

Article

Landscape Pattern Evolution Processes and the Driving Forces in the Wetlands of Lake Baiyangdian

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Abstract: The spatiotemporal features of land use changes and the evolution process of landscape pattern from 1980 to 2017 were investigated using historical satellite images from a Landsat Thematic Mapper (TM) for 1980, 1990, 2000, 2005, 2010 and 2017 in the wetlands of Lake Baiyangdian in the North China Plain (NCP). Landscape pattern indices were used to quantify landscape changes in wetlands, and a redundancy analysis (RDA) was conducted to analyze the driving forces and quantitatively explain the effects of human activities and natural changes on wetland fragmentation. The results showed that the total wetland area was 234.4 km² in 1980 but it decreased by 8.1% at an average decrease rate of 0.5 km² per year. The dominant transition between land use types was from natural wetlands to artificial wetlands, and wetland conversion to dry land and residential land. The RDA results suggested that agricultural activities and total population were the main driving factors affecting wetland landscape. Additionally, climate change provided a potentially favorable environment for agricultural development, due to the increased temperatures and decreased wind speeds. Additionally, governmental policy changes and dam construction also played the roles in land use changes.

Keywords: land use changes; evolution process; landscape pattern; wetland; Lake Baiyangdian; driving forces



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1. Introduction

Wetlands are key ecosystems in the global ecological system and carbon pool, and they provide important ecosystem services by mitigating flood damage, improving water quality, regulating the climate, and serving as a natural habitat supporting biodiversity [1,2]. Of all ecosystem types, wetlands are being lost at the fastest rate globally, which is a cause for both governmental and public concern [3]. The Organization of Economic Cooperation and Development estimated that approximately 50% of wetlands worldwide have been lost since 1990 [3–5], which is the fastest decline of all global ecosystem types. According to the second national wetland survey conducted by China's State Forestry Administration between 2009 and 2013, which was based on China Brazil Earth Resources Satellite remote sensing and field measurements, wetland area was reduced by 33,963 km², with a loss rate of 8.82% compared to the first national wetland survey [6]. It is evident that there has been a dramatic degradation and loss of wetlands over the past few decades in China [7], and the driving factors of wetland degradation and fragmentation may be related to the continuously changing climate conditions, intensive human disturbance, associated pollution, and human need for water and biological resources [2,6,8–10]. Wetland landscape fragmentation can be determined using the spatial distribution of vegetation (e.g., the shape, size, and quantity of landscape features) [11,12]. The first step in wetland degradation can be determined by identifying changes from uniform conditions to more heterogeneous and patchy conditions, and this is strongly associated with a reduction in wetland function and

biodiversity [4]. To enhance our understanding of the evolution of typical wetlands, it is necessary to determine the causes of wetland landscape pattern evolution processes.

In recent decades, remote sensing (RS) and geographic information system (GIS) technology had been usually used as the tools to obtain wetland management information and to calculate quantitative indicators and analyze the characteristics of landscape patterns on different scales. Such information is then used by researchers, policy makers, and planners [2,13]. To monitor and assess environmental and ecological changes, it has become important to obtain land use and land cover (LULC) data in wetland landscape patterns and degradation research [3,14]. Previous studies have shown that the LULC can affect hydrology, the water quality, the regional climate, and biodiversity [15]. Human activities are the most important factors affecting LULC conversion and wetland changes, and their effects on the environment and ecology have been continuously increasing [2,3,14,16,17]. Such human activities cause environmental pollution and mainly include land reclamation and infrastructure development projects (such as constructing roads and market nodes), agricultural activities (such as crop and livestock production and irrigation), and reservoir construction projects [2,8,18]. Intensive human activities affecting wetlands in developing countries have resulted in an increased frequency of drought, decreased river runoff and groundwater levels [19,20]. Apart from human activities, climate change is a major factor.

As the largest natural freshwater wetland in a semi-humid zone, Lake Baiyangdian (LBYD) played an important role in maintaining the regional ecosystem cycle and balance, such as that pertaining to water regulation and supply [21,22]. LBYD was once known as the “Pearl of North China” and the “Kidney of North China” [23,24]. However, owing to both natural conditions and the increase in human activities in recent decades, the lake has experienced wetland shrinkage, water scarcity, and water quality deterioration [21,25]. As most rivers have become seasonal or persistently dried out, the amount of water inflowing to LBYD has reduced, which has caused lowering water levels and a decrease in wetland area [26]. In addition, LBYD was one of the primary grain-producing areas in the NCP. The effective irrigation-cultivated area of 78,000 ha is in four large irrigation districts above 2000 ha and multiple medium irrigation districts [27]. After 1980, agricultural encroachment into natural wetlands for grain production was strongly stimulated by several national policies [28]. Additionally, technological innovations and advances in irrigation, the application of chemical fertilizer, and management systems began to occur in 1992, and these contributed to the increased farmland area [3]. These changes caused ecological problems, such as a reduction in biodiversity and water resources, a degradation in water quality, and a loss of wetland functions in LBYD [27]. It is critical to explore the reasons driving wetland degradation [29,30]. Additionally, it is thus necessary to analyze the factors affecting wetland changes and design policies for mitigating further degradation in LBYD.

Numerous studies have focused on various aspects of the LBYD wetlands, including landscape evolution [31–33], ecosystem services [26,34], environmental pollution [35,36], evapotranspiration [29], water demand [37] and hydrological changes [21]. However, most of these previous studies have only qualitatively described the driving mechanisms behind wetland changes, and have not quantified the contribution rates which these driving factors contribute to the area of wetland changes. Additionally, the climatic factors of wetlands in LBYD mainly focus on the temperature, precipitation, and potential evapotranspiration, and the actual evapotranspiration (AET) is less taken into account. Considering AET calculated by the Budyko-type equation [38–40], which was very important for the wetland landscape and hydrological changes, the processes and driving forces relating to wetland landscape fragmentation should be analyzed. Given this context of climate change and intensifying human activities, what was the main driving reason for the degradation of LBYD? [29,30] In order to understand this problem, the main research contents were: (1) to characterize the processes involved in wetland fragmentation during the years 1980–2017; (2) to characterize the changes in land use types over the 38-year period; and (3) to determine the driving forces promoting wetland landscape fragmentation. Research on wetland

fragmentation in typical semi-humid zones is important for promoting the restoration of degraded wetland ecosystems, accelerating sustainable development, and providing scientific location-based wetland conservation and restoration policies.

2. Materials and Methods

2.1. Study Area

LBYD is a typical grass-type shallow lake located in Baoding City between 115°38' E–116°07' E and 38°43' N–39°02' N (Figure 1). It is at the heartland of three cities: Beijing, Tianjin, and Shijiazhuang. LBYD is the largest plant-dominated freshwater wetland on the NCP, with a total area of 347 km². LBYD plays an important role in providing a habitat for native animal and plant species, protection against floods and water purification [35]. The major land use and land cover types are water bodies, farmland, construction land, residential land, and beach. The area has a semi-humid climate and lies within the monsoon region of the East Asia Warm Temperature Zone [41]; it therefore experiences hot, wet summers and cold, dry winters, and the mean annual temperature ranges from 7.3 to 12.7 °C [32]. The average annual precipitation is 563.9 mm, and it mainly occurs between June and September. The wetland area consists of 140 interrelated lakes of unequal sizes that are linked by 3700 crisscrossing ditches to form a unique landscape [21]. Historically, eight rivers flowed into the Baiyangdian wetlands, including the Baigouyin River, Ping River, Pu River, Cao River, Fu River, Tang River, Xiaoyi River, and Zhulong River, and water outflowed via the Zhaowangxin Canal [42]. However, the frequency of drought in LBYD has increased in recent years, particularly over the last three decades [25,34,43]. The surface runoff of the eight rivers has drastically reduced and the area has experienced seasonal and persistent droughts that have caused environmental problems, such as the disruption of the water cycle and the ecological balance [29]. Furthermore, the increased population causes increased water consumption and the decreased water supply, together with the wetlands being degraded [21,36].

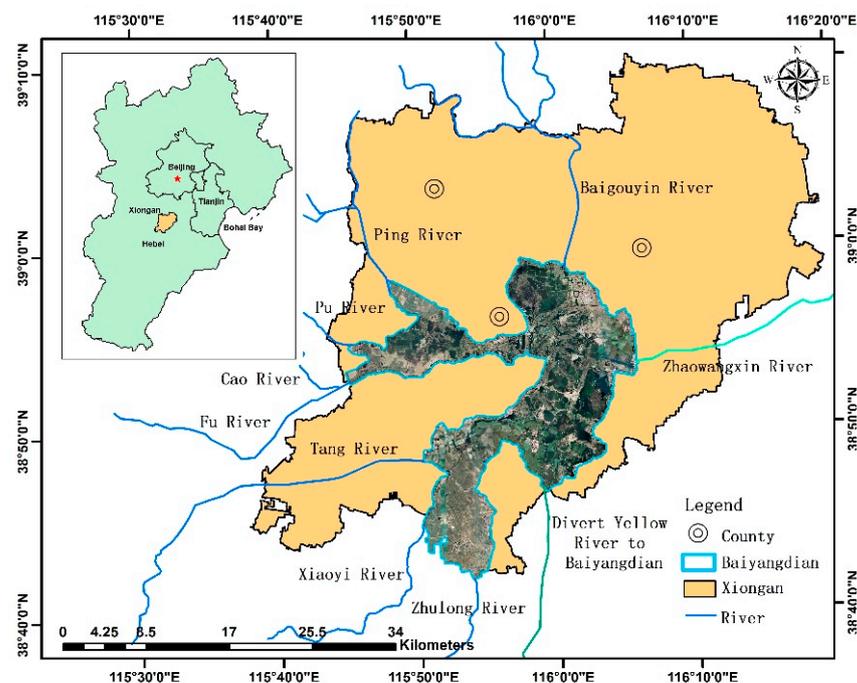


Figure 1. Location of the study area.

2.2. Data Sources and Processing

Six cloud-free Landsat remote sensing images taken in 1980, 1990, 2000, 2005, 2010, and 2017 were acquired from the United States Geological Survey Global Visualization Viewer (<http://glovis.usgs.gov/> (accessed on 15 October 2020)) with a resolution of 30 m.

All remote sensing image records where the frequency was once a year from June to September were selected, because this is the season for substantial plant growth, and land use types in northern China can be easily identified [16]. Data processing including image adjustment, geometric correction, image enhancement, and image cutting was conducted using ERDAS Imagine processing software (Version 9.2) and ArcGIS software (Version 10.2). The images were a composite of Red, Green and Blue. The land use classification system employed was based on the Chinese National Technical Standard for Land Use Survey (State Bureau of Quality and Technical Supervision of China, 2007) [44]. The widely used supervised classification method of maximum likelihood was utilized to classify the images into eight types of land use and land cover. The training data for the classification of the classes were selected by combining visual identification and site visits. Additionally, land use types were interpreted as paddy fields, dry land, woodland, rivers, lakes, reservoirs and ponds, beach, and residential land. Kappa coefficients were used to estimate the classification accuracy and Kappa values were more than 0.82, suggesting that the accuracy level of land use and land cover was suitable for further analysis. The wetland types were categorized into natural wetlands (rivers, lakes, and beach) and artificial wetlands (paddy fields, reservoirs, and ponds) according to the China Wetland Classification System [26,45]. To better understand the potential driving forces behind wetland landscape in LBYD, climate changes and socioeconomic development were considered to be the factors. In this respect, the daily precipitation, temperature, wind speed, relative humidity, and sunshine hours at Baoding weather station recorded during 1980–2017 were obtained from the China Meteorological Data Service Center (<http://data.cma.cn/> (accessed on 10 October 2020)). Annual precipitation (AP), annual average temperature (AAT), and actual evapotranspiration (AET) were used to assess climate change and variability. AET is the most excellent indicator for hydrological cycle and a central link to water balance calculations, with increasing importance in assessing the potential impacts of climate change [46]. Additionally, the AET was calculated based on the above meteorological data using the Budyko-type equation proposed by Choudhury [47,48]. Annual AET was derived by summing the monthly values within one year. Seven long-term socioeconomic data were collected for the period 1980–2017 from the Statistical Yearbooks of Baoding to analyze the associated possible factors relating to wetland shrinkage: gross domestic product (GDP), primary industrial output (PIO), secondary industrial output (SIO), total population (TP), urban population (UP), rural population (RP), and grain yield (GY). For hydrological factors, the water level of Shi Fangyuan for the period 1980 to 2017 was collected from the Hydrological Yearbook.

2.3. Research Methods

The spatial patterns of wetland landscape pattern can be described by several indices that efficiently summarize the landscape composition and spatial configuration characteristics [3,14,49]. Eight landscape indices were selected, and the names and definitions of parameters are acquired from FRAGSTATS (https://www.umass.edu/landeco/research/fragstats/documents/fragstats_documents.html (accessed on 25 October 2020)). These landscape indices were calculated on 30 m × 30 m grids using FRAGSTATS version 4.2 [2,4,49,50]. The concepts, calculation methods and ecological significance of these indexes can be found in the literature [51]. Changes in the land use and a matrix of the transitions between wetland landscape types were analyzed using ArcGIS 10.2 software. To explain the dynamics of wetland shrinkage, redundancy analysis (RDA) was employed to calculate the contribution ratio from socio-economic development and climate change using CANOCO 5.0 software.

3. Results

3.1. Wetland Changes and Landscape Pattern from 1980 to 2017

The spatial patterns of wetland areas for 1980, 1990, 2000, 2005, 2010, and 2017 are shown in Figure 2, and the temporal changes in wetland areas and the rates of change in

five corresponding stages (the first stage for 1980–1990, the second stage for 1990–2000, the third stage for 2000–2005, the fourth stage for 2005–2010, and the fifth stage for 2010–2017) are shown in Table 1. The results show that wetland types mainly included river, lake, reservoir and pond, and beach from 1980 to 2000, and paddy fields began to appear after 2000 (Figure 2). With the exception of the southern part, wetlands occupied 67.57% of the study area with many large patches in 1980 and were distributed widely. In 2000, paddy field wetland types began to appear, and the area of wetlands increased by about 5.41% to 253.22 km² at an average rate of 0.94 km²/year in relation to increases in natural and artificial wetland areas (although many large patches disappeared). Absolute losses in wetland areas occurred in the third stage (2000–2005, 37.79 km²), followed by the fourth stage (2005–2010, 19.36 km²), with annual change rates of −2.98% and −1.80%, respectively. However, wetland areas then increased by 9.91% at an annual change rate of 1.42% from 196.07 to 215.50 km² during 2010–2017 (Table 1).

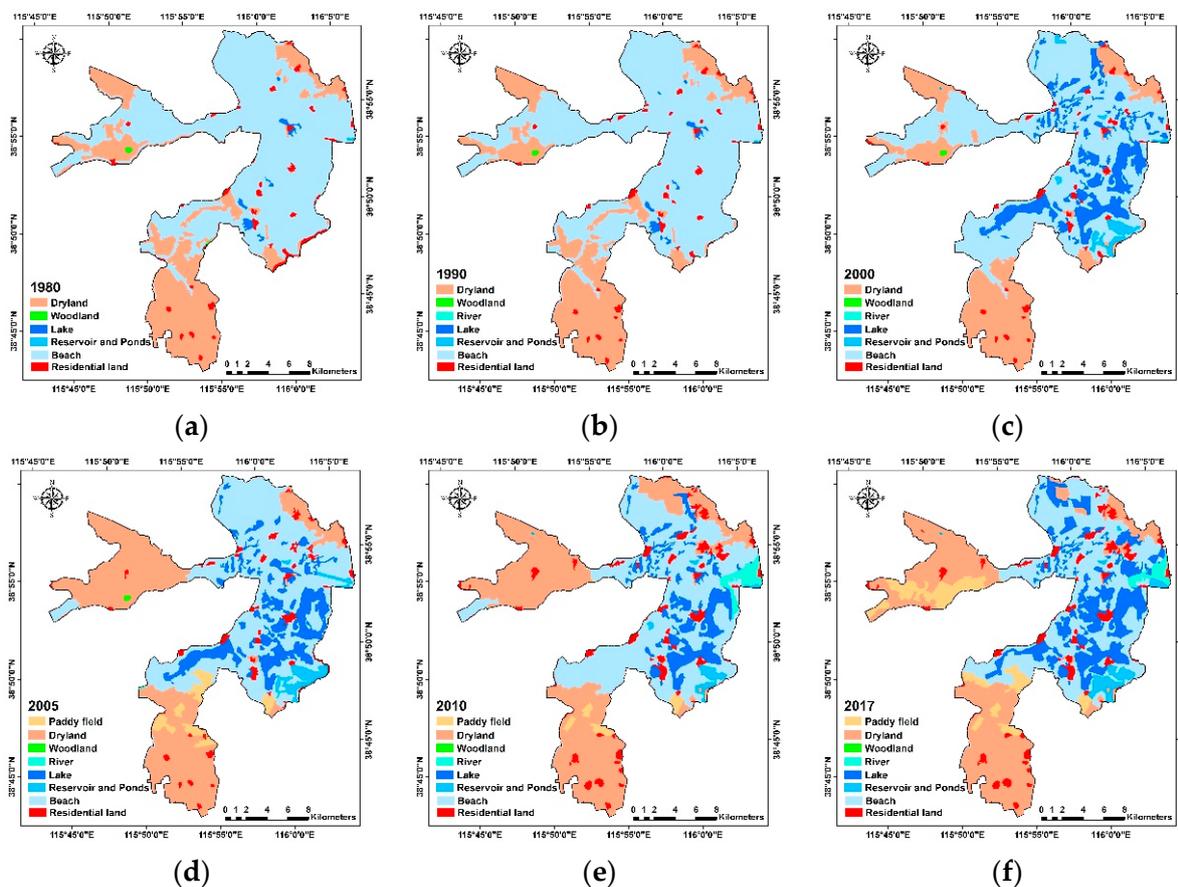


Figure 2. Spatial distribution of land use types in LBYD for 1980 (a), 1990 (b), 2000 (c), 2005 (d), 2010 (e) and 2017 (f).

Table 1. Wetland area from 1980 to 2017 and changes occurring during different stages.

Year	Wetland (km ²)	Percentage (%)	Stage	Change in Wetland Area (km ²)	Change Rate (%)	Annual Change Rate (%)
1980	234.44	67.57%	1980–1990	3.45	1.47%	0.15%
1990	237.90	68.57%	1990–2000	15.32	6.44%	0.64%
2000	253.22	72.98%	2000–2005	−37.79	−14.92%	−2.98%
2005	215.43	62.09%	2005–2010	−19.36	−8.99%	−1.80%
2010	196.07	56.51%	2010–2017	19.44	9.91%	1.42%
2017	215.50	62.11%	1980–2017	−18.94	−8.08%	−0.22%

The changes in wetland landscape metrics for 1980, 1990, 2000, 2005, 2010, and 2017 are shown in Figure 3 and Table 2. The NP increased by 72 patches from 1980 to 2000, and then decreased by 24 patches from 2000 to 2017. Meanwhile, the PD increased from 0.10 per 100 ha in 1980 to 0.38 per 100 ha in 2000, but then decreased to 0.33 per 100 ha in 2017. The ED and LSI increased from 1980 to 2017 and reached, respectively 16.20 and 11.64 in 2017. This indicates that human activities had already affected the wetland landscape in 1980, but the influence of human activities weakened during 2000–2010. After 2000, there was an increased awareness of environmental protection and environmental protection policies were formulated; therefore, human interference began to decrease and the wetland ecosystem gradually recovered [2,33,34]. The LPI and CONTAG decreased in 1980–2017. The SHDI and SHEI increased from 1980 to 2017 and reflect increased landscape heterogeneity and biodiversity.

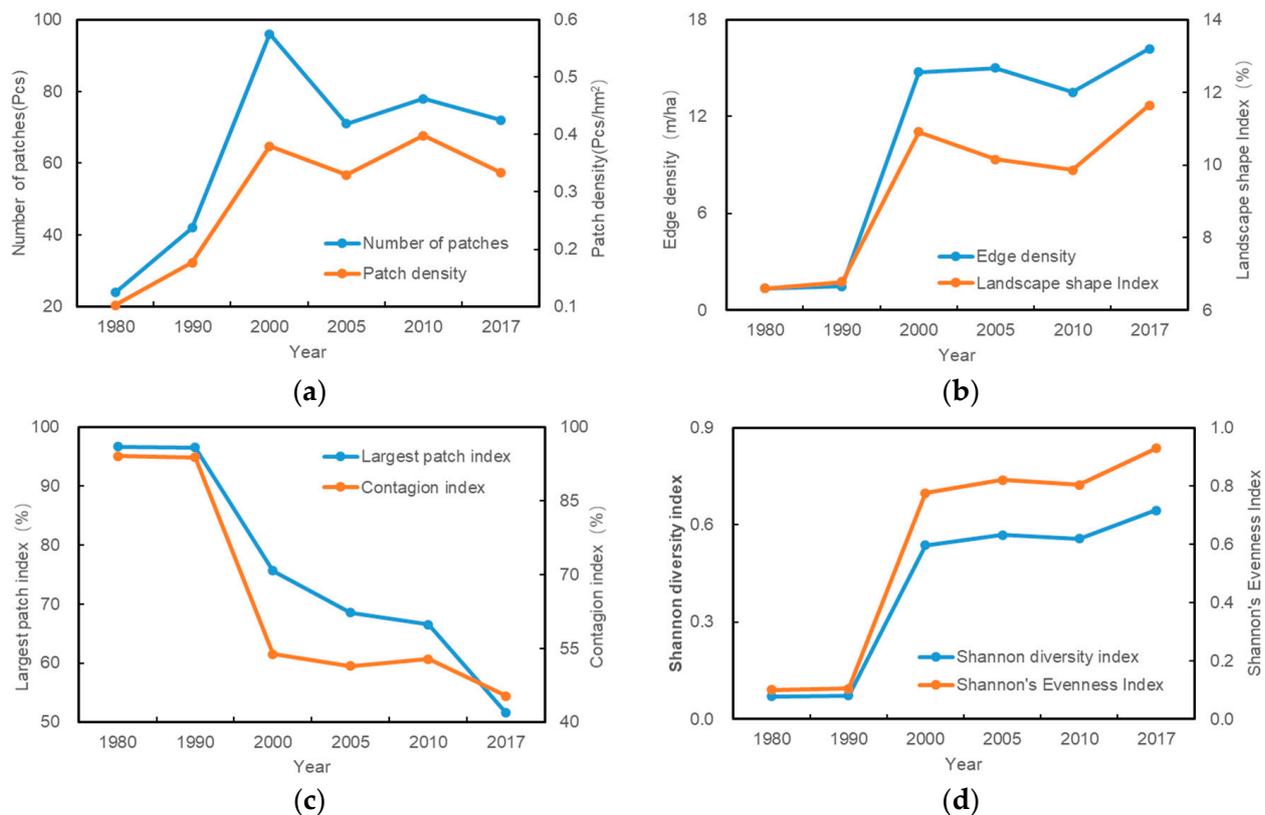


Figure 3. The changes of landscape metrics of wetlands in LBYD. (a) NP and PD; (b) ED and LSI; (c) LPI and CONTAG; (d) SHDI and SHEI.

3.2. Changes in Land Use Types over the Study Period

Figure 2 illustrates the spatial distribution of land use types in LBYD for 1980, 1990, 2000, 2005, 2010, and 2017, and the land use changes during 1980–2017 are shown in Table 3. During 1980–2017, dry land and beach were the two dominant land use types, and they accounted for 96.6%, 96.7%, 80.8%, 77.5%, 79.3%, and 65.9% of the total area, respectively. Dry land was predominantly located in the northwest and southern regions; it underwent a downward trend during 1980–2000 but an upward trend after 2000. Beach underwent a downward trend from 1980 to 2017, and it was mainly distributed in the northeast and central regions. Compared to beach, paddy fields and rivers began to appear in 2005, and although they were scattered over small areas, their presence showed an upward trend. The area covered by lake showed an upward trend before 2000, a downward trend during 2000–2010, and a significant upward trend after 2010. Reservoir and ponds occupied only 0.1% of the study area in 1980, but this increased to 2.5% in 2005, before decreasing again

to 2.4% in 2017. Woodland showed a decreasing trend, and the area was reduced to zero by 2010. Meanwhile, residential land expanded steadily; it accounted for 2.4% of the total land area in 1980 and 5.5% of the total land area in 2017.

Table 2. Landscape level indices in LBYD from 1980 to 2017.

Indice	Abbreviations	Definitions	Unit	1980	1990	2000	2005	2010	2017
Number of patches	NP	The degree of subdivision of a land use type	Pcs	24.00	42.00	96.00	71.00	78.00	72.00
Patch density	PD	Represent the density of patches for each land use type	Pcs/hm ²	0.10	0.18	0.38	0.33	0.40	0.33
Edge density	ED	The edge length between patches of heterogeneous landscape elements	m/ha	1.36	1.47	14.75	15.00	13.50	16.20
Landscape shape Index	LSI	The complexity of patch shape and the direction and intensity of human activity	%	6.60	6.78	10.91	10.15	9.86	11.64
Largest patch index	LPI	The percentage of the total landscape area comprising the largest patch	%	96.74	96.6	75.67	68.53	66.57	51.57
Contagion index	CONTAG	The agglomeration or spreading trends of different landscape patch types	%	94.11	93.85	53.81	51.36	52.85	45.28
Shannon diversity index	SHDI	Landscape heterogeneity	None	0.07	0.07	0.54	0.57	0.56	0.64
Shannon's Evenness Index	SHEI	Whether there are uniform plaque types in the area of distribution	None	0.10	0.10	0.78	0.82	0.80	0.93

Table 3. Total area and area changes in land use types during 1980–2017 (km²).

TYPE	1980	1990	2000	2005	2010	2017
Paddy field	0.00	0.00	0.00	11.29	5.11	24.85
Dry land	103.65	100.98	84.96	119.92	132.20	112.35
Woodland	0.47	0.35	0.36	0.36	0.00	0.00
River	0.00	0.02	0.02	0.25	7.06	4.70
Lake	2.77	3.05	50.53	46.20	36.06	61.04
Reservoir and ponds	0.31	0.19	7.30	8.76	4.94	8.63
Beach	231.37	234.63	195.38	148.92	142.90	116.28
Residential land	8.39	7.73	8.41	11.25	18.68	19.10

The changes in the above-mentioned land use types indicate that the natural wetland area showed a statistically downward trend, and the artificial wetland showed an upward trend from 1980 to 2017. Beach was the most important type of wetland, and its proportion decreased. These results suggest that the conversion between wetland types is one of the main reasons for these wetland changes. The changes in land use types is a mutual conversion process. The conversion matrix of land use types also showed that changes in LBYD land use during 1980–2017 mainly included a decrease in beach (−115.1 km²) but increases in lake (+58.3 km²), paddy fields (+24.8 km²), residential land (+10.7 km²), and dry land (+8.7 km²) (Table 4). During the period 1980–2017, 55.4, 36.5 and 11.4 km² of beach were correspondingly converted into lake, dry land, and paddy field, respectively. Lake underwent the second most drastic change, mainly due to the conversion from beach (55.4 km²) and dry land (4.2 km²). Paddy fields were transformed from 12.8 km² of dry land and 11.4 km² of beach. Most rivers, reservoirs and ponds were converted from beach. All woodlands were converted into paddy fields, and the increase in residential land was mainly due to the conversion from beach (9.7 km²) and dry land (4.6 km²). These results also indicated that apart from the internal transformation, the dominant transition between land use types was from natural wetlands to artificial wetlands.

Table 4. Conversion matrix of land use types from 1980 to 2017 (km²).

TYPE	Paddy Field	Dryland	Woodland	River	Lake	Reservoir and Ponds	Beach	Residential Land	Total
Dry land	12.8	74.2	0.0	0.0	4.2	0.4	7.4	4.6	103.7
Woodland	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
Lake	0.0	0.0	0.0	0.0	1.1	0.0	1.3	0.3	2.8
Reservoir and Ponds	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.3
Beach	11.4	36.5	0.0	4.6	55.4	7.7	106.1	9.7	231.3
Residential land	0.1	1.7	0.0	0.0	0.4	0.4	1.3	4.4	8.4
Total	24.8	112.4	0.0	4.7	61.1	8.6	116.2	19.1	347.0
Net change	+24.8	+8.7	−0.5	+4.7	+58.3	+8.3	−115.1	+10.7	

Figure 4 presents the conversions between wetland and other land use types during the different periods. The decrease in natural wetlands was related with its conversion into dry land, artificial wetlands, and residential land. The proportion of natural wetland converted into dry land was 77.49%, 23.01%, 81.38%, 72.68%, and 23.45% during the periods 1980–1990, 1990–2000, 2000–2005, 2005–2010, and 2010–2017, respectively. In addition, the percentage of natural wetlands lost to artificial wetland and residential land was 0.62% and 21.89%, 72.46% and 5.53%, 12.76% and 5.86%, 2.73% and 24.58%, and 73.02% and 3.53% in the five stages, respectively (Figure 4a). Additionally, compared to artificial wetlands and residential land, the transformed contribution into natural wetlands of dry land was the greatest. The contributions of natural wetlands derived from dry land were 78.62%, 98.61%, 20.34%, 22.46%, and 91.36% in the five stages, respectively (Figure 4b). In addition, the conversion of natural wetlands, dry land, and residential land into artificial wetlands was the major contributor to the increase in artificial wetlands. The proportion of natural wetlands converted to (from) artificial wetlands accounted for 98.09% (67.81%), 100.0% (98.62%), 94.76% (46.93%), 69.83% (63.54%), and 83.57% (46.39%) during the corresponding periods, respectively (Figure 4c,d).

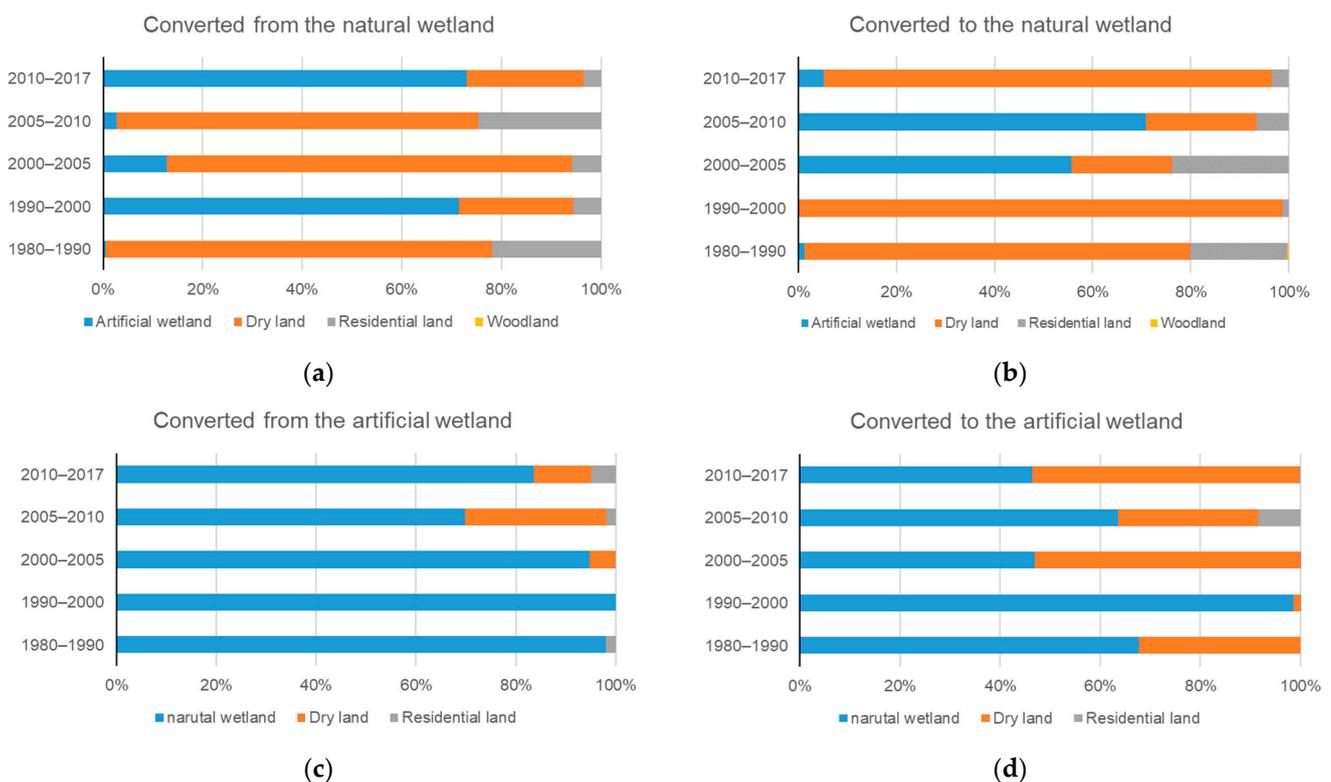


Figure 4. Area contribution of conversion between wetland and other land use types during the periods of 1980–1990, 1990–2000, 2000–2005, 2005–2010 and 2010–2017. (a) Converted from natural wetland; (b) converted to natural wetland; (c) converted from artificial wetland; (d) converted to artificial wetland.

3.3. Driving Forces behind Wetland Landscape Fragmentation

The changes in the wetland landscape patterns in LBYD were mainly affected by both natural and socio-economic factors [2]. Based on the RDA analysis, natural and socio-economic data were used to quantify the drivers behind wetland landscape changes during 1980–2017, and the RDA results for the landscape indices and natural and socioeconomic factors are presented in Figure 5 and Table 5. The primary industrial output (PIO), total population (TP), grain yield (GY), actual evapotranspiration (AET), and annual average temperature (AAT) reflected the relative contributions to wetland landscape fragmentation, and these five factors were selected to analyze the driving forces. As shown in Figure 5, the angles between the landscape indices and the five factors suggest that GY, TP, AAT, and PIO have positive correlations with the number of patches (NP), patch density (PD), edge density (ED), landscape shape index (LSI), Shannon's Evenness Index (SHEI), and Shannon diversity index (SHDI), but are negatively correlated with largest patch index (LPI) and contagion index (CONTAG). The length of the arrow shows that GY and TP made greater contributions to wetland landscape fragmentation than AAT and PIO. Moreover, AET is positively correlated with NP, PD, LPI, and CONTAG, but negatively correlated with ED, LSI, SHEI, and SHDI. These results indicate that the natural and socioeconomic factors have different impacts on the landscape indices. The importance ranking of the five factors was obtained (Table 5), and the order of importance with respect to its influence on LBYD was GY > TP > AET > PIO > AAT. GY and TP showed statistically significant impacts on wetland landscape indices at the 95% level. The contribution of GY and TP accounted for 85.3% and 9.3% of the total contribution, respectively, which indicates that GY and TP are the most important and critical factors affecting landscape changes in LBYD. In comparison with GY, the trends of AET, PIO, and AAT were non-significant and had relatively little impact on landscape changes. These results further demonstrate that compared with natural factors, human activities are the most important driving forces.

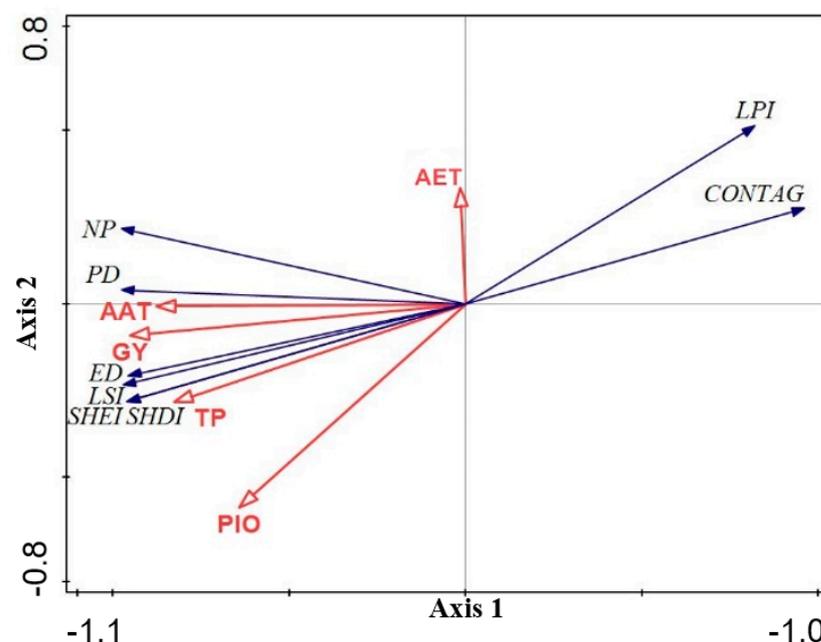


Figure 5. The redundancy analysis results for landscape indices and the natural and social–economic factors. The wetland landscape metrics are represented by black solid arrow connection, and the natural and social–economic factors are represented by red hollow arrow connection.

Table 5. Importance of natural and social–economic factors and associated significance levels.

Name	Importance Rank	Contribution (%)	F-Value	p-Value
Grain yield (GY)	1	85.3	23.2	0.016
Total population (TP)	2	9.3	5.1	0.034
Actual evapotranspiration (AET)	3	4.5	9.8	0.062
Primary industrial output (PIO)	4	0.7	3.8	0.220
annual average temperature (AAT)	5	0.2	<0.1	1.000

4. Discussion

Many previous studies have identified that human activities are the primary factor controlling the evolution of wetland landscape patterns [4,14]. While analyzing the features of wetland landscape patterns, the driving conditions between the effects of human activities and natural climate changes are also quantified. The increases in NP, PD, ED, LSI, SHDI, and SHEI, and the decreases in LPI and CONTAG reflected the trends in wetland landscape fragmentation and the decreases in wetland patch sizes [14]. No complete or detailed information about all natural and socioeconomic factors could be found; therefore, certain variables that could be regarded as proxies for the explanatory factors were selected [49]. For example, TP and RP could be representative of the intensification of agriculture, and a historical event could be considered to be an indicator of the impact of policy reform. Based on this consideration, the seven socio-economic factors (GDP, PIO, SIO, TP, UP, RP, and GY) and three natural factors (AP, AAT, and AET) were used to analyze the shrinkage and fragmentation of wetland landscape. The results showed that the contribution of GY and TP to wetland landscape changes were, respectively 85.3% and 9.3%. This suggested that GY is the most important factor involved in the process of wetland shrinking and fragmentation, and both these variables could be used to understand the aggregated land use changes. These changes resulted from anthropogenic activities, particularly agricultural activities over the past decades [3,28,49]. In addition, with the exception of the internal conversion of natural wetlands, the conversion to or from natural wetlands and artificial wetlands was largely related to dry land. Therefore, agriculture production had the greatest impact on the wetland landscape in LBYD.

As the second largest impact factor, the total population increased by 49.9%, from 758,000 persons in 1980 to 1,136,221 persons in 2017. The rural population accounted for 85.4% of the total population during 1980–2017, and the annual average ratio of rural population to urban population was greater than 10. With the rapid population growth after 1990 (Figure 6a), the concomitant requirement for grain and the reclamation of farmland increased, and this had a severe impact on dry land and wetlands. From 1980 to 2017, the GDP increased by 145.5%, from 0.15 billion RMB in 1980 to 21.84 billion RMB in 2017 at an average annual growth rate of 3.93% (Figure 6b), which indicated that GDP underwent an intensive change. Primary industrial output also experienced rapid growth from 0.09 billion RMB in 1980 to 3.04 billion RMB in 2017 (Figure 6b). Similar to the other undeveloped regions of China, agricultural production was of prime economic interest in LBYD, and it played an important role in the lives of rural residents [49,52].

Converting natural wetlands to farmland requires high-density human input. This was achieved in relation to the household responsibility system in operation in the 1980s, which allowed farmland to be leased to families for a 30-year period, and promoted crop cultivation with modern agricultural machinery and the establishment of large farms [28]. During the same period, local people expanded dry land and paddy fields to increase their incomes and support the growing rural and urban population. Paddy field areas began to appear in 2005, and their area increased by 120.41% from 11.3 km² in 2005 to 24.9 km² in 2017 (Figure 2). Rice growing was more profitable than dry farming; therefore, many farmers converted natural wetland/dry land to paddy fields during the period 2005–2017. Areas of farmland (dry land and paddy field) began to decrease from 1980 to 2000 and then increased sharply in 2005. The reason for the decrease in farmland area in 2000 is that the period from late 1988 to late 1999 was a wet stage. Heavy precipitation events

(from Baoding station) were in June to August of 1988, 1990, 1991, 1994, 1995, 1996, and 1998, and the precipitation in July 1988 especially exceeded 400 mm. Most areas were extensively inundated and there were strong inter-annual fluctuations, which caused the conversion from dry land to wetland [34]. Rapid expansion was simultaneously seen in urban areas, and residential land in towns and villages increased by 127.66% (Table 3). China began to adopt the market economy in 1992, which resulted in major land use changes and the promotion of grain trading [3,49]. However, the GY began to decrease from 640.6 thousand tons in 1999 to 595.4 thousand tons in 2006, which was inconsistent with the significantly increased grain production (22.5%) in China [28] but was partly due to the desiccation stage that began in late 1999 and continued to 2006 [34]. These results showed that economic and population growth were the most prominent underlying forces behind wetland conversion [53]. In addition, the total wetland area was restored from 196.1 km² in 2010 to 215.5 km² in 2017, mainly in relation to the increase in artificial wetlands, suggesting that wetland protection and restoration measures implemented by the local government played a vital role. Therefore, although the reduction in and fragmentation of wetland ecosystems were caused by increased agricultural activities and the rapid population growth, national policies also had a great impact on preserving wetlands in LBYD [14,28].

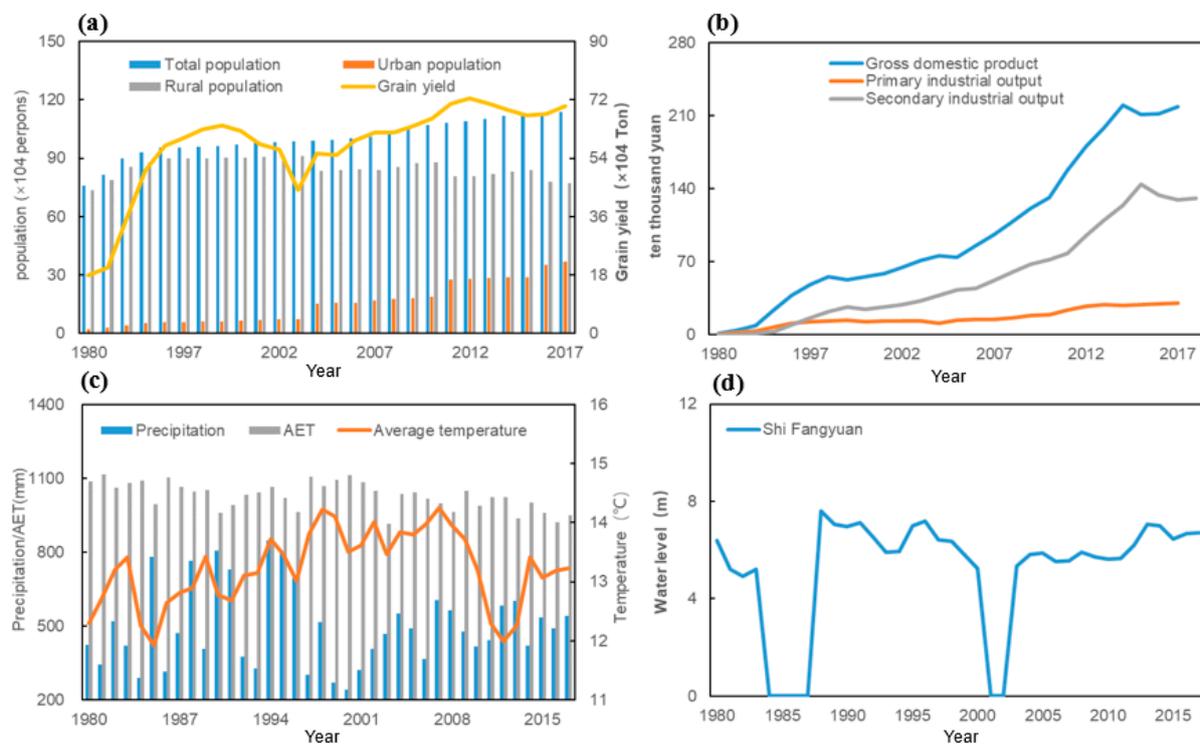


Figure 6. Changes of the environmental variables selected for different periods. (a) TP, UP, RP and GY; (b) GDP, PIO and SIO; (c) AP, AET and AAT; (d) water level.

Compared to agricultural activities, climate was also a factor controlling the dynamics of wetland formation and conversion [4], although the impacts of climate on the wetland landscape were not statistically significant. AET and AAT were the main climatic factors relating to the expansion and contraction of the wetlands, and this result was consistent with numerous studies conducted in other regions within China [3,4,14,25]. Over the 38 years studied, the AAT showed a significant warming trend ($p < 0.05$) (Figure 6c), and a decrease in wind speed in the Haihe River basin was reported. Climate warming and a reduction in wind speed were confirmed to benefit crop growth and promote the conversion from wetlands to farmland [3,54]. LBYD was dried up several times from 1984 to mid-1988 for five years [32,34,55], as confirmed by measurements of annual precipitation of less

than 350 mm in ten years, respectively (Figure 6c) and the water level at Shi Fangyuan hydrologic station during 1984–1988 (Figure 6d). The drier climate directly led to land type conversion from wetland to dry land and residential land [3], causing wetland shrinkage.

Additionally, other studies also documented that the development of reservoir projects and the extraction and utilization of groundwater for domestic use and agricultural irrigation had degraded the wetlands [34,56,57]. Over several decades, the water supply from upstream rivers decreased dramatically, from 1.83 billion m³ in the 1950s to 0.02 billion m³ in 2000 [34,58]. Additionally, six large reservoirs (Hengshanling, Koutou, Wangkuai, Xidayang, Longmen, and Angezhuang) and twelve medium-sized reservoirs in the upstream areas were built in succession to prevent flooding and provide irrigation since the 1950s [34]. Additionally, these changed rainfall infiltration conditions and created a dry lake in the Baiyangdian watershed since the 1980s [56]. After the construction of these reservoirs, runoff into LBYD declined significantly, which then altered the hydrological processes [58]. Wetland ecosystems are particularly sensitive to hydrological changes, and the water level is an important factor for controlling the formation and development of wetland vegetation [59]. In addition, water diversion also has a profound impact on the maintenance processes of wetland landscape patterns [34].

Certain protective measures have now been applied to mitigate water consumption stress, provide for ecological demands, and weaken the wetland damage trend. For example, to relieve dryness and repair wetland functions, water was transferred 24 times from upstream reservoirs and external watersheds (such as the Yellow River) to LBYD during 1991–2015, with a total volume of approximately 1.45 billion m³. Such water division projects are crucial for maintaining ecosystem services (such as wildlife habitats, pollution dilution, and recreation) in LBYD wetlands; however, the action can only temporarily alleviate water shortage problems.

Fortunately, the local government gave more attention to the loss and fragmentation after the establishment of the Xiongan New District and placed great importance on wetland ecosystem protection [60]. Certain ecological projective measures were implemented in 2002. For example, the LBYD Wetland Nature Reserve Region was established in 2002 to preserve the freshwater wetland ecosystem, especially for rare and endangered species [34]. Additionally, the LBYD Wetland Reserve Management Office was established in 2004 to include four core areas. Furthermore, the LBYD Ecological Environment Governance and Protection Plan (2018–2035) was promulgated, and various protection projects are planned to restore and protect ecological system. Due to the climate conditions and the limited availability of water resources in arid and semi-arid regions, the government needs to propose relevant protection policies to deal with the impact of climate change and land use changes on wetlands and water resources. Before the policy is proposed, it is necessary to conduct a general investigation into wetland resources to monitor dynamic changes and provide real and effective basic information about all aspects of the conditions. In addition, the restoration and protection of wetlands requires consistent attention from both the government and the public.

5. Conclusions

The characteristics of wetlands in LBYD were analyzed using six cloud-free Landsat remote sensing images from 1980 to 2017. The results showed that the total wetland area decreased from 234.4 km² in 1980 to 215.5 km² in 2017, while the area of natural wetlands decreased by 52.1 km² and the artificial wetland area increased by 33.2 km². The lost wetland areas were mainly converted into day land and residential land. The features of the transition matrix of land use types, and the changes in several landscape metrics, illustrated the shrinkage and fragmentation of the wetland landscape and the expansion of farmland and residential land. The driving forces behind wetland landscape fragmentation were analyzed based on a redundancy analysis, and the results showed that grain yield and total population were the major factors driving wetland fragmentation in our study area under the influence of increased agricultural activities and rapid population growth,

climate change, and national policies. These results were obtained in a particular location, but they can be extrapolated to other similar regions. The conclusions made in this study can assist in the formulation of governmental policies to conduct the ecologically friendly and sustainable utilization of land resources.

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