Research on the Evolution of Island Coastal Wetland Landscape Pattern

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Abstract. The wetland landscape in Ximen Island National Special Marine Protection Area, Zhejiang Province, was adopted as the study object. Remote sensing images in 2006, 2012, and 2017 were interpreted, and landscape indexes, such as the number of patches (NP), largest patch index (LPI), cohesion (COHESION), division, patch density (PD), Shannon diversity index (SHDI), Shannon equilibrium index (SHEI), and landscape shape index (LSI), were used to monitor and analyze the evolution of the coastal wetland landscape pattern on Ximen Island. Results showed that during 2006–2017, the wetland aquiculture area around Ximen Island presented a gradual decrease from 785 hectares to 712 hectares. The wetland vegetation area increased from 292 hectares to 467 hectares, and the area added was transformed from wetland aquiculture and naked mudflat. Total NP and PD decreased from 1,444 to 1,298 and from 60.3 to 52.2, respectively. From the angle of LSI, SHDI and SHEI gradually increased from 1.2515 to 1.358 and from 0.7776 to 0.8432, respectively, indicating a uniform landscape distribution in the wetlands. The COHESION index increased from 97.9281 to 98.26, manifesting a concentrated landscape distribution in the wetlands. The LSI in the protection area declined from 20.6717 to 18.512, showing that the wetland landscape shapes were regular in the protection area.

1. Introduction

Landscape pattern is an apparent result of natural and human factors jointly acting on a geographical space [1]. With ever-increasing human activities, the surface landscape pattern is subjected to increasingly intense human disturbance, and the characteristics of and changes in landscape patterns exert important effects on the ecosystem structure, functions, and processes [2, 3]. Current studies on landscape patterns have concentrated on the evolution and influencing factors of landscape patterns, and the study objects included continental geographical units, such as cities and river basins [4, 5, 6, 7]. Compared with the continental landscape pattern, the landscape pattern in island areas has been less investigated. Melis et al. conducted a paleoenvironmental survey on the coastal landscape changes in Sardinia in the Mediterranean Region that have been occurring since 8000 years ago and reported that the stability of the sea level and human activity are the primary causes of island landscape changes [8]. Giseli et al. studied the relationship between the urban regional evolution of Victoria Island and the
existing landscape [9]. Domestic (Chinese) studies with respect to island landscapes have only involved Xiamen Island in Fujian Province, Zhoushan Island in Zhejiang Province, and Miaodao Archipelago in Shandong Province [10, 11, 12]. Islands are expected to become the key regions in landscape pattern studies.

Surrounded by sea, an island, which is relatively independent, serves as a bridge connecting the inland and the ocean, and it is located in a dynamic sensitive zone under sea–land interaction [13]. An island ecosystem exhibits obvious vulnerability due to its unique conditions and complicated external disturbance; it can be easily damaged when confronted with any disturbance, and it can hardly recover through its autoregulation capability [14]. The extensive and frequent island development and utilization activities in China in recent years have resulted in the fragmentation of island natural landscapes, an increase in artificial landscapes, and significant changes in landscape patterns. Landscape patterns exert a far-reaching effect on the island ecosystem. Vegetation productivity, biodiversity, and other factors that are important manifestations of island ecosystem functions are affected by landscape type and pattern. An island ecosystem is composed of an island–land subsystem, an island–beach subsystem, and a peripheral sea area subsystem. The island–beach ecosystem (coastal wetland system), which connects the island–land area with the peripheral sea area, plays a crucial role in the entire marine ecosystem. Hence, this study on the evolution of coastal wetland landscape patterns on islands is of great theoretical and practical importance.

Ximen Island’s coastal wetland landscape in Zhejiang Province, China, was adopted as the study object. As the earliest national special marine protection area established in China, Ximen Island has a unique island environment. Coastal wetland landscapes are abundant around the island and accompanied with the northernmost mangrove forest community in China. Therefore, studying the evolution of coastal wetland landscape patterns on Ximen Island is essential. The evolution of the landscape pattern in coastal wetland areas on Ximen Island and its driving factors were mastered with ArcGIS10.3 by using landscape indexes, such as number of patches (NP), largest patch index (LPI), cohesion (COHESION), and Shannon diversity index (SHDI), to fully understand the response of the island coastal wetland ecosystem to human activities and provide a scientific basis for the construction of Ximen Island National Special Marine Protection Area.

2. Study area

![Figure 1. Location of Ximen Island Marine Specially Protected Area.](image-url)
Ximen Island is located in the Yueqing Bay sea area of Zhejiang Province, China. The shallow mudflat area is broad around the sea island. The island has various marine resources that constitute a coastal wetland ecosystem (Figure 1) centering on rich marine biological resources, the northernmost mangrove forest community in China, and various bird species. In March 2005, the State Oceanic Administration and Zhejiang Provincial People’s Government agreed to set up Ximen Island National Special Marine Protection Area, with a total area of 3,080.15 hectares. The land area of Ximen Island is about 7 km², and the coastal wetland area around the sea island is 19.2 km². Ximen Island is rich in coastal wetland resources, among which 37 are reef organism species and 92 are mudflat organism species, indicating the great biodiversity on this island, which is an area with a high biological value in the East China Sea.

3. Data and Method

3.1. Interpretation of remote sensing images

The data in this study were mainly derived from satellite remote sensing images, which were multi-view Landsat-7, SPOT-4/5, and WorldView-1/2 remote sensing images of Ximen Island and its surrounding coastal wetland areas from 2006 to 2017. The remote sensing images were mainly visually interpreted. By identifying the surface features with interpretation marks, the computer-assisted automatic information extraction method was adopted to acquire information on different landscape types, such as wetland aquiculture, wetland vegetation, mangrove forest, naked mudflat, and water channel, on Ximen Island in three periods, namely, 2006, 2012, and 2017.

Table 1. Remote Sensing Interpretation Marks of Coastal Wetland Landscapes on Ximen Island.

| Type             | Remote sensing image | Site photo | Feature description                      |
|------------------|----------------------|------------|-----------------------------------------|
| Wetland aquiculture | ![Remote sensing image] | ![Site photo] | Regular shape, monotonic texture       |
| Wetland vegetation | ![Remote sensing image] | ![Site photo] | Rough surface, rich but irregular texture |
| Mangrove forest   | ![Remote sensing image] | ![Site photo] | Irregular distribution, rich texture    |
| Naked mudflat     | ![Remote sensing image] | ![Site photo] | Flaky irregular distribution, fine texture |
3.2. Calculation methods for landscape indexes

Proposed in the field of landscape ecology, the landscape index can be divided into five types: area, shape, diversity, spatial configuration, and fragmentation indexes. In accordance with the features and spatial scale of the study area, eight landscape indexes, such as SHDI, evenness index, and dominance index, were used in this study.

(1) Number of patches (NP)

\[ NP = N \]  

NP, which reflects the spatial landscape pattern, is usually used to describe the heterogeneity of the entire landscape, and its value is positively correlated with the degree of landscape fragmentation.

(2) Largest patch index (LPI)

\[ LPI = \frac{\text{Max}(a_1, a_2, \ldots, a_n)}{A} \times 100, \]  

where \( A \) is the total landscape area and \( a_i \) is the largest patch area in the landscape. LPI is the proportion of the largest patch of one landscape type in the entire landscape area. Its value decides ecological characteristics, such as the abundance of dominant species and internal species in the landscape, and reflects the direction and intensity of human activities.

(3) Cohesion (COHESION)

\[ AI = \frac{\delta_{ii}}{\text{Max} \rightarrow \delta_{ii}} \times 100, \]  

where \( \delta_{ii} \) is the quantity of similar adjacent patches of the corresponding landscape type.

COHESION is used to indicate the connection degree between patches, and the larger the COHESION value is, the stronger the interconnection between patches is and the greater the substance and energy exchange is between patches.

(4) Division (DIVISION)

\[ V_i = \frac{D_{ij}}{A_{ij}}, \]  

where \( D_{ij} \) and \( A_{ij} \) are the distance and area indexes of landscape type \( i \), respectively.

Landscape division refers to the discrete degree of patch distribution in the same landscape type.

(5) Patch density (PD)

\[ PD = \frac{n_i}{A} \times 100, \]  

where \( n_i \) is the total area of elements of landscape type \( i \) and \( A \) is the total area of all landscapes.

PD is used to reflect the degree of landscape fragmentation and express the number of patches in the unit area.

(6) Shannon diversity index (SHDI)

\[ SHDI = -\sum_{i=1}^{m} (p_i \ln p_i), \]  

where \( p_i \) is the proportion occupied by landscape patch type \( i \).

SHDI is utilized to express the heterogeneity of landscapes. The greater the value is, the higher the heterogeneity is and the higher the degree of fragmentation is.

(7) Shannon equilibrium index (SHEI)

\[ E = \frac{H}{H_{\text{max}}} \times 100, \]  

where \( H \) is the Shannon diversity index and \( H_{\text{max}} \) is the maximum value of SHDI.

The equilibrium index is used to express the uniformity of landscapes, and when its value is close to 1, the landscape patches present a uniform distribution in the study area, and the diversity reaches the maximum.
Landscape shape index (LSI)

\[ LSI = \frac{0.25E}{\sqrt{A}} \]  

where \( E \) is the total length of the landscape boundary and \( A \) is the total area of landscapes.

LSI indicates the shape complexity of patches in the landscape. The greater the LSI value is, the more irregular the landscape shape is.

4. Results and Discussion

4.1. Change analysis of coastal wetland landscapes

The data (Table 2 and Figure 2) on coastal wetland landscape maps of Ximen Island in 2006, 2012, and 2017 were acquired through the remote sensing imagery interpretation method.

Table 2. Statistical Information of Coastal Wetlands in Ximen Island National Special Marine Protection Area.

| Type                | Year | Area (m²) | Proportion | Area (m²) | Proportion | Area (m²) | Proportion |
|---------------------|------|-----------|------------|-----------|------------|-----------|------------|
| Wetland vegetation  | 2006 | 2918605   | 12.16%     | 4229688   | 17.73%     | 4674942   | 19.71%     |
| Wetland aquiculture | 2006 | 7858914   | 32.75%     | 7174789   | 30.08%     | 7122705   | 30.03%     |
| Wetland vegetation  | 2012 | 4229688   | 17.73%     | 4674942   | 19.71%     | 4674942   | 19.71%     |
| Wetland aquiculture | 2012 | 7174789   | 30.08%     | 7122705   | 30.03%     | 7122705   | 30.03%     |
| Wetland vegetation  | 2017 | 4674942   | 19.71%     | 4674942   | 19.71%     | 4674942   | 19.71%     |
| Wetland aquiculture | 2017 | 7122705   | 30.03%     | 7122705   | 30.03%     | 7122705   | 30.03%     |
| Naked mudflat       |      |           |            |           |            |           |            |
| Mangrove forest     |      |           |            |           |            |           |            |
| Water channel       |      |           |            |           |            |           |            |
| Total               |      | 23996389  | 12.16%     | 23849812  | 100%       | 23718632  | 100%       |

Figure 2. Statistical Chart of Coastal Wetland Types in Ximen Island National Special Marine Protection Area.

During 2006–2017, the wetland aquiculture area in Ximen Island National Special Marine Protection Area presented a gradual declining trend. Small-scale aquiculture areas were laid to waste and transformed into naked mudflats. The wetland aquiculture area was reduced by about 74 hectares. The area of wetland vegetations increased by about 170 hectares mainly because Spartina alterniflora Loisel
encroached upon a large quantity of mudflats. When the national marine ecological rehabilitation project was implemented, the planting area of the mangrove forest in 2017 grew by a large margin in comparison with that in 2006 (by about 9 hectares), but it was still small relative to the entire wetland area, accounting for only about 0.5% in the coastal wetland area.

The transformation matrixes between wetland types in Ximen Island National Special Marine Protection Area during 2006–2012 and 2006–2017 were acquired using the intersect spatial analysis method of the geographical information system software ArcGIS. The analysis indicated that the wetland vegetations added in 2012 were mainly transformed from wetland aquiculture and naked mudflats, where the area transformed from wetland aquiculture area was 0.68 km$^2$ and that from naked mudflats was 1.36 km$^2$. From 2006 to 2012, the wetland aquiculture area was gradually reduced. Specifically, 0.68 km$^2$ was transformed into wetland vegetations, an area as large as 2.07 km$^2$ was transformed into naked mudflats, and most of the wetland aquiculture areas gradually became obsolete and were transformed into naked mudflats. In 2012, the area of the mangrove forest in the protection area was mainly transformed from wetland vegetations, wetland aquiculture, and naked mudflats. The transformation trend of different wetland landscape types during 2006–2017 was basically consistent with that during 2006–2012; the only difference was in several numerical values.

### 4.2. Change analysis of coastal wetland landscape indexes

#### 4.2.1. Analysis of landscape patch indexes

From the angle of landscape patches, the total NP in Ximen Island National Special Marine Protection Area presented a declining trend from 1,444 to 1,298. With the decrease in the total NP, PD was also reduced from 60.3475 to 52.1567. However, LPI increased from 18.8688 to 23.186. This change analysis of patch indexes preliminarily indicates that the wetland landscapes presented a gradual concentrated distribution in the protection area, and the interconnectivity of landscape patches was gradually strengthened.

| Year | Index | NP  | PD      | LPI     |
|------|-------|-----|---------|---------|
| 2006 |       | 1444| 60.3475 | 18.8688 |
| 2012 |       | 1359| 56.2521 | 24.398  |
| 2017 |       | 1298| 52.1567 | 23.186  |

![Graph of NP](image1.jpg)

![Graph of PD](image2.jpg)
Figure 3. Change Curves of Landscape Patch Indexes in the Protection Area.

4.2.2. Analysis of landscape configuration indexes. From the perspective of landscape configuration index, SHDI and SHEI gradually increased from 1.2515 and 0.7776 in 2006 to 1.358 and 0.8432 in 2017, respectively, indicating that no dominant species appeared in the coastal wetland ecosystem of the protection area and that the wetland landscapes were uniformly distributed. In addition, the COHESION index of the protection area presented an increasing trend from 97.7281 to 98.26, manifesting a concentrated distribution of wetland landscapes. LSI decreased in the protection area from 20.6717 to 18.512, indicating the presence of regular wetland landscape shapes in Ximen Island National Special Marine Protection Area.

Table 4. Analysis of Landscape Spatial Configuration Indexes in the Protection Area.

| Year | Index | SHDI   | SHEI   | COHESION | LSI    |
|------|-------|--------|--------|----------|--------|
| 2006 |       | 1.2515 | 0.7776 | 97.7281  | 20.6717|
| 2012 |       | 1.325  | 0.8233 | 98.0704  | 18.617 |
| 2017 |       | 1.358  | 0.8432 | 98.26    | 18.512 |
5. Conclusions and Suggestions

Through the interpretation of remote sensing images in three periods, namely, 2006, 2012, and 2017, site inspection data were adopted to analyze the evolution of the wetland landscape pattern in Ximen Island National Special Marine Protection Area. The following conclusions were obtained.

(1) Relative to the island–land area of Ximen Island, the wetland aquiculture area in the protection area presented a decrease during 2006–2017. By 2017, except for several sporadic large aquiculture areas, other small-scale aquiculture areas were laid to waste and transformed into naked mudflats. The scope of wetland vegetation (*Spartina alterniflora* Loisel) was gradually enlarged, and the distribution was concentrated. In 2006, the maximum number of wetland vegetation patches was 263, and that in 2012 and 2017 was 203 and 185, respectively. The expansion of growth scope of *Spartina alterniflora* Loisel, which is an alien species with an extremely strong reproductive capacity, would certainly result in a steep decline of living environments for other species in the protection area. Therefore, the growth trend of *Spartina alterniflora* Loisel should be regularly evaluated, and its growth scope should be controlled in the future management of the protection area.

(2) From 2006 to 2017, the wetland aquiculture area around Ximen Island was gradually reduced from 785 to 712 hectares. The area of wetland vegetation obviously increased from 292 to 467 hectares, and most of the area added was transformed from wetland aquiculture and naked mudflats. From the angle of landscape patches, the total number of coastal wetland landscape patches decreased from 1,444 to 1,298. PD also decreased from 60.3 to 52.2. Meanwhile, LPI presented an increase from 18.9 to 23.2. With regard to the landscape configuration indexes, SHDI and SHEI gradually increased from 1.2515 and 0.7776 to 1.358 and 0.8432, respectively, indicating the uniform distribution of wetland landscapes. The COHESION index increased from 97.9281 to 98.26, manifesting the gradually concentrated distribution of wetland landscapes. The LSI in the protection area changed from 20.6717 to 18.512; hence, the wetland landscapes tended to be of regular shapes in the protection area.

(3) From 2006 to 2017, the planting area of the mangrove forest in the coastal wetlands on Ximen Island increased considerably from 8,947 m² before the construction of the protection area to 106,700 m² in 2017. However, the total area of the mangrove forest is still small and accounts for only 0.45% of the total coastal wetland area. Thus, the protection and cultivation work on the mangrove forest should be enhanced. Meanwhile, the wetland aquiculture area in the mangrove forest area increased slightly after 2012, and this situation needs some attention. Human development activities in the mangrove forest area should be restricted in a planned manner in the future to protect the growing environment of the mangrove forest and prevent the excessive human development activities in the mangrove forest area from destroying the mangroves’ habitat.

Figure 4. Change Curves of Landscape Configuration Indexes in the Protection Area.
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