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Reclamation-oriented spatiotemporal evolution of coastal wetland along Bohai Rim, China

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Abstract

Coastal wetlands are located in the ecotone of interaction between the land surface and sea, and anthropogenic activities extensively interfere with these wetlands through the reclamation of large tidal wetlands and destruction of the function of the ecosystems. In this study, we investigated the dynamic evolutionary characteristics of the Bohai Rim coastal area over the past 40 years using the Modified Normalized Difference Water Index, the fractal dimension, object-oriented classification, the land-use transfer trajectory, and regression analysis. Additionally, we quantified and monitored the evolution of reclamation and analyzed the correlation between reclamation and coastal wetlands based on 99 Landsat-2, -5, and -8 images (at 60 m and 30 m spatial resolution) over the period 1980–2019. The results are as follows. (1) The coastline of the Bohai Rim increased by 1 631.2 km from 1980 to 2019 with a zigzag variation. The artificial coastline increased by 2 946.1 km, whereas the natural coastline decreased by 90%. (2) The area of man-made wetlands increased by 3 736.9 km^2, the area of construction land increased by 1 008.4 km^2, and the natural wetland area decreased by 66%. The decrease of tidal flats is the main contributor to the decrease of natural wetland area (takes account for 91.1%). Coastal areas are affected by intense human disturbance, which was taken place across a large area of tidal flats and caused the landscape to fragment and be more heterogeneous. The coastal zone development activities were primarily concentrated in the southern Laizhou Bay, the Yellow River Delta, the Bohai Bay, the northern Liaodong Bay, and the Pulandian Bay. The solidified shorelines and increase in sea level have resulted in intertidal wetlands decreasing and impaired wetland ecology. (3) There is a good agreement between reclamation and the size of the coastal wetlands. Both land reclamation and the reduction in coastal wetland areas are significantly related to the population size, fishery output value, and urbanization rate. In summary, human activities, such as the construction of aquaculture ponds and salt pans, industrialization, and urbanization, are the primary forces that influence the environmental changes in the coastal region. This study is beneficial for establishing and improving the systems for the rational development and utilization of natural resources, and provides theoretical references for restoring wetland ecology and managing future reclamation activities in other coastal zone-related areas.

Key words: Bohai Rim, coastal wetlands, land reclamation, evolutionary mechanisms, coastal management

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1 Introduction

Coastal wetlands are regionally vulnerable to tidal action and anthropogenic activities owing to the interaction zone between land and sea. The maximum tide line is the continental boundary to the seaward 6 m isobaths (Gardner and Davidson, 2011). They are the maintenance of coastal biodiversity, provide transit stations and habitats for migratory birds (Huang et al., 2021), play a key role in the prevention of coastal erosion (Alizad et al., 2018), and increase blue carbon sequestration (Krauss et al., 2018). The conflict between the shortage of land and the growing demand for additional living space for humans has considerably increased since the 1950s (He et al., 2014). Consequently, large-scale, intensive reclamation activities occurred frequently. Although coastal reclamation eases land shortages, it has had a negative environmental impact (Gittman et al., 2015). When coastal wetlands are reclaimed and occupied, thus soil properties, hydrological conditions, and ecological functions in this area are strongly altered (Carol et al., 2014), causing the proliferation of ecological and environmental problems (He et al., 2014). For example, species diversity has decreased markedly, the natural function of tidal regulation and purification has declined, and marine environmental pollution (such as red tides) has increased (Chen et al., 2017; Duan et al., 2016; Mou et al., 2018). The destruction of coastal wetlands negatively affects human welfare by the reduction in environmental carrying capacity. In recent years, the Ministry of Ecology and Environment of the People’s Republic of China (www.mee.gov.cn) has been endeavoring to rectify some of these environmental problems and has achieved impressive achievements; however, the ecological situation is still harsh. It is of great theoretical and practical significance for ecological protection and restoration to analyze the evolution and reclamation processes of coastal wetlands (e.g.,

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clarifying the influencing factors and the mechanisms).

Since the 1950s, China's total coastal wetlands have been reduced by 50%, and the area of man-made wetlands and reclaimed wetlands has substantially increased (He et al., 2014). Since 1978, high-intensity human activities have accelerated the degradation of coastal ecosystems in China and the fragmentation of wetland landscape patches (Cui et al., 2011; Ding et al., 2020; Qiu et al., 2021). Reclamation activities are the dominant factors reducing natural wetlands (Ma et al., 2019), and causing natural disasters, such as land subsidence, environmental pollution, and seawater intrusion (Duan et al., 2016; Syvitski et al., 2009; Taramelli et al., 2015). A large number of wetlands and coastal areas have been cultivated and/or exploited for fisheries and the salt pan (Ren et al., 2018), resulting in the loss of biological habitats and a sharp decrease in biodiversity (He et al., 2014). In addition, reclamation activities have changed the extent and properties of coastlines (Kelly, 2014; Wang, 2019). When the sea level rises, artificial boundaries, such as breakwaters obstruct the landward migration of coastal wetlands, resulting in their shrinkage (Pontee, 2013). The current studies focused on the development, evolution, ecological evaluation, environmental effects, and management of coastal wetlands and their reclamation (Huang et al., 2021; Redfield, 2000; Shan and Li, 2020; Tian et al., 2016; Imbrenda et al., 2018; Wang et al., 2021). However, the wetland changes and their connection to different forms of reclamation in a long-term period scale are very limited, which obstacle the clarification of the driving forces in coastal wetland evolution.

Along with national reformation and the opening up of China, the coastal economy has developed rapidly. The implementation of a series of policies has promoted the economic development of the Bohai Rim, along with the increasingly frequent reclamation activities in the region. The area reclaimed represents 46% of the coastal zone of China (Tian et al., 2016). The development and utilization levels in the Bohai Rim are greatly higher than the national average level (Yang and Mei, 2019), where is the highest concentration of reclamation in China. Therefore, unraveling the effects of reclamation activities on the evolution characteristics of coastal wetlands is of significance in implementing their future protection and restoration. The objectives of this study are to (1) clarify the landscape pattern evolution characteristics, (2) elucidate the changes in the coastline of coastal wetland areas under the influence of reclamation activities, (3) investigate the impact of reclamation on the coastal wetland ecosystem, and (4) propose some suggestions for improving the management of reclamation activities by providing a scientific and reliable theoretical basis for the rational development and sustainable utilization of wetland resources.

2 Data and methods

2.1 *Study area description*

The coastal area of the Bohai Rim is encompassed by the border from the north at Dalian, Liaodong Peninsula and onwards to Penglai, Shandong Peninsula (36°52′02″–41°00′15″N, 116°54′–123°30′E) (Fig. 1). In this study, the coastline determined by visual interpretation was used as the coastal boundary of the Bohai Rim coastal wetland due to beyond the scope of the oceanographic field, and the administrative county boundary was utilized as the land margin boundary. This area includes the four provincial administrative regions including Shandong Province, Hebei Province, Tianjin City, and Liaoning Province, covering a total area of approximately 69 042 km^2 with an average land range of (70±42.8) km, and comprises 8.56% of the total population of China (Guo et al., 2009). The Bohai Rim region includes three major bays (the Laizhou Bay, the Bohai Bay, and the Liaodong Bay) and two large estuarine deltas, including the Yellow River Delta and the Liaohe Delta (Bianchi and Allison, 2009). The Bohai Rim area has important trading ports, including Dalian, Dayaowan, Tianjin, Yingkou, Qinhuangdao, Tangshan, Huanghua, Dongying, Weifang, and Longkou, which are key national gateways and areas of economic development (Wang and Yu, 2012).

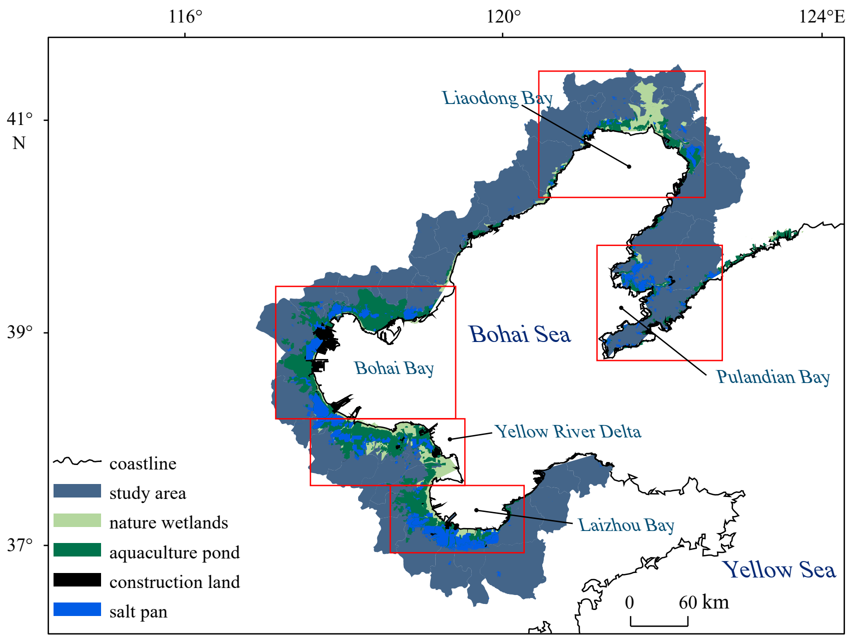

Fig. 1. Monitoring of the Bohai Rim coastal zone change from 1980 to 2019 (red boxes show the hotspots of reclamation changes for the Laizhou Bay, the Yellow River Delta, the Bohai Bay, the Liaodong Bay, and the Pulandian Bay, respectively).

2.2 *Data sources*

The data used in this study include field investigational data, remote sensing image data, national night light data (1995–2019), a 1980 land-use cover of the Bohai Rim, a 1:200 000 topographic map of the Bohai Rim, historical observed tidal level data, and a digital bathymetric chart. The frequent reclamation activities in the Bohai Rim began in the 1980s and 1990s, therefore, the remote sensing data of the coastal areas in the Bohai Rim for nine periods (1980, 1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2019) during 1980–2019 were collected to investigate the variation of coastal wetlands. The cloud cover for all the remote sensing images was less than 6%. The details are summarized in Table 1.

2.3 *Mapping coastal wetlands from 1980 to 2019*

2.3.1 *The classification system of coastal wetlands*

Based on the national standard for *Guidelines for the Classification of Land Use for Land and Space Investigation, Planning, and Use Control (Trial)* (Ministry of Natural Resources of the People's Republic of China, 2020), a coastal wetland landscape types classification system was developed for the Bohai Rim (Table 2), the coastal wetland landscape was divided into first-level and second-level including natural and man-made wetlands and non-wetland areas. The secondary classifications are construction land, aquaculture pond, dryland, forest and grassland, paddy field, water body, marsh, tidal flat, and salt pan (Gong et al., 2011).

2.3.2 *Extractions and validation of coastal wetlands*

Currently, remote sensing is a common and robust approach for obtaining information on coastal wetlands. It is used to monitor the types and quantities of wetlands in real-time, and it provides first-hand materials for wetland protection (Mao et al., 2021). The object-oriented nearest neighbor classification method (eCognition9.0 software) was used to interpret the remote sensing images of the Bohai Rim region during the nine periods from 1980 to 2019. And then we modified the classification based on Google Earth satellite images (using ArcGIS 10.4 as a platform).

To improve the classification and interpretation accuracy, the land-use classification in 2015 was validated by the data of field surveys (i.e., 274 GPS controlling points in 2016). For the other yearly classification, 200 controlling points were collected from Google Earth images to conduct the verification. These verification control points covered all landscape types.

We build the transfer trajectory in the different phases to determine the variations of coastal wetlands (under ArcGIS 10.4).

2.3.3 *Extraction and validation of coastlines*

According to technical regulations for the coastal zone survey (State Oceanic Administration 908 Special Office, 2005), this study divided the coastline into natural and artificial coastlines based on their properties. During the extraction process, artificial shorelines were easily identified and obtained by visual interpretation (ArcGIS 10.4). The boundary of the natural shoreline was unclear; therefore, the interpretation was implemented by the image interactive interpretation. The Modified Normalized Difference Water Index was adopted to extract instantaneous water boundary (McFeeters, 1996; Xu, 2005). The tidal level correction model was used, first to calculate the intersection line

Table 1. Data sources of the coastal wetlands in the Bohai Rim

Name	Sources
GPS controlling points (274)	field surveys (2016)
Landsat-2/MSS, Landsat-4 /MSS, Landsat-5 / TM, Landsat-8 /OLI, and Gaofen-1/WFV	the Geospatial Data Cloud (www.gscloud.cn), the website of the US Geological Survey (earthexplorer.usgs.gov), the Remote Sensing Market Website (www.rscloudmart.com)
A 1:200 000 topographic map of the Bohai Rim	the National Basic Geographic Information Center (www.ngcc.cn)
National night light data (1995–2019)	the Geological Survey Cloud Platform (www.dsac.cn)
A 1980 land-use map of the Bohai Rim	the Geological Survey Cloud Platform (www.dsac.cn)
Google Earth satellite images	The Google Earth (www.goole.cn)
Historical tidal level	the China Maritime Service Website (www.cnss.com.cn)
A digital bathymetric chart	the Ship Information Network (www.shipxy.com)
Shoreline dataset extracted from Google Earth remote sensing images	the Global Change Research Data Publishing & Repository (www.geodoi.ac.cn)

Table 2. Classification system of the coastal wetlands in the Bohai Rim

Primary classification	Secondary classification	Definition
Natural wetlands	tidal flat	a mudflat or sandy beach with very low vegetation coverage in the intertidal zone
	marsh	a muddy area with thick vegetation and long-standing water
	river	a type of wetland formed by a river and its surrounding vegetation, intertidal estuary
	lake	freshwater lakes
	offshore area, lagoon	coastal buffer zone, brackish mixed area of the estuary; at the edge of the sea, salinity is constantly changing under the influence of tides
Man-made wetlands	aquaculture pond	fish, shrimp, and other aquaculture pond, and artificial cultivation of reed fields
	paddy field	farmland, such as rice fields
	reservoir	reservoir
	salt pan	salt field and salt field storage tanks
Non-wetland	construction land	maintenance of the land needed for urban functions, residential land, industrial parks, and ports
	dryland	dry land
	forest and grassland	natural woodland, artificial woodland, and grassland

between the national elevation datum and the land, second, through the water boundary line and historical tidal level data within two periods with a relatively close time interval, and then complete the shoreline extraction (Wu and Hou, 2015). To avoid the double image phenomenon, images in the other years were interpreted based on the extraction results from 2019, and only the areas that had changed were updated (Xu, 2016). Shoreline information in 1980 was extracted combined with the 1981 remote sensing image, and the 1980 Bohai Rim land-use map and historical tidal level data.

We randomly select long-term stable locations (such as breakwater dams, bedrock shorelines, road shorelines, etc.) on the coastlines extracted in 1980, 1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2019. And calculated the root mean square error (RMSE) (Liu et al., 2019). The spatial resolution of remote sensing images in 1980 was 60 m, and the spatial resolution of remote sensing images from 1985 to 2020 was 30 m. The calculated theoretical maximum permissible error value in 1980 was 56.6 and the theoretical permissible error in 1985–2019 was 28.8.

2.4 *Changes of coastal wetlands through landscape structure analysis from 1980 to 2019*

We combined with the research methods of landscape ecology, five indices, including the Shannon diversity index (SHDI), Shannon evenness index (SHEI), patch density (PD), patch number (NP), and largest patch index (LPI) were selected to reflect the landscape pattern characteristics of Bohai Rim (under Fragstats 4.2) (Wu, 2000). In order to abundantly reflect the development and evolution of the Bohai Rim. Specifically, the NP, the PD, and the LPI were selected to represent the degree of landscape pattern fragmentation. The uniform distribution of landscape types was assessed using the SHEI. The SHDI was used to analyze the complexity of landscape pattern components (e.g., quantity and species diversity).

2.5 *Dynamics of coastlines from 1980 to 2019*

2.5.1 *Shoreline growth rate*

We calculated the average annual percent change in coastline length in any period which is conducive to the intuitive comparison of changes in the length of coastlines in different regions (Wu et al., 2014). As shown in Eq. (1):

$$\mathrm{LCI}_{ij} = \frac{L_i - L_j}{L_i(j-i)} \times 100\%, \tag{1}$$

where LCI_{ij} is the varying intensity of coastline length from year i to year j; L_i and L_j are the coastline lengths in the years i and j, respectively, and the denominator is the product of the coastline length and time interval in the year i.

2.5.2 *Fractal dimension*

We also used the grid method to calculate the fractal dimension to examine the morphology variations of coastlands (Liebovitch and Toth, 1989). The principle of the grid method is to establish square grids of different lengths to continuously cover the coastline to be measured without overlapping. When the values of grid edge length r differ, the total number of grids covering the shoreline N changes accordingly. According to the fractal theory:

$$N(r) \propto r - D, \tag{2}$$

taking the logarithm of both sides of Eq. (3) provides the following

$$\ln N(r) = -D \ln r + C, \tag{3}$$

where C is the undetermined constant, and D is the fractal dimension of the coastline to be measured. The fractal dimension D ($1<D<2$) can be obtained by substituting the fit analysis described above with different grid side length r values and the corresponding total number of grids covering the shoreline ($N(r)$ values). The greater the value of D, the more complex the coastline. In this study, 60 m and 30 m integer times were used. Eight length indices were used for the two grid lengths of 30 m and 60 m: 1 200, 1 260, 1 320, 1 380, 1 440, 1 500, 1 560, and 1 620 and 1 200, 1 230, 1 260, 1 290, 1 320, 1 350, 1 380, and 1 410, respectively. Using the Feature to Raster tool function of the ArcGIS software, the mesh number of the 16 grid length indices above was counted. Using Eq. (2), the fractal dimension could be obtained by least-squares fit and regression analysis.

2.6 *Attribution analyses of coastal wetland changes*

We used a linear regression method in the SPSS version 17.0 platform to analyze (1) the relationship between land used for construction, man-made wetlands, and the tidal flat change; (2) the correlation between the reclamation area, the tidal flat, population size, the fishery output value (FOV), and urbanization rate (UR) was observed to change.

3 Results

3.1 *Coastal wetlands dynamics in the Bohai Rim*

3.1.1 *Temporal and spatial changes of coastal wetlands in the Bohai Rim*

Land-use information data of the Bohai Rim in 1980, 1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2019 were interpreted (Fig. 2), and the area conversion of each land-use type from 1980 to 2019 was calculated (Figs 2b, c).

The primary land-use types of the Bohai Rim were the construction land, the aquaculture pond, the dryland, the forest and grassland, the paddy field, water, the marsh, the tidal flat, and the salt pan. As shown in Fig. 2, the areas of the construction land, the aquaculture pond, the dryland, the paddy field, and the salt pan in the Bohai Rim increased overall, and the total growth over 40 years was 145.5%, 247.9%, 21.4%, 41.5%, and 189.2%. The forest and grassland, the water body, the marsh, and the tidal flat decreased rapidly, and the total decrease over the 40 years was 45.7%, 39.6%, 71.6%, and 91.1%. Among them, the salt pan, the aquaculture pond, and the paddy field are man-made wetlands, and the water, the marsh, and the tidal flat are natural wetlands, whereas the land used for the forest and grassland, the construction land, and the dryland were non-wetlands.

From the perspective of changes in time, the natural wetlands decreased from 1980 to 2019 (9 615.9 km^2) (Fig. 2). The changes in the natural wetlands from 1980 to 1990 and from 2000 to 2019 were greater than in other periods. The area of man-made wetlands increased by 11 706.5 km^2. On the whole, the non-wetlands had changed relatively a little.

From the perspective of changes in space, natural wetlands in the Bohai Rim were primarily distributed in the Yellow River Estuary, the Liaohe Estuary, the Luanhe Estuary, the south bank of Laizhou Bay, and the Pulandian Bay in the southwest of

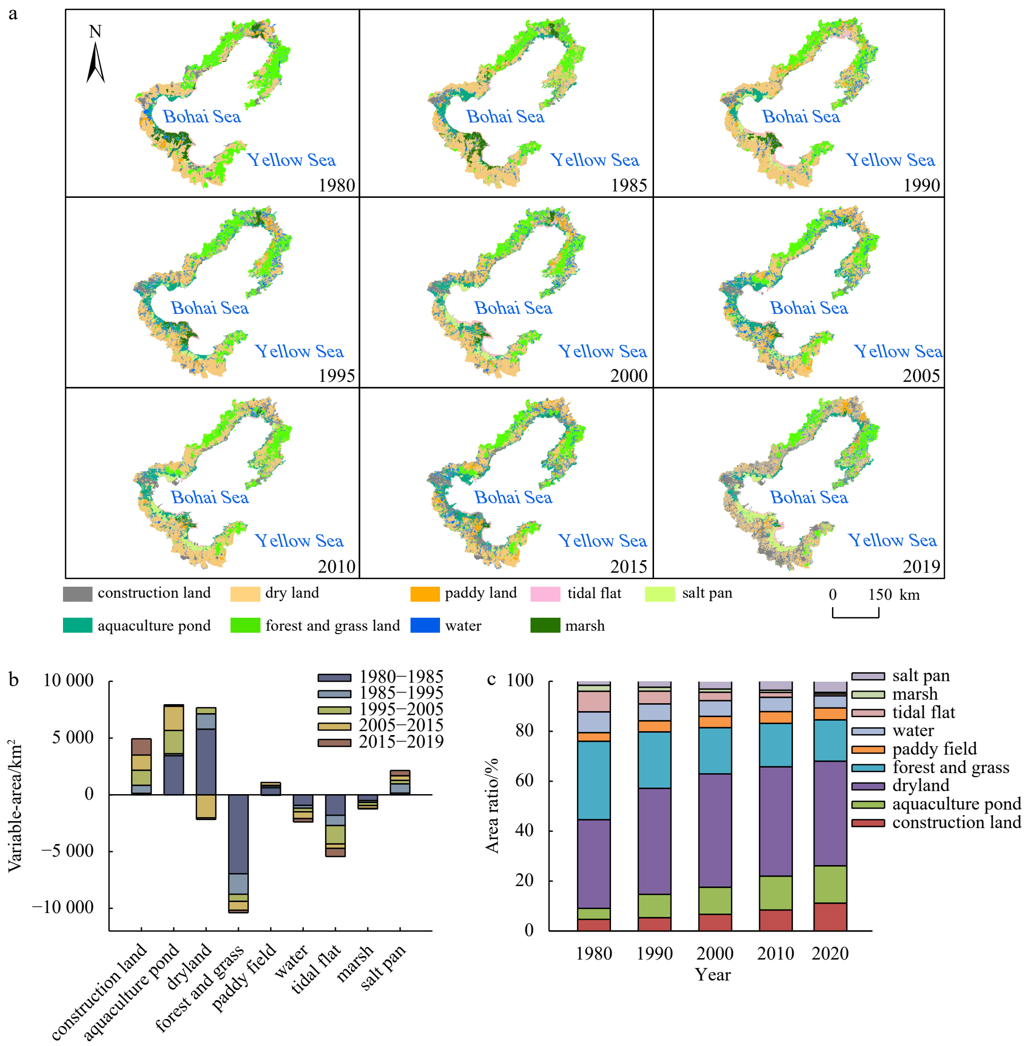

Fig. 2. Spatial and temporal evolution atlas of land-use types in the Bohai Rim from 1980 to 2019 (the overall accuracy from 1980 to 2019 was 83%, 87%, 85%, 87%, 89%, 92%, 90%, 89%, and 93%, respectively).

Liaodong Bay in 1980. By 2019, the natural wetlands were greatly reduced, and their distribution was primarily in the Yellow River and the Liaohe estuary areas. Specifically, a large area of the tidal flat existed in the Caofeidian area in an earlier period was studied, but the area was converted into the aquaculture pond and the construction land. The natural wetlands in the Liaohe Delta and the south bank of Laizhou Bay have been significantly reduced and replaced by the paddy field and the aquaculture pond. The tidal flat of the Pulandian Bay were reclaimed as the salt pan in an early period and later converted into the aquaculture pond. And the small number of natural wetlands that existed in the coastal areas of Tianjin in the early period, which have also been primarily replaced by the construction land. But it's worth mentioning that even though the number of natural wetlands in the Yellow River Delta was reduced, they still cover a larger area than other regions.

These results show that the area of natural wetlands in the Bohai Rim has decreased considerably over the past 40 years, with a trend of artificial and non-wetland.

3.1.2 *Evolution of coastal wetlands structure in the Bohai Rim*

From the analysis in Fig. 3a, a certain degree of transfer relationship occurred among the nine land-use types from 1980 to 2019. In general, salt field and dry land had higher retention rates (83.9% and 53.5%), and the conversion of wetland types was more frequent than that of non-wetlands. Natural wetlands were primarily transformed into man-made wetlands and non-wetlands, with the amount of transfer to man-made wetlands being relatively large. Non-wetlands were relatively intact and rarely changed into man-made wetlands (Fig. 3b). The conversion rate of natural wetlands to construction areas, the salt pan, the aquaculture pond, and dry land was relatively high, indicating that this was the main reason for the reduction in wetlands. “Marsh-construction land”, “marsh-salt pan”, “marsh-aquaculture pond”, “marsh-dryland”, “paddy field-construction land”, “salt pan-aquaculture pond”, “salt pan-construction land”, “tidal flat-salt pan”, “tidal flat-construction land”, “water-aquaculture pond”, “water-construction land”, are all tendency conversion modes. The conversion of the salt pan, the paddy field, the tidal flat, the forest and grassland, and non-wetlands into the tidal flat are all avoidance conversion modes.

Using a 10-year interval, 40 years could be divided into four time periods: 1980–1990, 1990–2000, 2000–2010, and 2010–2019. From different periods, the higher conversion rates of land types were the marsh, the paddy field, and the tidal flat. From 1980–1990 and 1990–2000, non-wetlands (the construction land,

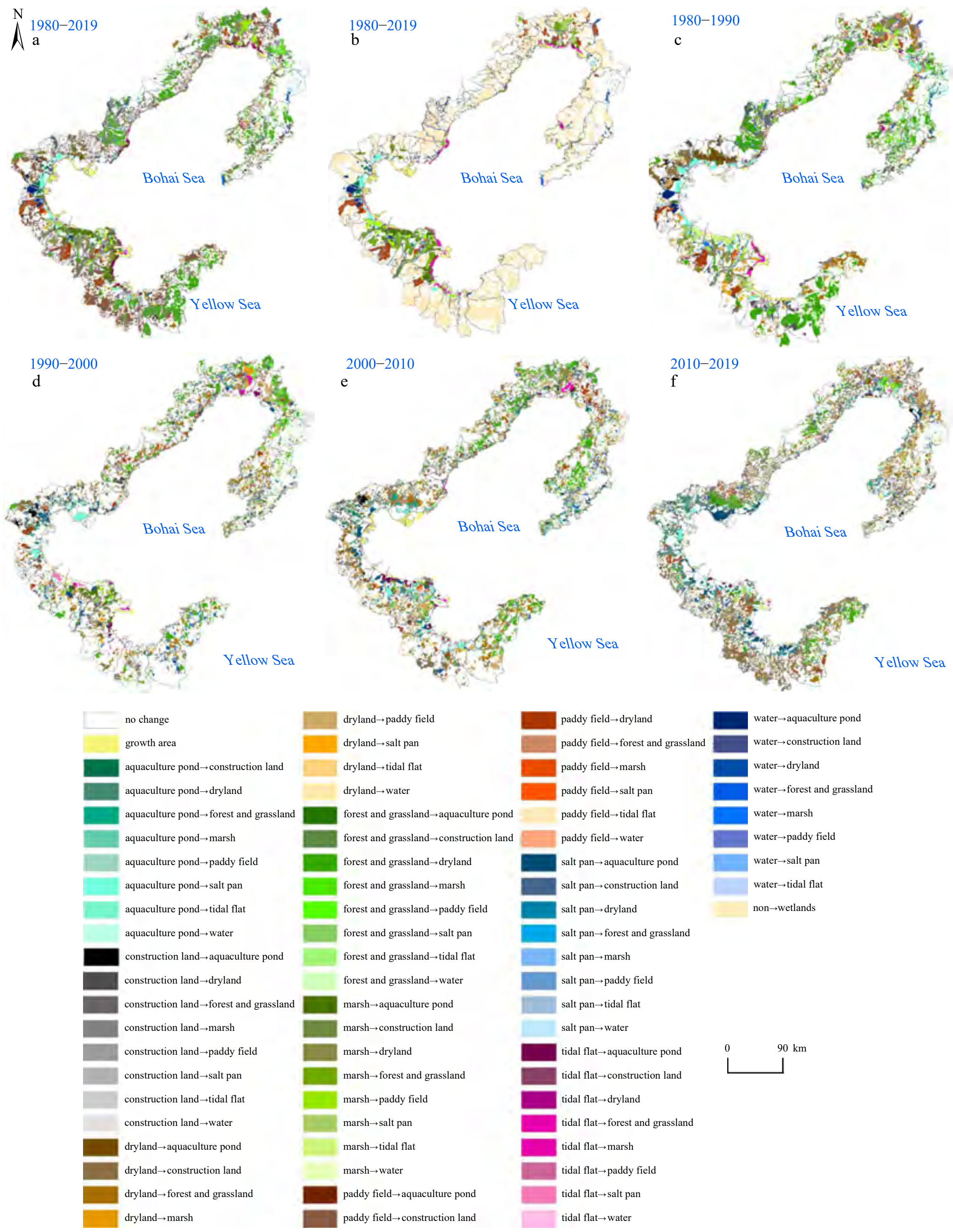

Fig. 3. Map of coastal wetlands structure transformation in the Bohai Rim from 1980 to 2019.

the dry land, the forest, and grassland)—"tidal flat" was an avoidable transformation model, and natural wetlands (the marsh, the paddy field, water) —"dryland", "tidal flat-salt pan", and "marsh-aquaculture pond" had the tendency of a transformation mode (Figs 3c, d). In 2000–2010 and 2010–2019, man-made wetlands—"tidal flat" and non-wetlands—"tidal flat" were the avoidance transformation models, and "forest and grassland-dryland", "forest and grassland-tidal flat", "marsh-aquaculture pond", "water-dryland", and conversion of other land types to "construction land" were inclined transformations (Figs 3e, f). In summary, the wetland areas exhibited a trend of artificial construction and wetland destruction, with difficulty reversing the transformation of natural wetlands converted into non-wetlands and man-made wetlands. Therefore, when developing and utilizing wetland resources, considerable caution should be exercised and rational planning implemented.

3.1.3 *Changes of coastal wetlands in the Bohai Rim through landscape structure analysis*

Figure 4 indicates that the PD and NP increased, whereas the LPI continually decreased. This indicated that the degree of landscape fragmentation in the Bohai Rim had been increasing. The SHEI (Fig. 4d) and the SHDI (Fig. 4e) decreased overall, indicating that the landscape pattern of the study area was balanced, and the landscape types had less control. After the year 2000, the two indices increased, caused by increased national awareness of the need to conserve natural areas. Human interference in natural environments lessened, and habitat heterogeneity increased slightly. Overall, high-intensity anthropogenic activities lead to landscape fragmentation and reduced biodiversity.

3.2 *Influence mechanism of reclamation on coastal wetlands in the Bohai Rim*

3.2.1 *Reclamation dynamics in the Bohai Rim*

The primary land-use type of coastal reclamation were man-made wetlands and the construction land. Among them, man-made wetlands referred to as the aquaculture pond and the salt pan (Fig. 5). From 1980 to 2019, the tidal flat area in the Bohai Rim decreased by 91.1%, the man-made wetland areas increased by 3 736.9 km^2, and the construction land increased by 1 008.1 km^2 (Fig. 5). Figure 6 indicates that the proportions of the tidal flat, man-made wetlands, and the construction land were 41.6%, 57.2%, and 1.2%, respectively, in 1980. By 2019, the percentage of the tidal flat had decreased to 3.1%, and man-made wetlands and the construction land were 84.5% and 12.3%, respectively.

From the perspective of changes in time, 1980–1985 and 2000–2005 were periods of rapid growth for man-made wetlands, whereas 2000–2005 and 2015–2019 were periods of rapid growth for the construction land. Correspondingly, 1980–1985, 2000–2005, and 2015–2019 were periods of significant decreases in the tidal flat. From the perspective of changes in space, man-made wetlands were primarily distributed in the Bohai Bay and the south bank of Laizhou Bay from 1980 to 1990 and expanded to the mouth of the Liaohe River and the Pulandian Bay from 1995 to 2019. The construction land was primarily distributed in the Tianjin Port from 1980 to 2000 and expanded to the entire Bohai Bay coast, the south bank of Laizhou Bay, and the west side of Liaodong Bay from 2005 to 2019. The tidal flat was primarily distributed in the Yellow River Estuary, the Luanhe River Estuary, and the Liaohe River Estuary from 1980 to 2005, comprising large and relatively complete landscape patches. From 2005 to 2019, they were primarily distributed in the Yellow River Delta. Based on the above results, from 1980 to 2000, the tidal flat was primarily reclaimed as man-made wetlands, and from 2000 to 2019, they were primarily reclaimed as man-made wetlands and the construction land.

3.2.2 *Significant change regions of reclamation dynamic*

The Bohai Rim is divided into five significant change regions, the south bank of Laizhou Bay, the Yellow River Delta, the Bohai Bay, the northern Liaodong Bay, and the Pulandian Bay (Fig. 1). Over the past 40 years, reclamation activities in the Bohai Rim have increased on a large scale, and the attributes of the coastline have also changed. From 1980 to 2019, the coastal area around the Bohai Rim increased by 1 631.2 km, and the rate of the shoreline change was 2.0%. From 1990 to 2000 was one of rapid coastline growth, with an average annual growth of 52.3 km. The rate of the shoreline change was 2.7%, and the shoreline continuously expanded toward the ocean. Figure 7f indicates that the length of the natural shoreline decreased by 90%, whereas that of the artificial shoreline increased by 2 946.1 km. In addition, the fractal dimension of the shoreline continually increased, indicating that the tortuosity of the shoreline also increased. However, it has decreased in recent years because shorelines are straightened when reclamation areas are large.

As shown in Fig. 7, the shorelines of all regions tended to increase overall, increasing sharply after 2005. In terms of the rate of variation in the shoreline, Bohai Bay varied the most (3.77%), whereas the Pulandian Bay varied the least (0.57%). The natural shoreline of the Bohai Bay region was the smallest and almost disappeared after 2010 (Fig. 7c), with similar trends in variation in the other regions (Figs 7b, d, e). The artificial coastline increased slowly from 1980 to 2005, and the natural coastline decreased sharply. After 2005, the artificial coastline increased substantially, and the natural coastline decreased slowly. The length of the artificial coastline was greater than 70%.

From the perspective of changes in hotspots, the overall rate of change in the south of Laizhou Bay was greater than that in other areas. By 2019, the area of reclamation of this area was 550.6 km^2, followed by the Bohai Bay and the Yellow River Delta, which were 666.6 km^2 and 460.6 km^2, respectively, in 2019. The area of reclamation at the northern of the Liaodong Bay and the Pulandian Bay changed little. In 2019, the areas of reclamation were 282.6 km^2 and 298 km^2.

Reclamation activities in Bohai Bay led to the transformation

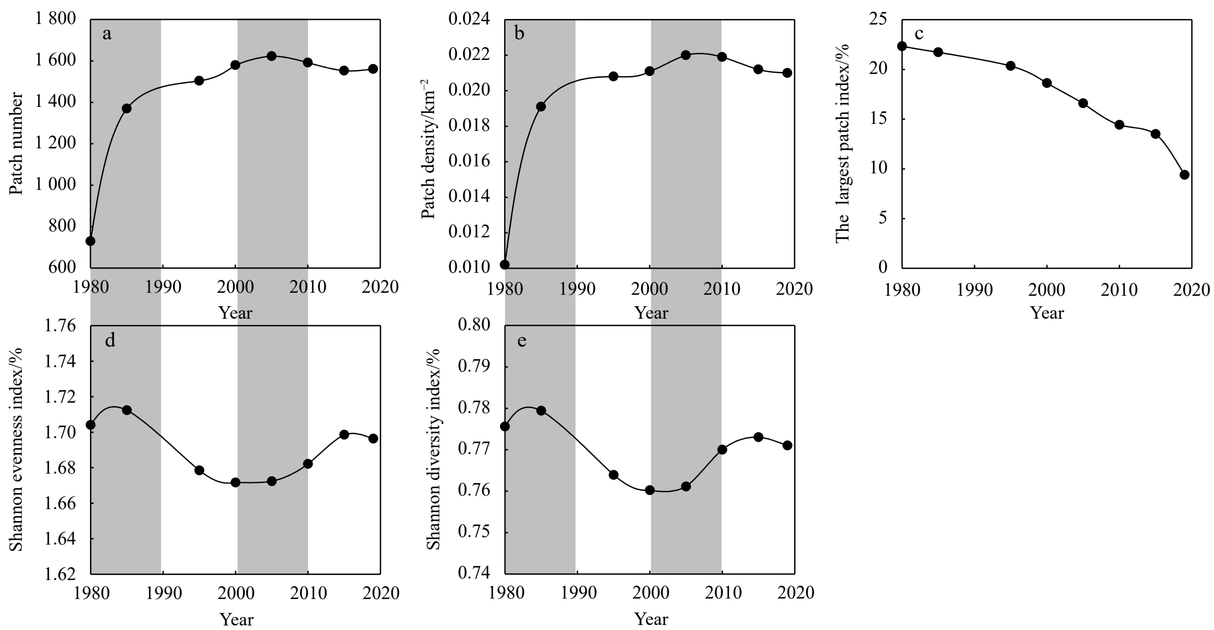

Fig. 4. Changes in landscape indices in the Bohai Rim from 1980 to 2019.

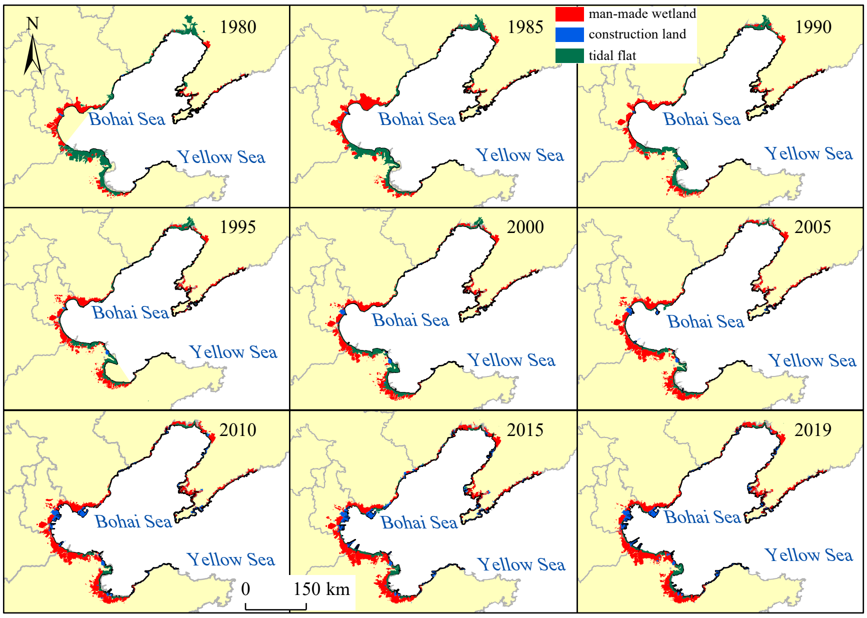

Fig. 5. Dynamic changes in the tidal flat reclamation in the Bohai Rim (the RMSE values from 1980 to 2019 were 28.2, 25.2, 23.5, 23.1, 22.5, 21.0, 19.4, 19.1, and 17.9, respectively).

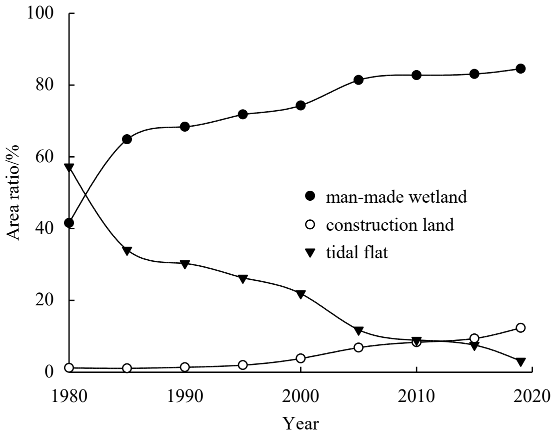

Fig. 6. Changes in the proportion of reclamation and the tidal flat in the Bohai Rim.

of almost completely natural shoreline to an artificial shoreline. On the one hand, this area was covered by mudflats suitable for activities, such as marine aquaculture and salt production. In contrast, with the support of national policies, the construction of large-scale industrial parks, transportation, urban land, and port terminals has greatly increased the reclamation area in the Bohai Bay and changed the nature of the coastline.

There are many types of reclamation activities in the Yellow River Delta. Oil extraction activities in this region were active in the 1990s, and the construction of the Gudong oilfield solidified the coastline. After 2005, the construction of ports, such as those at Binzhou, Dongying, and other areas, significantly increased the land area for construction. However, the Yellow River Delta protection zone is large, which effectively controls human activities that greatly interfere with its functions, such as industrial parks and port construction, in addition to a large number of man-made wetlands.

Before 2000, Liaoning Province was economically backward and lacked industrial technology and capital, primarily focused on low-cost breeding activities. In 2003, the country introduced a strategy to revitalize the old industrial base in northeast China and implemented policies to promote economic development. In 2009, the State Council of the People's Republic of China adopted the "development plan of Liaoning coastal economic zone", which promoted the industrial development of Liaoning Province, and a large area of land reclamation was used for industrialization and urbanization.

The coastal changes in the Pulandian Bay were the least obvious, primarily consisting of the aquaculture pond, the salt pan, and the construction land, but the proportion of the construction land was larger than that in the other hotspots (Fig. 7). Before 2000, the coastal area consisted primarily of the salt pan, and after 2005, the growth of the consturction land accelerated. This was because the coast of the Pulandian Bay consists of mud and bedrock. Liaoning Province put forward the "five points and one line" opening policy in 2005 to build the Dalian Huayuankou and the Dandong Industrial Parks, resulting in an evident increase in the construction land.

3.2.3 *Drives of coastal wetlands evolution in the Bohai Rim*

Figure 8d indicates man-made wetlands and the construction land was negatively correlated with the tidal flat. In contrast, the tidal flat continuously decreased with the increase in man-made wetlands and the construction land, which indicated that human activities are an important reason for the degradation and loss of coastal wetlands.

Based on the above research results, we believe that reclamation has a significant influence on coastal wetlands. In order to confirm it, we selected population size, FOV, and UR as driving factors to explore the correlation between these factors and the construction land, man-made wetlands, and the tidal flat.

Figures 8a–c indicate population size, FOV, and UR were positively correlated with man-made wetlands and the construction land and negatively correlated with the tidal flat. With the increase in population size and UR, the construction land continued to increase, and the increase in FOV indicated the rapid development of the marine aquaculture industry, which was also accompanied by the continuous loss of the tidal flat. This showed

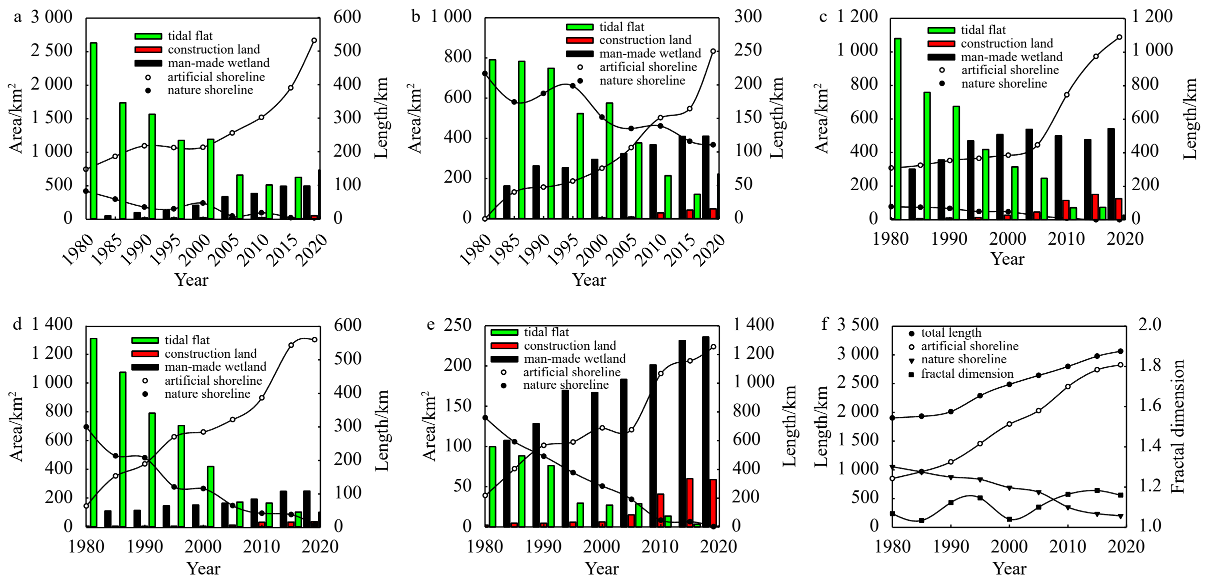

Fig. 7. Significant change regions of reclamation in the Bohai Rim. a. South of Laizhou Bay; b. Yellow River Delta; c. Bohai Bay; d. north of Liaodong Bay; e. Pulandian Bay; f. Bohai Rim shoreline.

that reclamation activities had negative impacts on coastal wetlands. In addition, it also revealed that population, economic, and social development have a positive effect on reclamation activities.

In summary, we believe that human factors are an important factor affecting the evolution and degradation of coastal wetlands. And reclamation activities have brought direct and indirect impacts on coastal wetlands.

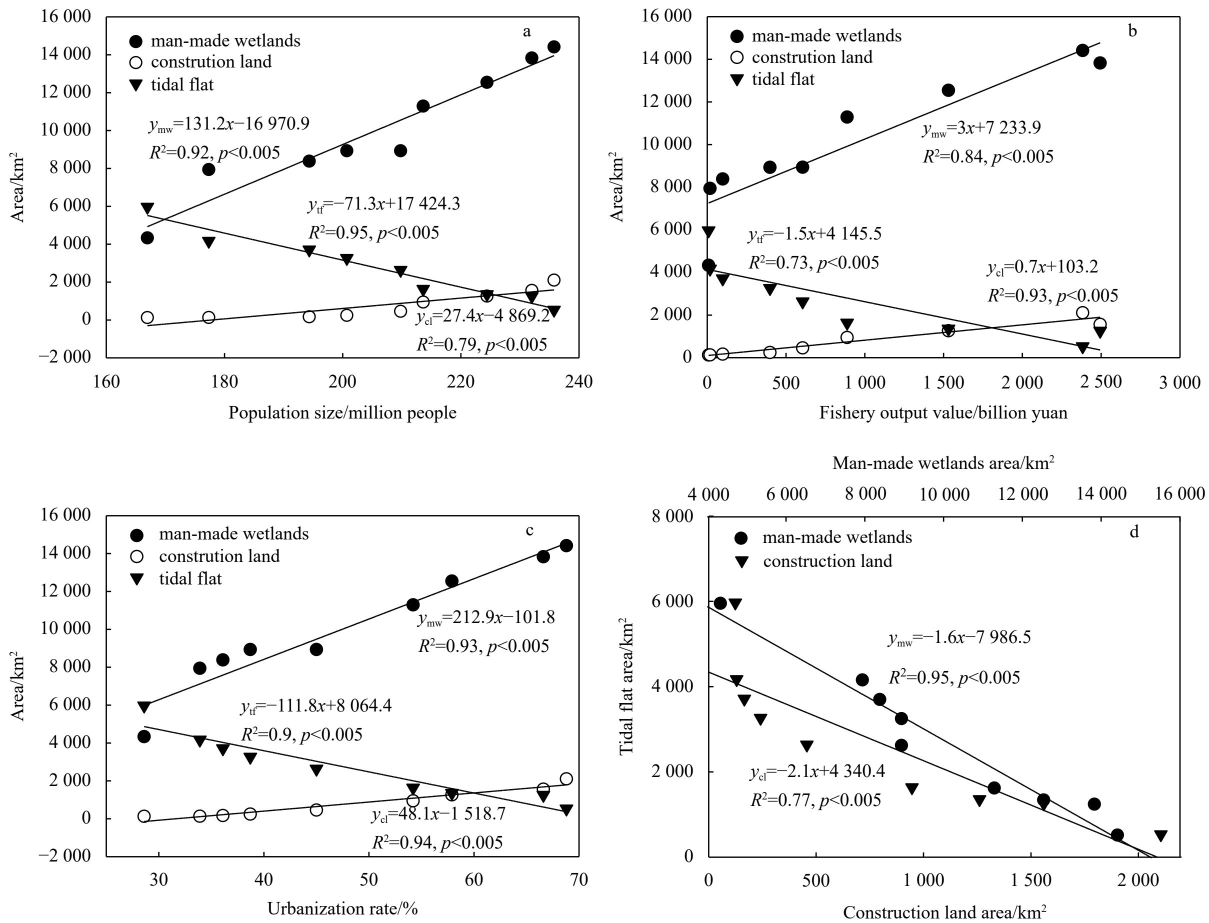

Fig. 8. Correlation between reclamation and the tidal flat in the Bohai Rim. mw: man-made wetlands; cl: construction land; tf: tidal flat.

4 Discussion

4.1 *Accuracy of interpretation results for the coastal wetlands around the Bohai Rim*

The image interactive interpretation of wetland and reclamation information by researchers observing the spectral and textural features of the images has great accuracy and meets the extraction accuracy requirements for different land-use types (Ding et al., 2019; Pardo-Pascual et al., 2012).

When interpreting land-use type information, we used band combination 134 to extract the water body data (water), band combination 432 to extract vegetation data (the forest and grassland, the paddy field, the dryland, and the marsh), and the more informative band combination 543 combined with texture features to extract the other land types (the salt pan, the aquaculture pond, the construction land, and the tidal flat) (Yan et al., 2017). This visual interpretation method could affect the reliability of the land-use extraction. Furthermore, we evaluated the accuracy of land-use feature information by many random points to increase reliability, and the final remote sensing interpretation has good performance (Figs 2 and 5), which meets the research needs, making the results scientific and credible.

4.2 *Evolution mechanism of coastal wetlands in the Bohai Rim*

The results of this study showed that natural wetlands in the Bohai Rim region were primarily distributed in the Yellow River Estuary, the Liaohe Estuary, the Luanhe Estuary, the south bank of Laizhou Bay, and the Pulandian Bay in the southwest of Liaodong Bay. From 1980 to 2019, natural wetlands in the Bohai Sea Rim area decreased by 66%, and constructed wetlands increased 1.3 times. The isolation of habitat landscapes has become more intense. The periods 1980–1985 and 1995–2005 exhibited the greatest changes. This is consistent with the conclusions by Liang et al. (2018), Yan et al. (2019), and Yu et al. (2020).

Judging from the strategic planning of Shandong Province, Hebei Province, Tianjin City, and Liaoning Province over the past 40 years, 1980–1990 was the key period for optimizing and adjusting the industrial infrastructure. It was a transitional period from traditional industries to modern industries, and it was also a period when the agricultural economy accounted for a large proportion of the national economy. Since 1990, all provinces have attached importance to the development of the marine economy and urbanization. In 2000, they emphasized the importance of ecological and environmental protection in the developmental era. The reclamation from 1980 to 1990 was primarily used for marine aquaculture to meet societal demand for seafood (Ding et al., 2020). Since 1990, it has been primarily focused on harbors, industries, and land use for urbanization in coastal zones. By combining the socio-economic development plan and the developmental stage of reclamation, we can explain the transformation characteristics of land use of the coastal wetlands in the Bohai Rim at each stage. Correspondingly, from 1980 to 1990, coastal wetlands were transformed into breeding ponds, the salt pan, and dry land. After 2000, there was a transformation trend from wetlands to breeding ponds, the salt pan, and the construction land. It is not difficult to conclude that human activities promoted the evolution of coastal wetlands and changed their attributes, making the wetlands appear artificial.

According to these results, the main areas of transformation of coastal wetlands in the Bohai Rim were concentrated in the Yellow River Estuary, the southern bank of Laizhou Bay, the Tianjin Binhai New Area, the Caofeidian Industrial Zone, the Luanhe River Estuary, the Liaohe River Estuary, and the Pulandian Bay. These are the tidal flat wetlands, especially the Yellow River Estuary, the Caofeidian, the Liaohe Estuary, and the Pulandian Bay. The reclamation of the tidal flat in the Liaohe Estuary and the Pulandian Bay were primarily through the aquaculture pond and the salt pan (Liang et al., 2018). This was probably because of their superior geographical location, rich fishery resources, and a large area of the tidal flat. The natural wetland retention rate of the Yellow River Estuary was the highest, which was also the most diverse reclamation mode of the tidal flat, including the construction land, the aquaculture pond, the salt pan, the paddy field, and dry land (Wang et al., 2021). This was because of the superior geographical location of the river delta, being rich in oil and fishery resources, unique bird habitat, and large areas of national protected areas. In 1990, Shandong Province's Tenth Five-Year Development Strategy pointed out the need to vigorously develop the marine industry, and the Eleventh Five-Year Plan in 2000 emphasized marine economic development and urban construction. Therefore, during the coastal wetland changes in the Yellow River Delta over the past 40 years, the reclamation activities of the aquaculture pond and the salt pan were the focus around 1990. After 2000, there was a sea reclamation mode in which the aquaculture pond, the salt pan, and the construction land coexisted. Similarly, before 2000, the wetland conversion types in the Caofeidian area were primarily the salt pan and the aquaculture pond (Yue et al., 2016). There are the Changlu Salt Farms, one of the four largest the salt pan in China, and the Balitan the aquaculture pond in this area (Zhu et al., 2017). In 2005, the state established the Caofeidian Industrial Zone. Since then, the proportion of inland conversion of the construction land has increased. The Tianjin Binhai New Area was established in 1994 and was written into the Eleventh Five-Year Plan in 2005, elevated to a national development strategy (Yang et al., 2011). The Binhai New Area led, and Tianjin vigorously developed high-tech industries and modern marine and logistics industries. The corresponding research results also show that since 2000, the land transfer type in this area is primarily the construction land. Breeding ponds have dominated the Luanhe Estuary since 1990. The Laizhou Bay is rich in fisheries, petroleum, and the salt pan, but the shallow water of the bay is not conducive to the construction of a port. Therefore, the southern bank of Laizhou Bay uses the the aquaculture pond and salt fields as the main transfer land categories of the tidal flat wetlands. The Pulandian Bay is located on the western side of the Liaodong Peninsula. It has rich the tidal flat resources and has been reclaimed as a large area of the salt pan and breeding ponds.

In summary, the coastal wetlands in the Bohai Rim have undergone tremendous changes over the past 40 years. Natural wetlands have been reduced over a large area, man-made wetlands have continued to grow, and natural wetlands have been transformed into man-made wetlands and non-wetlands. The main driving force of this change has been sea reclamation activities, such as the salt pan, breeding ponds, and the construction land. These human activities are closely related to social and economic development. Therefore, human reclamation activities play a major role in the evolution of coastal wetlands.

4.3 *Impact of reclamation processes on coastal wetlands*

Frequent human activities in the coastal areas have seriously affected the marine ecological environment (Lai et al., 2015). Therefore, it is necessary to analyze the evolutionary characteristics of coastal reclamation activities and their influence on coastal wetlands.

Since the 1980s, coastal zone reclamation in China has gone through three stages: the cultivation circle, “dormant period” and the urban expansion circle. During the transition from the “dormant period” of reclamation to urban expansion and reclamation, the social and economic development level played a leading role (Tian et al., 2016). Since Economic Reform and open up in 1978, the state has provided policy support to coastal areas and established the Caofeidian, the Binhai New Area, and other industrial parks, which greatly promoted the economic development of coastal areas and accelerated the rapid development of reclamation projects in them. Reclamation is a way for human beings to expand their living and production spaces. This results from the difference in profit between the economic benefits brought by the value of the land and the reclamation cost (Gaglio et al., 2017). Both natural and social factors influenced it. Among them, natural factors primarily include the types of shoreline and resources, whereas social factors include the needs of the population, policy, agriculture, industrialization, and urbanization (Gao et al., 2014). Since 1980, the state has exercised systematic management of coastal development activities. Reclamation has been transformed from the traditional development model of agricultural reclamation to comprehensive development and large-scale operation modes. Moreover, continuous and rapid economic growth has expanded the demand for land for construction and ports, leading to a continuous increase in port areas.

Coastal reclamation activities have an impact on coastal wetlands. Reclamation activities directly diverted coastal wetland areas. Aquaculture, reclamation, urbanization, industrialization, and port construction took over coastal wetlands, resulting in a significant decrease in the areas of the tidal flat and marsh. This is consistent with the conclusions of Ma et al. (2019) and Liu et al. (2020). The coastline length in the Bohai Rim coastal area increased continuously from 1980 to 2019, and the natural coastline decreased by 90%. From 1990 to 1995, the growth rate was the highest. This is consistent with Xu et al. (2016) from 1980 to 2010 (1 074.4 km). In addition, the proportion of reclamation activity for the artificial coast increased substantially, causing the integration of the coastline (Qiu et al., 2021). The solidified shoreline prevents natural tidal action (Bi et al., 2014). This hinders the matter and energy exchange between the normal tidal wetlands and the ocean, affects the normal vegetation succession process, converts the intertidal wetland into non-intertidal wetland (Yang et al., 2018), leads to a change in the ecosystem structure of the coastal wetland, and reduces the area of natural wetlands, particularly tidal wetlands (Kirwan and Megonigal, 2013; Lazarus et al., 2016).

Natural and social factors jointly determine the types of reclamation utilization in different regions (Gao et al., 2014). The mudflats in coastal areas were large and cost less to reclaim; they are primarily used for aquaculture and salt production. Some examples include the Bohai Bay, the Laizhou Bay, and the Liaodong Bay. In areas where sandy and rocky coasts are widely distributed, reclamation is primarily used to meet the demand for land available for construction generated by urban expansion, such as the coastline of the Pulandian Bay.

Different reclamation methods also lead to different impacts on coastal wetlands. Enclosing the sea is an open or semi-open use method, and the nature of the land itself will not change and can be restored (Shan and Li, 2020). However, reclamation requires a change in the land category and cannot be reversed. Although recycled marine aquaculture and salt farms will pollute the environment, we compared the two methods in which many the tidal flat restored by the the aquaculture pond can still restore the function of wetlands several years later owing to the restoration ability of wetlands. Some research results have revealed that a stable reclamation model is conducive to maintaining the stability of coastal wetlands. Today, the national development strategy emphasizes technological innovation, industrial upgrading, and green development. In the context of technological updates and model optimization, healthy aquaculture has become mainstream, such that reasonable sea reclamation activities can continue. Moreover, reclamation activities were created to solve the contradictions in land use. This method can promote social and economic development under the premise of balancing the health of the ecological environment and economic development. Therefore, proper disposal of land for reclamation is another issue that should be discussed.

5 Conclusions

China has a long history of reclamation activities that have made important contributions to economic growth and also have a prolonged influence on the ecological environment. Since the reform and opening up of the economy in 1978, various national strategies and economic policies have been successively promulgated and implemented. These promoted the industrialization and urbanization of coastal areas and the reclamation process, leading to a deeper degree of landscape fragmentation, and creating a decline in the ecological service function of the coastal wetlands, a substantial reduction in the area. On July 14, 2018, the State Council issued a notice on strengthening the protection of coastal wetlands and strictly controlling reclamation, and this emerging policy strongly restricted reclamation activities. In this context, therefore, it is important to investigate the dynamic changes in coastal areas for marine ecological conservation and restoration. This study explored the characteristics and rules of the evolution of coastal wetlands, shoreline changes, and the reclamation process of the Bohai Rim. The specific conclusions are summarized as follows:

(1) The coastal changes of the Bohai Rim are primarily concentrated on coastal silt, such as in the south of Laizhou Bay, the Yellow River Delta, the Bohai Bay, and the north of Liaodong Bay. Large-scale reclamation activities of the Bohai Rim (e.g., the aquaculture pond, the salt pan, and the construction land) results in the landscape fragmentation of coastal wetlands, with natural wetlands decreasing by 66%.

(2) Reclamation activities led to the solidification of the shoreline, changed its original properties, blocked the material and energy exchange of the wetlands, affected the normal succession of coastal wetlands, and led to their decline. And under the influence of reclamation, natural wetlands have been transformed into man-made and non-wetlands, and the land categories transformed into non-wetlands cannot be restored.

These results show that strict control of reclamation activities is the key to protecting coastal wetlands. During the management of reclamation activities in the future, we can promote the development of the modern marine industry, advocate healthy aquaculture, and choose correct and reasonable reclamation methods to reduce the negative impact on coastal wetlands.

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