selected the appropriate segmentation parameters, among which the optimal segmentation parameter was 5, the shape factor was set to 0.1, and the compactness index was 0.6. The best combination of bands was as follows: TM/ETM used bands 4, 3, and 2 for color synthesis, while OLI used bands 6, 5, and 4 for synthesis, so the weight of each band was set to 1. Using the assign class algorithm in the eCognition environment, the near-infrared waveband value was used to distinguish between water and non-water; the brightness value was used to identify artificial surfaces; the NDVI characteristic value was established; and mangrove, mudflat, and *Spartina alterniflora* were distinguished by debugging to the appropriate threshold range. Finally, combined with various high-resolution satellite images and relevant information, the error classification type was manually adjusted to improve the accuracy.

3.3. Selection of Wetland Landscape Index

Landscape spatial patterns result from various ecological processes, including disturbances at different scales. Landscape pattern analysis can quantitatively study the distribution of patches in a landscape to discover potentially meaningful patterns of order in an apparently disordered landscape [37]. The landscape pattern index includes the patch level index, patch type level index, and landscape level index. This research used multiple patch levels, the overall landscape level, the patch area (CA), the landscape percentage (Pland), the patch number (NP), the patch density (PD), the landscape shape index (LSI), the split index (SPLIT), the tag index (Contag), the Shannon evenness index (SHEI), and the Shannon diversity index (SHDI). The formula and significance of the landscape index are as follows [38,39]:

Number of patches (NP): The total number of patches associated with a landscape. When a certain landscape area in the study area remained unchanged, its information transfer significance was the same as that of PD, reflecting the integrity and fragmentation of the landscape.

PD: To some extent, the number of patches per unit area reflects the degree of landscape fragmentation and the impact of human activities.

Patch area (*CA*): Total patch area of the landscape type.

$$CA = \sum_{j=i}^{n} a_{ij} \tag{1}$$

Here, n is the number of patches of landscape type i, and a_{ij} is the area of the patch.

Percentage of landscape (PLAND): Landscape type as a percentage of the area of all landscape types.

LSI: The larger the shape index, the more irregular the patch shape.

$$LSI = \frac{0.25\sum_{k=1}^{m} \mathrm{e}^*{}_{ik}}{\sqrt{A}} \tag{2}$$

Here, $\mathrm{e}^*{}_{ik}$ is the total length of the edge in the landscape between patch types i and k, and A is the total landscape area.

Split index (*SPLIT*): *SPLIT* = 1 when the landscape contains only one patch.

$$SPLIT = \frac{A^2}{\sum_{i=1}^{m}\sum_{j=1}^{n} {a_{ij}}^2} \tag{3}$$

Here, a_{ij} is the area of patch ij, and A is the total landscape area.

Contagion index (*CONTAG*): The lower the *CONTAG*, the poorer the connectivity of the components and the higher the degree of landscape fragmentation.

$$CONTAG = 1 + \sum_{i=1}^{m}\sum_{j=1}^{m} P_{ij}\ln\left(P_{ij}\right)\frac{P_{ij}\ln\left(P_{ij}\right)}{2\ln(m)} \tag{4}$$

Here, m is the total number of patch types in the landscape, and P_{ij} is the probability of similarity between landscapes i and j.

SHDI reflects the landscape heterogeneity. The higher the *SHDI* value, the more balanced the distribution of the components of the landscape system, the higher the degree of fragmentation, and the more abundant the land-use types.

$$SHDI = -\sum_{i=q}^{m}(p_i \times \ln p_i) \tag{5}$$

Here, m is the number of landscape types, and p_i is the probability of the appearance of a type i landscape.

SHEI measures changes in the diversity of landscape components over time in the same landscape. When $0 \leq SHEI \leq 1$, the closer the $SHEI$ value is to 1, the more uniform the distribution of each component in the landscape.

$$SHEI = \frac{-\sum_{i=1}^{m}(p_i \times \ln p_i)}{\ln m} \tag{6}$$

Here, m is the total number of patches in the landscape, and p_i is the proportion of the type i landscape area in the total area.

3.4. Accuracy Evaluation

On the basis of eCognition, we used the object-oriented threshold classification method to select the corresponding parameters and set the threshold range according to the different spectral characteristics of ground objects. However, threshold classification can lead to the classification of different types of ground objects in the same category, i.e., objects that do not exhibit obvious differences in spectral characteristics in remote sensing images. Therefore, on the basis of threshold classification, manual error correction classification can increase classification accuracy. A uniform selection of 50 points was applied on the classification maps of the 2021 study area. The points selected on the 2021 remote sensing images were manually interpreted and compared with Arcgis online high-resolution satellite images and related data, and on-site investigations were conducted (Figure 2). The final classification accuracy was 92%. Misclassification control results are shown in Table 2. The main reason for misclassification between different land types is that threshold classification defines a specific range for the selected classification features, which will clearly separate the vast majority of two different types of land objects, but there may also be other individual land types that meet this specific range value at the same time. Manual adjustment of misclassification types is based on visual interpretation of high-resolution images to modify obvious misclassification, but it cannot guarantee that all misclassification types will be detected, especially for feature categories located at boundaries or with very similar colors on the images. Therefore, the misclassifications, as shown in Table 2, may occur.

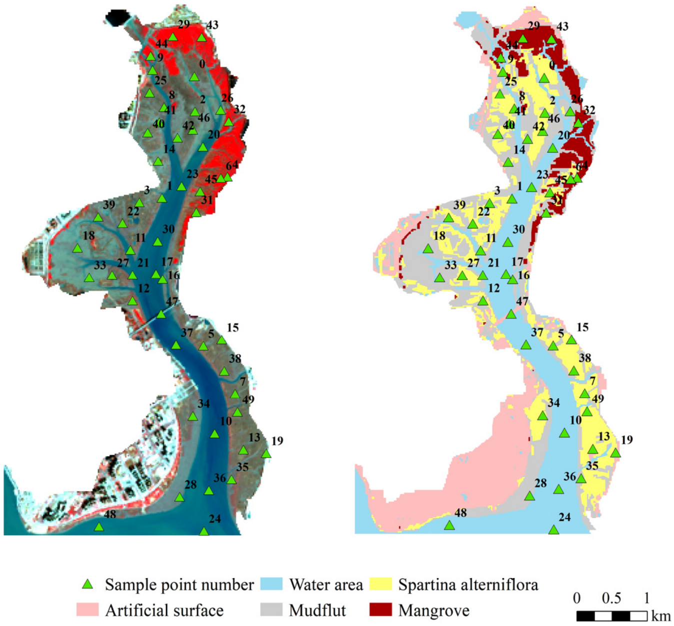
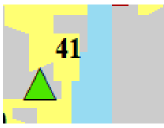
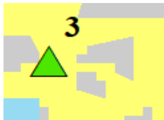
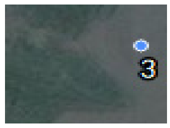
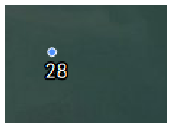


Figure 2. Point selection for the validation of classification results. The left image is Landsat8 from 2021, sourced from the Geospatial Data Cloud (https://www.gscloud.cn), accessed on 26 July 2021. It is a field verification point selected based on remote sensing images. The right image is a classification result based on image interpretation.

Table 2. Verified results of random control points.

Point Number	Classification Point Type	Classification Result Graph	Actual Point Type	High-Resolution Images
41	*Spartina alterniflora*		Mudflats	
6	*Spartina alterniflora*		Mudflats	
28	Mudflats		Water	
31	Mangroves		*Spartina alterniflora*	

Note: High-resolution images from Google Earth.

4. Results

4.1. Variations in Landscape Components of Estuarine Wetland

According to the classification results of the remote sensing images (Table 3), the water area was the largest among the various landscape types in the Luoyangjiang River estuary wetland in 2021, i.e., 966.64 hm^2 and 28.37%. Among other landscape types, *Spartina alterniflora* and the mudflat were dominant at 676.34 hm^2 and 816.77 hm^2, accounting for 19.85% and 23.97%, respectively. The number of mudflat patches in the study area was the highest (180), followed by the number of *Spartina alterniflora* patches (109). The PD of the mudflats in the study area was the highest, followed by that of *Spartina alterniflora* and the artificial surfaces, indicating that these three types of landscapes were highly fragmented. The PD in the water area was low, indicating that the water area was characterized by a low fragmentation and a concentrated distribution. According to the separation index, the mangroves, *Spartina alterniflora*, and the artificial surfaces in the estuary wetland of the Luoyangjiang River had a high separation index, which indicates a dispersion distribution. The water had a low separation index, which indicates a clustered distribution.

Table 3. Characteristic value of the landscape type index in 2021.

Wetland Type	CA (hm^2)	PLAND (%)	NP (n)	PD (n/hm^2)	LSI	SPLIT
Mudflat	816.77	23.97	180	5.36	20.36	134.08
Water area	966.64	28.37	46	1.37	7.99	13.44
Mangrove	251.14	7.38	43	1.28	7.39	824.69
Spartina alterniflora	676.34	19.85	109	3.25	15.28	278.64
Artificial surface	696.18	20.43	69	2.06	8.23	48.33

The classification results of the remote sensing images in different periods show that the area of mangrove and *Spartina alterniflora* wetlands increased significantly from 1983 to 2021, especially around 2002, which exhibits a large variation. By 2021, the mangrove and *Spartina alterniflora* wetlands reached 251.14 hm^2 and 676.34 hm^2, respectively; the water area and the mudflat area decreased slightly; and the artificial surface area in the study area steadily increased (Figure 3 and Table 4).

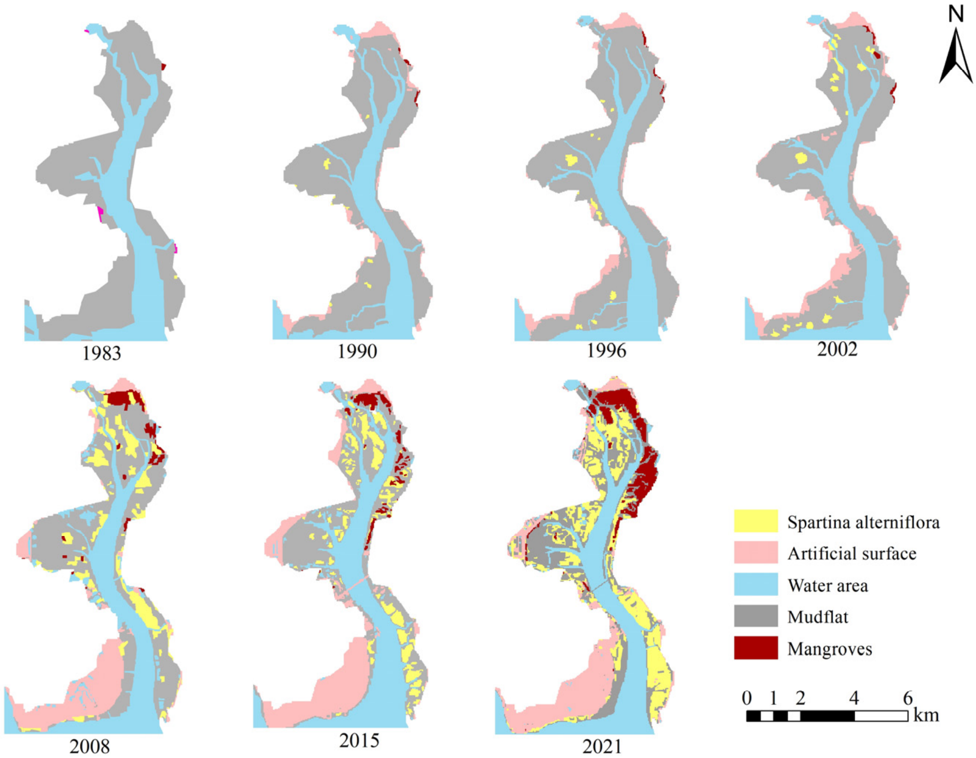


Figure 3. Mangrove wetland landscape classification map, 1983–2021.

Table 4. Landscape area of various types of wetlands in Luoyangjiang River estuary, Fujian.

Year	Total Area (hm^2)	Water		Mudflats		*Spartina alterniflora*		Artificial Surface		Mangroves	
		Area (hm^2)	Percentage (%)	Area (hm^2)	Percentage (%)	Area (hm^2)	Percentage (%)	Area (hm^2)	Percentage (%)	Area (hm^2)	Percentage (%)
1983	3348.63	1168.36	34.89	2163.74	64.61	1.73	0	11.69	0.35	3.11	0.09
1990	3328.41	1088.00	32.69	2041.75	61.34	20.39	0.61	169.17	5.08	9.10	0.28
1996	3353.30	1091.69	32.56	2010.36	59.95	41.07	1.22	199.93	5.96	10.25	0.31
2002	3354.80	940.38	28.03	1994.69	59.46	87.32	2.60	317.72	9.47	14.69	0.44
2008	3361.88	1036.80	30.84	1279.12	38.05	365.18	10.86	584.76	17.39	96.02	2.86
2015	3292.94	1152.06	34.98	1028.51	31.23	322.96	9.81	695.00	21.11	94.41	2.87
2021	3407.07	966.64	28.37	816.77	23.97	676.34	19.85	696.18	20.43	251.14	7.38

4.2. Variations in Wetland Landscape Pattern

On the basis of the information extracted from the remote sensing images from 1983 to 2021 and Fragstats, the overall characteristics of landscape patterns in the study area were obtained. The Shannon's diversity and evenness indices increased continuously from 1983 to 2021. This finding indicates that the landscape heterogeneity in the study area gradually increased, the proportion of different types of landscapes gradually decreased, and all the types of landscapes gradually became more evenly distributed (Figure 4 and Table 5).

From 1983 to 2021, the PD in the study area increased significantly from 0.42 to 13.32 patches/hm^2; thus, the fragmentation of the wetland landscape in the Luoyangjiang River estuary increased. Since 2008, the fragmentation increased rapidly (Figure 4).

The spread index measures the overall distribution of a landscape, indicating the degree of the aggregation of different patch types in the landscape [40]. The calculated results show that the wetland spread index of the Luoyangjiang River estuary decreased from 75.90 to 39.05 from 1983 to 2021 (Table 5), indicating that the overall aggregation of the various types of landscape in the study area decreased.

Table 5. Characteristics of landscape patches in Luoyangjiang River estuary, 1983–2021.

Year	Index			
	Patch Density (n/hm^2)	**Spread Index**	**Shannon's Diversity Index**	**Shannon's Evenness Index**
1983	0.42	75.90	0.68	0.42
1990	2.13	67.79	0.86	0.54
1996	2.74	65.75	0.91	0.57
2002	2.03	62.18	1.00	0.63
2008	6.13	47.53	1.38	0.86
2015	7.50	46.58	1.39	0.86
2021	13.32	39.05	1.54	0.95

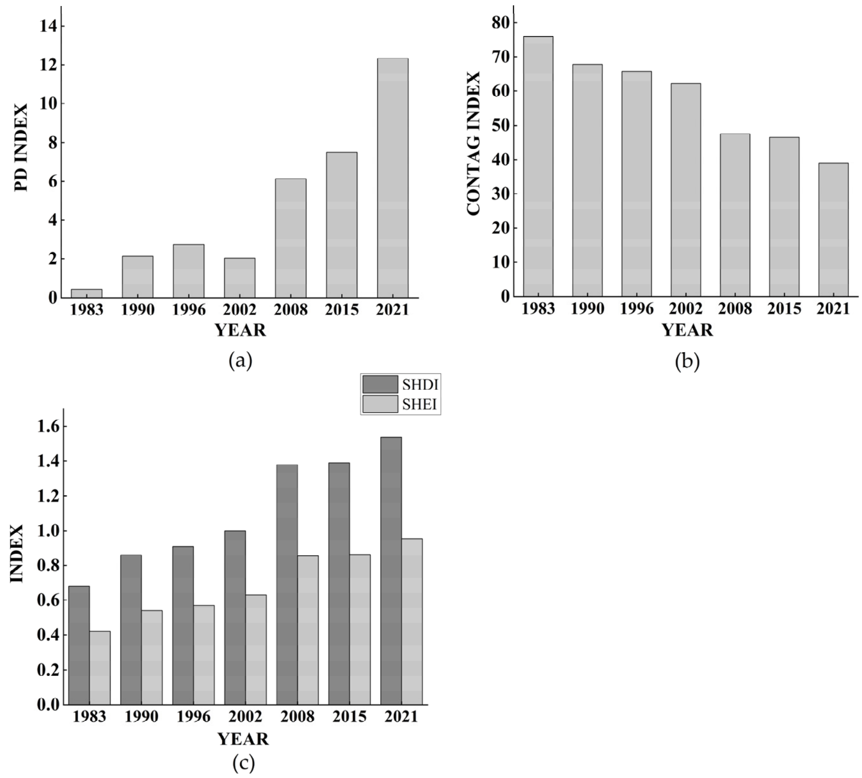


Figure 4. Four indices for different years. (**a**) Patch density value of the study area in different years. (**b**) Contagion index value of the study area in different years. (**c**) Shannon's diversity and evenness index values of the study area in different years: the darker gray bars represent the diversity index, and the lighter bars represent the evenness index.

4.3. Transformation between Different Wetland Landscape Types

As shown in Tables 6 and 7, from 1983 to 2002, the wetland mainly transformed from mudflats to other types of wetlands. The areas transformed from mudflats into mangroves, *Spartina alterniflora*, artificial surfaces, and water were 13.05 hm^2, 81.62 hm^2, 266.71 hm^2, and 72.51 hm^2, respectively. Contrarily, the area transformed from mangroves, *Spartina alterniflora*, and water into mudflats was low. From 2002 to 2021, the transformation of wetlands was mainly manifested by the transformation of mudflats and water into other types of wetlands, in which the areas that transformed from mudflats to mangroves, *Spartina alterniflora*, artificial surface, and water were 225.31 hm^2, 595.92 hm^2, 377.47 hm^2, and 129.23 hm^2, respectively, and the areas transformed from water to mangroves, *Spartina alterniflora*, artificial surface, and mudflats were 1.38 hm^2, 17.19 hm^2, 11.60 hm^2, and 85.79 hm^2, respectively. In addition, another 11.15 hm^2 of *Spartina alterniflora* was transformed into mangroves. From the perspective of landscape patterns, the mutual transformation of various landscape types increased the fragmentation of the study area, and the distribution gradually became discrete and uniform.

Table 6. Transition matrix of wetland landscape, 1983–2008 (hm^2).

Type	Mangroves	*Spartina alterniflora*	Artificial Surface	Water	Mudflats	Total
Mangroves	0.00	0.00	0.65	0.01	2.63	3.28
Spartina alterniflora	0.00	0.00	0.00	0.00	1.44	1.44
Artificial surface	0.00	0.00	9.41	0.26	0.60	10.27
Water	0.00	5.14	21.13	861.27	276.20	1163.74
Mudflats	13.05	81.62	266.71	72.51	1688.46	2122.35
Total	13.05	86.76	297.90	934.04	1969.33	3301.08

Table 7. Transition matrix of wetland landscape, 2002–2021 (hm^2).

Type	Mangroves	*Spartina alterniflora*	Artificial Surface	Water	Mudflats	Total
Mangroves	9.44	0.27	0.58	2.69	1.59	14.58
Spartina alterniflora	11.15	25.68	27.17	1.04	21.73	86.76
Artificial surface	7.18	30.66	213.33	8.04	44.34	303.56
Water	1.38	17.19	11.60	825.83	85.79	941.85
Mudflats	225.31	595.92	377.47	129.23	653.70	1981.64
Total	254.47	669.72	630.21	966.84	807.16	3328.39

5. Discussion

The evolution of coastal wetlands is mainly driven by natural environmental changes and human activities. The interaction of the two factors on different temporal and spatial scales not only shapes the current situation of coastal wetland landscape patterns but also changes landscape patterns and functions on a large temporal scale and over a large spatial range [3,41]. Research has shown that the degradation of global coastal wetlands from 1983 to 2021 was mainly caused by intensive human activities, such as reclamation, aquaculture, and urbanization [3], and the main factors controlling the degradation of different coastal wetlands are not consistent. For example, mangrove wetlands have decreased by approximately 50% over the past few decades, and most have been converted into aquaculture ponds [42,43]. In China, aquaculture expansion is the most important factor driving the transformation of mangrove wetland areas, accounting for approximately 68% of their total transformation [44]. The degradation of coastal salt marsh wetlands is primarily caused by reclamation [3]. To recover damaged wetlands and protect the ecological environment, many countries have conducted extensive research on the theory and practice of ecological restoration, which has a significant impact on the landscape pattern of wetlands [3,16,45].

Quanzhou Bay is an important starting point for the "Marine Silk Road" and has long been an important area for human activity. Intense human disturbances have brought substantial ecological and environmental pressure to the coastal wetlands of Quanzhou Bay [28]. According to the results of the remote sensing interpretation in this study, from 1983 to 2021, the water and mudflat area in the Luoyangjiang River estuary decreased by approximately 54% (Table 4), and the landscape pattern changed significantly (Table 6). This change was mainly caused by large-scale human interventions, such as reclamation, during rapid urbanization and ecological restoration (Tables 6 and 7).

5.1. Impacts of Rapid Urbanization on Landscape Pattern Change in Estuary Wetlands

Urbanization represents the process of social and economic changes, including for the nonagricultural population; the continuous expansion of the urban population; the continuous expansion of urban land into the suburbs; the increasing number of cities; and the continuous infiltration of urban society, the economy, technology, and culture into rural processes. Although urbanization in Europe and North America has slowed since 1950, it has been progressing rapidly in developing countries [46]. Urbanization has significantly promoted socioeconomic development and improved living standards and quality of life. However, these changes have resulted in social, ecological, and environmental problems. For example, rapid urbanization not only affects the hydrodynamic and sedimentary environment and geomorphological evolution processes in coastal areas [47,48] but also significantly affects environmental quality and ecosystem evolution processes in coastal areas [49–51].

Since the reformation and opening up, the urbanization process in the southeastern coastal areas of China has accelerated significantly, and the urban population and built-up areas have been expanding continuously [47]. Statistical results show that the population, the urban built-up area, and the number of enterprises around Quanzhou Bay are increasing continuously [52,53]. Rapid urbanization has brought great environmental pressure to the coastal wetlands of Quanzhou Bay. Research has shown that reclamation is one of the main factors responsible for the reduction in coastal wetland areas and the changes in landscape patterns in Quanzhou Bay [28]. In the Luoyangjiang River estuary, there has been little mariculture since the 1980s, and reclamation has been the main factor controlling water and mudflat area degradation (Figure 3 and Table 4). The results of remote sensing interpretation in different periods show that the coastline of the Luoyangjiang River estuary was significantly pushed towards the sea from 1983 to 2008 (Figure 5), with a total of 696.18 hm^2 of coastal wetland being reclaimed and transformed into urban built-up areas. The results show that the urbanization process in Quanzhou City accelerated significantly from 1995 to 2010 and that the urbanization process in coastal areas was significantly faster than in inland areas. According to the comparison of the area of wetland reclamation and urban built-up areas around the Luoyangjiang River estuary in different periods, the wetland area reclaimed and transformed into urban built-up areas in the study area was significant from 1996 to 2015. This was especially true from 2002 to 2008, when it reached 267.04 hm^2 (Figure 6), which was approximately 30% of the total urban built-up area in Quanzhou City in the same period. From 2008 to 2021, the area of coastal wetland decreased by 407.52 hm^2 due to wetland reclamation, and the reduction rate decreased significantly. Because the wetland reclamation of the coastal wetlands in the Luoyangjiang River estuary was conducted based on the original shoreline, the wetland reclamation significantly reduced the area of coastal wetlands but had no significant impact on the landscape pattern index. The PD, SHDI, and SHEI, which represent the landscape patterns of coastal wetlands, indicate an increase, and the contagion index indicates a slow decrease (Table 5 and Figure 4).

5.2. Impact of Coastal Ecological Restoration of Coastal Wetland on Landscape Pattern Change

Since the two landmark works in the field of wetland and coastal habitat restoration in the early 1990s, "Wetland Creation and Restoration: The Status of The Science" published by the National Wetland Management Association of the United States and the National Environmental Protection Agency [54] and "Restoring The Nation's Marine Environment" published by the National Oceanic and Atmospheric Administration of the United States [55], significant progress has been made in terms of scientific theory, methods, techniques, monitoring, standards, and indicators of success and failure, and many coastal wetland restoration projects have been conducted [1,3,56–58]. The implementation of coastal wetland restoration projects has gradually curbed the trend of coastal wetland degradation, significantly improving the quality of the ecological environment and the living environment in coastal areas [59,60].

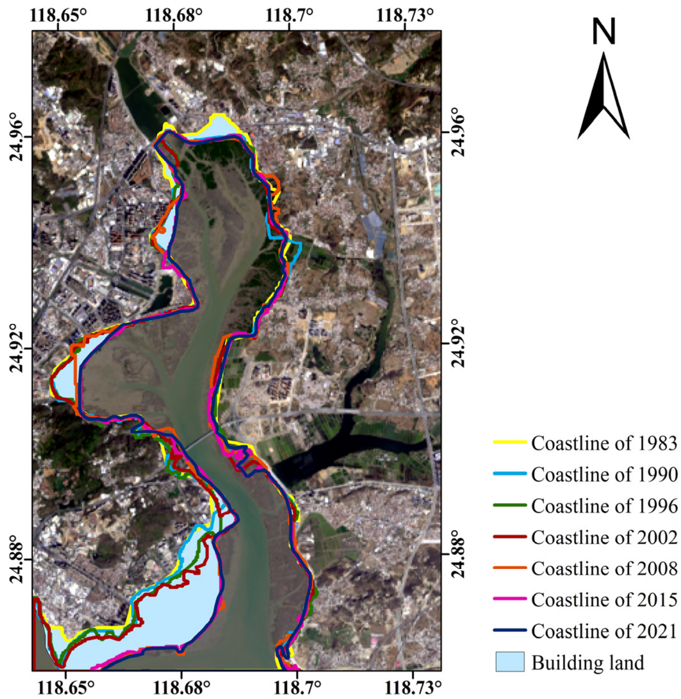


Figure 5. Comparison of coastline location in different years.

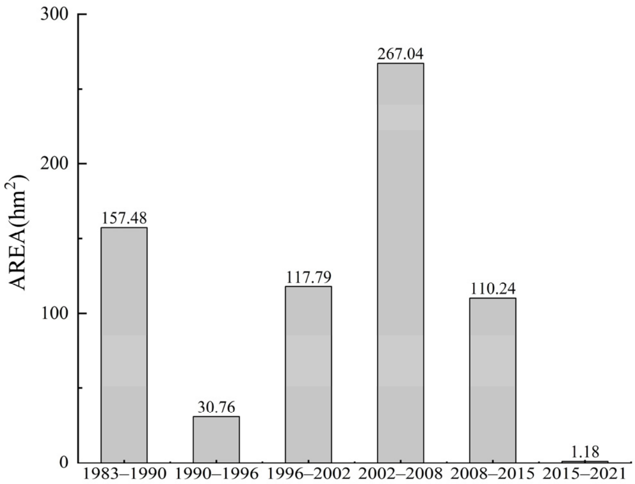


Figure 6. Growth in built-up area due to wetland reclamation in particular periods.

Since the 1950s, China has implemented many coastal wetland restoration projects and, in recent years, has entered a period of rapid development, halting the degradation of wetlands in coastal areas and significantly improving the quality of the ecological environment [57,61]. According to variations in the wetland landscape distribution and types, the ecological restoration of the Luoyangjiang River estuary since 2002 has mainly focused on two aspects: the ecological restoration of mangroves and the removal of *Spartina alterniflora*. Mangrove ecological restoration is one of the most important and largest coastal wetland restoration goals in China [57]. To strengthen the coastal protection of Quanzhou Bay, the Quanzhou Municipal Government planted a large area of mangroves in Quanzhou Bay, most of which grew well. However, by the 1980s, owing to intensive human activities, a large area of mangrove wetlands had been destroyed. By 2001, the area of mangrove wetlands in Quanzhou Bay was less than 17 hm^2, and most were scattered [62]. To further protect the coastal wetland of Quanzhou Bay, mangroves have been planted in the Luoyangjiang River estuary since 2002, and the Quanzhou Bay Estuarine Wetland Provincial

Nature Reserve was approved in 2003, which has an area of 7045.88 hm^2 [63]. Since establishing the reserve, the government has implemented a series of conservation measures, which have strengthened infrastructure construction, attempted to approve fewer large-scale engineering projects that affect the ecological environment and wetland resources, promoted awareness, and resulted in the implementation of the "Blue Bay" policy [29]. With the continuous implementation of ecological restoration projects, the mangrove area has increased rapidly from 14.69 hm^2 in 2002 to 251.14 hm^2 in 2021 (Table 4), and the proportion of mangrove wetland is increasing. The ecological restoration of mangrove wetlands has caused significant changes in the wetland landscape pattern of the Luoyangjiang River estuary area. On the basis of the calculated results of the landscape index for different periods, as shown in Table 5, the density of wetland patches in the Luoyangjiang River estuary increased by 383%, the contagion index decreased by 18%, and the diversity and evenness indices increased by 47% and 50%, respectively, from 1983 to 2002. From 2002 to 2021, PD increased by 556%, the contagion index decreased by 37%, and the diversity and evenness indices increased by 54% and 51%, respectively, indicating that the variation range significantly accelerated. This significant variation was mainly due to the large quantity of mangroves planted throughout the Luoyangjiang River estuary area since 2002. On the one hand, mangroves were planted on the mudflat; on the other hand, mangroves were planted after the removal of *Spartina alterniflora*. Therefore, the PD increased significantly, and landscape heterogeneity and fragmentation increased.

As shown in Table 4, since 2002, in addition to the rapid increase in mangrove wetland, the area of *Spartina alterniflora* has rapidly increased. *Spartina alterniflora*, a perennial grass herb, has taken root in the intertidal zone along the coast of China since its introduction and has spread rapidly. Today, the area of Spartina alterniflora wetlands distributed along the Chinese coast exceeds 54,580 hm^2 [64,65], making it the largest coastal salt marsh in China, which has a significant impact on the ecosystem health of coastal wetlands [65]. Fujian is ranked fourth in terms of the area distribution of *Spartina alterniflora* wetland in China, with the area of *Spartina alterniflora* wetland increasing by 5236 hm^2 from 1990 to 2015 [64,66]. The area increased by 302.57 hm^2 in the Luoyangjiang River estuary during this period (Table 4), which accounted for 5% of the total area increase in the province at that time. Although much of the *Spartina alterniflora* has been cleared and transformed into mangrove wetlands since 2002, *Spartina alterniflora* has spread rapidly, covering most of the mudflats in the study area (Table 7) and increasing the diversity and evenness indices of the wetland landscape and fragmentation over the entire study area. Over this time, the distribution of each wetland landscape has gradually become more uniform.

6. Conclusions

This paper used remote sensing image data from the Luoyangjiang River estuary in Quanzhou Bay in different periods from 1983 to 2021 and the object-oriented method to classify and analyze the landscape pattern change and its driving mechanisms in the study area by selecting the landscape index. On the basis of this research, the following conclusions were drawn:

(1) From 1983 to 2021, the water area and mudflats in the study area decreased significantly, and the areas of mangroves and *Spartina alterniflora* increased most significantly. The overall PD of the landscape increased significantly, indicating the high fragmentation of the landscape in the study area. Except for water and artificial areas, the split index of other landscape types changed greatly, and the largest change was observed for mangroves, distributed in patches, and concentrated. The evenness and diversity indices of the coastal wetland landscapes exhibited increasing trends. The fragmentation and diversity of the landscape increased, and the contagion index decreased. The overall distribution of landscape patterns tended to be uniform and widely dispersed.

(2) The main factors affecting changes in wetland landscape patterns in the study area were rapid urbanization and the implementation of ecological restoration projects. Over the

past 40 years, with the continuous intensification of urbanization in Quanzhou City, the Luoyangjiang River estuary wetland has been damaged by the implementation of many wetland reclamation projects, and the wetland area has been significantly reduced. Since 2002, many ecological restoration projects, such as mangrove planting and *Spartina alterniflora* removal, have been conducted in many places in the Luoyangjiang River estuary wetland. The mangrove area has increased significantly, but the degree of wetland fragmentation has also increased in the study area, and the distribution of various types of wetland landscape has gradually become uniform.

(3) To further promote the ecological restoration of coastal wetlands, the government of Fujian issued the "Action Plan for Eliminating *Spartina alterniflora* in Fujian Province". This plan requires the removal of 9108 hm^2 of *Spartina alterniflora* by the end of September 2023 and the scientific restoration of the mudflat after this removal by the end of 2024, of which 20% will be native plants (mangroves and other salt marsh plants), to further improve the stability and service function of the coastal wetland ecosystems [67]. According to a field survey, as of December 2022, *Spartina alterniflora* in the Luoyangjiang River estuary has been completely cleared. The large-scale removal of *Spartina alterniflora* and the planting of native plants have a significant impact on the landscape patterns of coastal wetlands. Therefore, the follow-up ecological restoration process should include a reasonable, scientific ecological restoration plan with regional characteristics to improve the landscape quality of coastal wetlands in the Luoyangjiang River estuary.

Author Contributions: Conceptualization, Y.Y. and A.W.; methodology, Y.Y.; investigation, Y.Y. and X.Y.; data discussion and guidance, X.Y.; writing—original draft preparation, Y.Y.; writing—review and editing, Y.Y., X.Y. and A.W.; supervision, A.W.; project administration, A.W.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (Nos. 41961144022, 41776099), and the project was sponsored by the Scientific Research Foundation of the Third Institute of Oceanography, MNR, China (No. 2019018).

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank Shu-ren Huang and Jin-jian Xie for their help with the field work.

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

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