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Evolution of landscape dynamics in the Yangtze River Delta from 2000 to 2020

Zhe Chen Zhou and Jun Wang*

Department of Landscape Planning and Design, East China University of Science and Technology, No.130, MeiLong Rd, Shanghai, China
*Corresponding author. E-mail: denief@163.com, wangjun81@ecust.edu.cn

ZCZ, 0000-0001-9801-2218; JW, 0000-0003-0687-6911

ABSTRACT

Based on the 2000–2020 land cover data, the landscape dynamics and landscape pattern index are used to study the landscape pattern changes of the Yangtze River Delta. The results show that with the growth of built-in land area, the dominance of natural landscape in the Yangtze River Delta is gradually weakened. From the perspective of the overall landscape pattern, the degree of landscape fragmentation in this area is increasing, and the degree of landscape connectivity and aggregation are decreasing in varying degrees. The regional landscape is developing toward homogeneous distribution and increasing complexity. At the same time, from the perspective of classified landscape, the spatial distribution of various landscapes shows a strong correlation between climate and landform. Through comparative analysis, this study puts forward that the development of the Yangtze River Delta needs to pay attention to maintaining the integrity of the regional dominant landscape and paying attention to the diversity and connectivity of the natural landscape with high ecological service value.

Key words: landscape index, landscape pattern, spatial-temporal evolution, Yangtze River Delta

HIGHLIGHTS

- From the perspective of overall landscape pattern, this paper studies landscape fragmentation, connectivity, and aggregation.
- The study found that the spatial distribution of various landscapes showed a strong correlation between climate and landform.
- The study found that the change degree of landscape structure such as forest land and wetland with high ecological service value.

1. INTRODUCTION

China's rapid urbanization process in the past 40 years has increased the urbanization rate from 17.9% in 1978 to 60.6% in 2019 (Liu & Ye 2020). Rapid urbanization, while meeting the growing needs of the people for a better life, has inevitably caused a series of ecological and environmental problems due to the rough and disorderly urbanization and the rapid expansion of land for construction (Bai *et al.* 2014). The encroachment and destruction of the natural bedrock of the region caused by human activities further affect the ecological function of the region due to the changes of the regional landscape pattern, which resulted in the ecological landscape differentiation on the territorial spatial scale of the country. Human activities are also the main cause of global warming, while land-use changes are an intuitive manifestation of the environmental impact of human activities (IPCC 2014; Mundaca & Markandya 2016), and changes in the types of surface cover in the region can affect the structure, function, and ecological processes of ecosystems (Zhao *et al.* 2004, 2013; Priess *et al.* 2007; Ricketts *et al.* 2008). Different types of surface cover have corresponding ecological effects, such as vegetation as a link to natural factors that can respond to climate change and further slow it down (Mahmood *et al.* 2014; Wang *et al.* 2015), wetlands that can regulate climate, conserve water sources and maintain biodiversity (Ramachandra *et al.* 2005), and waters that are highly correlated with hydrological processes, often coupled with climatic conditions, can have an impact on the intensity and frequency of extreme weather events (Chang *et al.* 2018; Ekwueme & Agunwamba 2020; Hamid *et al.* 2021). The disorderly expansion of built-in land will further lead to environmental risks, extreme weather, geological disasters, urban flooding, and other problems (Liu *et al.* 2021; Qiu *et al.* 2016; Jaiswal *et al.* 2017; Shan *et al.* 2019; Kavianpour *et al.* 2020; Yan *et al.* 2021). Therefore, studying the interaction law of regional construction and development with regional ecological functions and ecological processes from the perspective of territorial spatial planning is of great significance for guiding the urban development and even urban agglomerations.

Landscape patterns are the distribution patterns and composite structures of landscape units in the space in different numbers, types, densities, and configurations (Turner 1990; Hu 2003), which are influenced by both natural and anthropogenic factors, which in turn restrict various ecological processes, thus further influencing the social and economic aspects of the region (Hao *et al.* 2017; Hashem *et al.* 2019). Quantitative studies of landscape patterns often use the landscape pattern index directly related to land use (Alberti 2005), or evaluate the resources and environmental status of the research area (Guiamel & Lee 2020) and forecast the future development (Gao *et al.* 2021; Zango *et al.* 2021) by various kinds of assessment and prediction model. The scope of study includes watersheds (Nuanchan *et al.* 2015; Li *et al.* 2019), deserts (Duan *et al.* 2012), wetlands (Gong *et al.* 2011), etc., delimited by ecological scope, as well as provinces and municipalities delimited by administrative or territorial scope, and countries (Zhao *et al.* 2007; Cirelli & Vineri 2014; Burgalassi & Luzzati 2015; Li & Qi 2019). The research content extends to urban structure (Yang *et al.* 2017), urban flooding (Velasco *et al.* 2014; Philip *et al.* 2021), low-carbon cities (Piao *et al.* 2009; Li & Zhou 2021), and urban climate (Suder & Szymanowski 2014). Urban expansion, a process of human-driven disturbance, has an increasingly significant impact on regional landscape patterns and ecological functions and processes (Zeng & Jiang 2000). The corresponding landscape patterns changes are also greatly influenced by climate change, geographical conditions, socio-economic conditions, regional population, and other factors (Zhang *et al.* 2021). Yang used runoff data from eight hydrologic stations in the upper reaches of the Yangtze River to study the spatial-temporal characteristics in runoff change between 1951 and 2013, and the results showed that runoff decreased at a rate of 7.6 km^3 per decade during the study period, of which climate change was the main cause of this phenomenon. Yang *et al.* (2021) studied the effects of climate change on runoff in the upper reaches of the Yangtze River over the next 30 years by coupling the Statistical Downscaling Model (SDSM) and the Soil and Water Assessment Tool (SWAT). The results showed that with the increase of emissions, the maximum temperature and minimum temperature in the study area increased and the annual runoff showed an upward trend. Wu *et al.* (2020) used the land use data of Shenzhen for nearly 20 years to study the spatiotemporal changes in the landscape pattern of the region using the landscape pattern index and the landscape transfer index, and analyzed the main drivers of land expansion in the region, proposed that the urbanization process should maintain as much as possible the landscape diversity of ecological areas and urban green spaces. Li & Qi (2019) quantitatively depict the evolution of the landscape pattern over the whole of China over the past 40 years based on the land use data, while analyzing the spatiotemporal dimensional influence of the urbanization process on the evolution of the landscape pattern. The results show that the intensity and frequency of human activities' interference with the landscape have been increasing for 40 years.

From the above-mentioned research progress, we can learn that the research content of landscape pattern covers climate change, environmental pollution, extreme weather, ecological process, etc. The research area also covers many scales such as land, ecological area, and individual city and study areas related to landscape patterns cover a variety of scales such as territory, ecological zones, and individual cities. However, the regional ecological characteristics and the impact of disturbances on regional ecology reflected in different research scales may vary, due to the scale effects and research methods. National-scale landscape pattern research often cannot reflect the internal connections of urban ecosystems in an all-round way due to the large scale of the research grid, while single-city-scale research lacks the expression of regional ecosystem heterogeneity. Besides, it is difficult for the ecological zone-scale research to reflect the driving or restricting effect of regional socio-economic factors on the evolution of landscape patterns. Therefore, it is still necessary to study the overall and local landscape heterogeneity in the evolution of landscape patterns under multi-scale synthesis, in order to further combine regional socio-economic data under administrative divisions to carry out research.

With the help of ArcGIS and FRAGSTATS software, this paper quantitatively studies the temporal and spatial differentiation and evolution law of landscape pattern in the region of the Yangtze River Delta Urban Agglomeration in 2000–2020. This paper mainly discusses the connectivity and aggregation of the landscape in the Yangtze River Delta from the perspective of the overall landscape pattern, and discusses the characteristics of the regional landscape. At the same time, from the perspective of classified landscape, this paper discusses the correlation between the spatial distribution of various landscapes and climate and landform. This paper puts forward the important significance of maintaining the diversity and continuity of high ecological landscape in the Yangtze River Delta.

2. METHODOLOGY

2.1. Research area overview

The Yangtze River Delta region includes three provinces as Jiangsu, Zhejiang, and Anhui provinces and one city as Shanghai municipality (Figure 1), with a total scale of 350,000 km^2 and contains both subtropical monsoon climate and temperate monsoon climate types. The region is economically developed and densely populated and is the most economically powerful, densely populated, and densely populated area with the highest urban density in China (Li & Gu 2018). By the end of 2019, the resident population reached 235 million, accounting for 16.76% of the national population in the same period, the urbanization rate reached 67.78%, and the regional GDP reached 23.73 trillion RMB, accounting for 23.94% of the national GDP.

2.2. Data information and pre-processing

The spatial and temporal scope included in this study is the Yangtze River Delta region of China from 2000 to 2020, with a 10-year time section for data extraction and research analysis. The data sources used are:

Three phases of the Yangtze River Delta surface cover raster data (2000, 2010, and 2020) with a spatial resolution of 30 m×30 m, from the Ministry of Natural Resources of China (http://www.globallandcover.com/defaults.html?src=/Scripts/map/defaults/browse.html&head=browse&type=data). Since the proportion of landscape types such as bare land and tundra within the study area is very small, the surface cover types in the 0 study area are reclassified into six landscape types: cropland, forest land, grassland, wetland, water body, and built-in land.

The 2019 administrative division data of the provinces and cities included in the Yangtze River Delta region were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/).

2.3. Landscape degree of the dynamics model

The landscape degree of dynamics can reflect the trend of regional landscape change and its dramatic degree, and in order to fully reflect the spatial and temporal scale changes of various landscape types in the study area, the degree of dynamics model and the relative degree of dynamics model were introduced (Wang *et al.* 2017).

$$K = \frac{U_b - U_a}{TU_a} \times 100\% \tag{1}$$

where K is the degree of dynamics of a landscape type; U_a and U_b are the areas of a landscape type at the beginning and end of the study period, respectively; and T is the time span of the study.

$$R = \frac{(K_b - K_a)/K_a}{(C_b - C_a)/C_a} \tag{2}$$

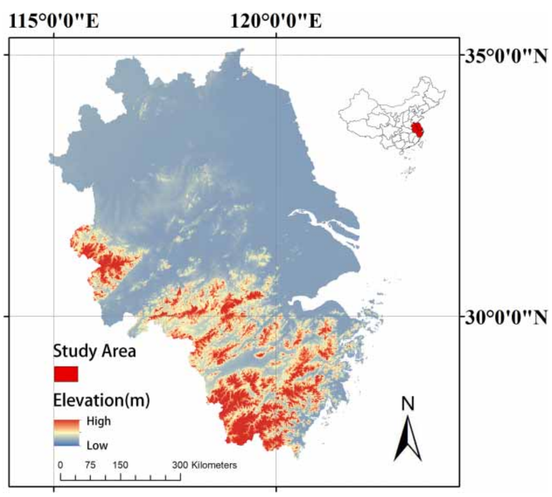

Figure 1 | Details of the study area.

where R is the relative degree of dynamics of a landscape type; K_a and K_b are the area of a landscape type in a region at the beginning and end of the study period; and C_a and C_b are the area of a landscape type in the whole study area at the beginning and end of the study period, respectively.

2.4. Selection and calculation of landscape index

In this study, the raster data reflecting the land use form is selected as the basis of the landscape index calculation. Considering the limitation of calculation volume and the accuracy and continuity of landscape type discrimination, the raster data of ground cover data were resampled to a grid with a resolution of 100 m × 100 m in ArcGIS, retaining the landscape plaques of villages, urban river corridors, waterfront green areas, and other land types within the study site as accurately as possible while reducing the calculation volume. The landscape pattern index was calculated using the landscape pattern analysis software FRAGSTATS 4.2 to analyze the landscape pattern characteristics of the study area in different areas and at different times.

According to the landscape type and scale, the landscape pattern index can be divided into three classes as plaque, Class, and Land, in order to effectively quantify the spatial and temporal variation of various landscape types in the study area, as well as the changing characteristics of the overall landscape system in the Yangtze River Delta region. With reference to related studies (Li *et al.* 2004; Wang *et al.* 2017), 11 landscape indices were selected in this paper, namely plaque type area, plaque number, plaque density, edge density, average plaque area, bonding index, spreading index, aggregation index, fragmentation index, SHDI diversity index, and SHDI evenness index in the two classes of class and landscape (Table 1).

3. RESULTS AND DISCUSSION

3.1. Landscape dynamics in the study area

In this study, with the help of ArcGIS, the dynamic area and proportion of various types of landscapes in the study area were counted (Table 2 and Figures 2–4), and the dynamic changes of various types of landscapes in the Yangtze River Delta, the three provinces and one city, and the overall region were calculated using the landscape degree of dynamics model (Tables 3 and 4), and the results showed below.

From the overall area dynamics of the study area, cropland has always been the dominant landscape in the Yangtze River Delta as a whole, accounting for 56, 54, and 49% of the landscape, respectively, in the past two decades, all exceeding the second largest and stable proportion of 27% of the woodland landscape. Wetland landscape area is the smallest, with the proportion in 20 years at about 1%. The proportion of land used in woodland, grassland, wetland, and waters in the study area did not change by more than 1% during the study period. The main changes in surface cover are reflected in the transfer of cropland to built-in land, which is closely related to the rapid economic development of the Yangtze River Delta region. The spatial variation of the internal landscape of the study area is obvious, Shanghai, as the area with the highest economic strength of the Yangtze River Delta urban group, has the fastest decline in the proportion of cropland, accounting for 57, 46, and 38%, respectively, in the 3 years, while the proportion of built-in land area is 23, 34, and 39%, and the dominant landscape has been transformed from cropland to built-in land in 2020. The area change of woodland, grassland, and wetland was about 1%, and the proportion of waters landscape decreased by 3%. Jiangsu Province has the highest proportion of cropland landscape, but the proportion decreased from 73 to 63%, of which the rate of decline between 2010 and 2020 reached 8%, mainly for built-in land. Zhejiang Province's dominant landscape has always accounted for more than 50% of the woodland, with only 1% change in 20 years, the main landscape transformation process takes place between cropland and built-in land. The proportion of landscape composition in Anhui Province is similar to that of the Yangtze River Delta as a whole, with no significant changes in the proportion of each type of landscape during the study period. The landscape dynamics of the provinces and cities in the study area are unified, showing the trend of the flow of cropland to built-in land. The proportion of landscape area in various regions also shows the characteristics of comprehensive influence of landform, climate, and economic development. For example, located south of the Qinling-Huaihe River line, the climate type is the subtropical monsoon climate of Zhejiang Province, southern Anhui Province, with a relatively high forest landscape. The terrain is mainly plain in Jiangsu Province and the northern plain area of Zhejiang Province, with a high proportion of cropland landscape. Shanghai, which has the most active economic activities and the highest degree of opening up to the outside world in the Yangtze River Delta region, has a high proportion of built-in land area, which has been transformed into dominant landscape in 2020.

Table 1 | Landscape pattern index

Landscape Pattern Index	Index Name	Index Range and Meaning
CA	area of plaques type, unit: hm^2	CA > 0, reflecting the dominant plaques and inferior plaques type in the landscape
NP	number of plaques, unit: piece	NP > 0, reflecting the number of plaques of the type
PD	plaques density, unit: piece/100 hm^2	PD > 0, reflecting the number of certain landscape plaques per unit area; if the PD value becomes larger, the landscape tends to be composed of mostly smaller plaques
ED	edge density, unit: m/hm^2	ED ≥ 20, an indicator of plaques shape, indicating the degree of landscape fragmentation; the larger the ED value, the greater the degree of landscape fragmentation and the more dispersed the layout
AREA_MN	average plaques area, unit: hm^2	AREAMN > 0, reflecting the fragmentation degree of the type landscape; the smaller the value, the higher the fragmentation degree of the plaques, and the landscape tends to be composed of mostly smaller plaques
COHESION	cohesion index	0 < COHE SION < 100, reflecting the degree of connectivity of the class landscape; the higher the value, the higher the degree of aggregation or interconnectivity of the class landscape, and vice versa, the smaller
CONTAG	spreading index	O < CONTAG ≤ 100, reflecting the connectivity of the dominant landscape; the larger the value, the higher the integrity of the landscape pattern
AI	aggregation index	O ≤ AI ≤ 100, reflecting the degree of aggregation of plaques; if the AI value becomes smaller, the landscape tends to be composed of smaller plaques with uniform distribution; if the AI value becomes larger, the landscape is composed of a smaller number of large plaques or highly connected between plaques
DIVISION	division index	0 ≤ DIVISION < 1, reflecting the fragmentation degree of the landscape; when the value is 0, the landscape is composed of single plaques; the larger the value, the higher the degree of fragmentation of the landscape by different plaques
SHDI	SHDI diversity index	SHDI ≥ 0, reflecting the heterogeneity of the landscape; the higher value indicates the increase of plaque types or the tendency of the plaques in the landscape to homogenize the distribution
SHEI	SHEI evenness index	O ≤ SHEI ≤ 1, indicating the maximum possible diversity of the landscape under a certain landscape abundance; the higher the value, the more stable the regional ecosystem tends to be; the lower the value; the lower the regional ecosystem stability accordingly

Note: The formula for calculating a specific landscape index refers to the Fragstats 4.2 help file.

From the viewpoint of landscape dynamics in the Yangtze River Delta, the landscape types showing an increasing trend are grassland, waters, and built-in land, while those showing a decreasing trend are cropland, woodland, and wetland. In the overall landscape of the study area, the landscape dynamics of built-in land is the largest, reaching 4.58% during 2010–2020, the main landscape transfer direction is the conversion of cropland to built-in land, with a conversion area of over 20,000 km^2, with the main driver of landscape transfer is human activity. The increase of waters landscape is also related to water resources development, flood, and other reasons, such as the transfer of large areas of cropland to the waters landscape in the water source area of the South-North Water Transfer Project, the construction of reservoirs directly leads to the increase of water area (Kong *et al.* 2018). Woodland landscape dynamics are the smallest, with only 0.04% between 2000 and 2020. The largest decline in landscape activity was in wetlands, which fell by 1.29% from 2000 to 2020. The area of woodland and wetland with high ecological service value in the study area is decreasing continuously, and the overall landscape dynamics in the Yangtze River Delta is strongly disturbed by human activity during 2000–2020.

From the perspective of the relative dynamics of the landscape within the study area, among the landscape types accounting for more than 10% of the total area in 2020, only the dynamic direction of Shanghai's waters landscape is opposite to that of the Yangtze River Delta as a whole, and the relative dynamic attitude of the landscape is −1.11, which continues to decrease under the circumstances of the increase of the overall water area of the Yangtze River Delta region. The main reason is the increase of flood disasters in the Yangtze River basin under the background of climate change, and the

Table 2 | The scale and proportion of various landscapes in the study area

Year	Landscape type	Yangtze River Delta Area (km^2)	Yangtze River Delta Percentage	Shanghai Area (km^2)	Shanghai Percentage	Jiangsu Area (km^2)	Jiangsu Percentage	Zhejiang Area (km^2)	Zhejiang Percentage	Anhui Area (km^2)	Anhui Percentage
2000	Cropland	197,428	0.56	4,474	0.57	75,096	0.73	34,644	0.34	83,223	0.59
	Woodland	96,572	0.27	2	/	2,202	0.02	57,414	0.56	36,952	0.26
	Grassland	7,464	0.02	18	/	433	/	4,074	0.04	2,946	0.02
	Wetland	2,048	0.01	126	0.02	814	0.01	251	/	859	0.01
	Waters	23,903	0.07	1,484	0.19	13,396	0.13	2,741	0.03	6,284	0.04
	Built-in land	25,532	0.08	1,807	0.23	10,330	0.10	3,650	0.03	9,748	0.07
2010	Cropland	191,132	0.54	3,682	0.46	72,370	0.71	33,090	0.32	81,991	0.59
	Woodland	95,907	0.27	10	/	2,108	0.02	57,227	0.55	36,566	0.26
	Grassland	7,767	0.02	21	/	728	0.01	3,947	0.04	3,078	0.02
	Wetland	1,723	0.01	231	0.03	614	0.01	350	/	529	/
	Waters	24,413	0.07	1,374	0.17	13,386	0.13	2,847	0.03	6,812	0.05
	Built-in land	32,859	0.09	2,738	0.34	13,171	0.13	5,907	0.06	11,043	0.08
2020	Cropland	175,001	0.49	3,107	0.38	64,642	0.63	27,732	0.27	79,519	0.57
	Woodland	95,895	0.27	101	0.01	2,447	0.02	57,238	0.55	36,116	0.26
	Grassland	7,748	0.02	111	0.01	673	0.01	3,858	0.04	3,106	0.02
	Wetland	1,519	0.01	250	0.03	584	0.01	148	/	540	/
	Waters	26,262	0.07	1,321	0.16	14,075	0.14	4,220	0.04	6,646	0.05
	Built-in land	47,902	0.14	3,189	0.39	20,201	0.20	10,432	0.10	14,082	0.10

Note: Values less than 0.01 in the table are omitted by /.

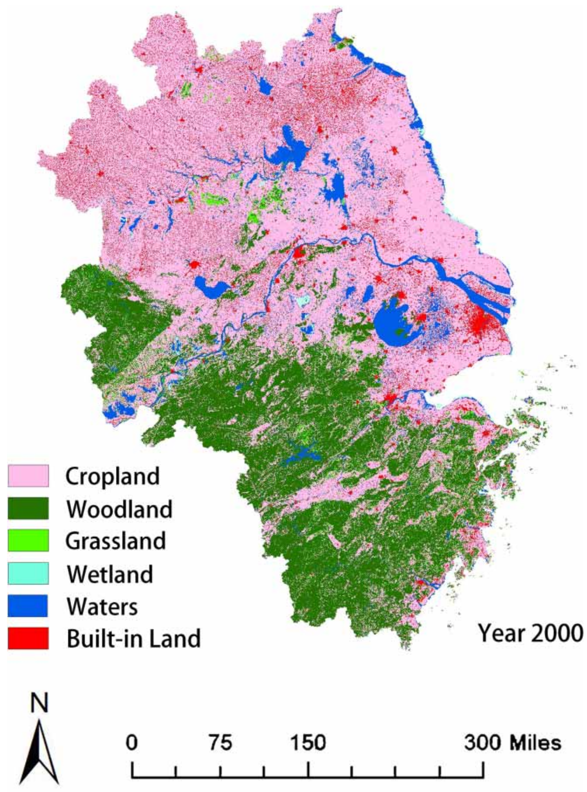

Figure 2 | Surface cover in the Yangtze River Delta region in 2000.

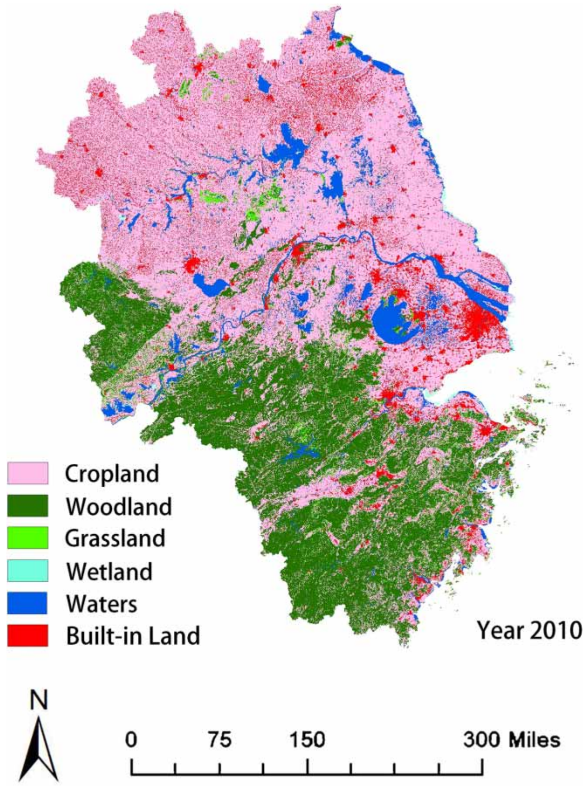

Figure 3 | Surface cover in the Yangtze River Delta region in 2010.

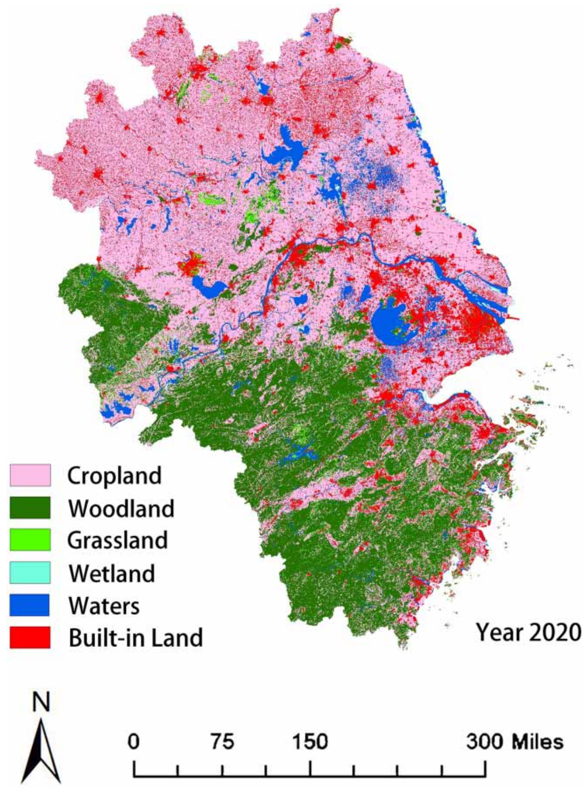

Figure 4 | Surface cover in the Yangtze River Delta region in 2020.

Table 3 | Landscape dynamics in the Yangtze River Delta

Research Scope	Landscape Type	2000–2010 Area Change (km²)	2000–2010 Degree of dynamics (%)	2010–2020 Area Change (km²)	2010–2020 Degree of dynamics (%)	2000–2020 Area Change (km²)	2000–2020 Degree of dynamics (%)
The Yangtze River Delta	Cropland	−6,296	−0.32	−16,131	−0.84	−22,427	−0.57
	Woodland	−665	−0.07	−12	−0.01	−677	−0.04
	Grassland	303	0.41	−19	−0.02	284	0.19
	Wetland	−325	−1.59	−204	−1.18	−529	−1.29
	Waters	510	0.21	1,849	0.76	2,359	0.49
	Built-in land	7,327	2.87	15,043	4.58	22,370	4.38

Table 4 | Relative dynamics of the landscape in the three provinces and one city in the study area

Research Scope	Landscape Type	2000–2010 Area Change (km²)	2000–2010 Relative degree of dynamics	2010–2020 Area Change (km²)	2010–2020 Relative degree of dynamics	2000–2020 Area Change (km²)	2000–2020 Relative degree of dynamics
Shanghai	Cropland	−792	5.55	−575	1.85	−1,367	2.69
	Woodland	8	−580.88	91	72,729.48	99	−7,061.03
	Grassland	3	4.11	90	−1,751.95	93	135.79
	Wetland	105	−5.25	19	−0.69	124	−3.81
	Waters	−110	−3.47	−53	−0.51	−163	−1.11
	Built-in land	931	1.80	451	0.36	1,382	0.87
Jiangsu	Cropland	−2,726	1.14	−7,728	1.27	−10,454	1.23
	Woodland	−94	6.20	339	−1,285.28	245	−15.87
	Grassland	295	16.78	−55	30.88	240	14.57
	Wetland	−200	1.55	−30	0.41	−230	1.09
	Waters	−10	−0.03	689	0.68	679	0.51
	Built-in land	2,841	0.96	7,030	1.17	9,871	1.09
Zhejiang	Cropland	−1,554	1.41	−5,358	1.92	−6,912	1.76
	Woodland	−187	0.47	11	−1.54	−176	0.44
	Grassland	−127	−0.77	−89	9.22	−216	−1.39
	Wetland	99	−2.49	−202	4.87	−103	1.59
	Waters	106	1.81	1,373	6.37	1,479	5.47
	Built-in land	2,257	2.15	4,525	1.67	6,782	2.12
Anhui	Cropland	−1,232	0.46	−2,472	0.36	−3,704	0.39
	Woodland	−386	1.52	−450	98.36	−836	3.23
	Grassland	132	1.10	28	−3.72	160	1.43
	Wetland	−330	2.42	11	−0.18	−319	1.44
	Waters	528	3.94	−166	−0.32	362	0.58
	Built-in land	1,295	0.46	3,039	0.60	4,334	0.51

implementation of the policy of 'returning farmland to lake' after the great flood in 1998, which led to an increase in the overall water area of the region (Haas & Ban 2014). There is no complete river and lake basin system in Shanghai, and the waters landscape is more affected by human activities such as agricultural development and reclamation. The relative dynamic magnitude of all types of landscapes in Zhejiang and Anhui provinces is small, only the woodland landscape area in Anhui Province decreases by 450 km^2 from 2010 to 2020, and the relative dynamic attitude reaches 98.36, and the landscape shift basically presents the same as that of the Yangtze River Delta as a whole. Shanghai and Jiangsu show larger relative dynamic attitude of two types of landscapes, woodland and grassland, because the overall area share is about 1%, and these two types of landscapes in the Yangtze River Delta overall region base is high and dynamic attitude is not high, so the relative dynamic attitude value is higher, but also it may be related to the regional development of green space system, country park construction, and the increase of woodland and grassland landscape. The relative dynamic attitude of wetland landscape in Jiangsu, Zhejiang, and Anhui provinces is greater than 0, which shows that the wetland landscape in the three provinces has decreased to different degrees. Only the wetland area of Shanghai has been increasing continuously, there are more wetland patches in the mouth of the Yangtze River on the south side of Chongming Island, the landscape of natural wetlands, marshes is still shrinking, the main increase in area comes from artificial wetlands (Jia *et al.* 2020), so it is necessary to strengthen the protection and attention of natural wetlands in the basin.

3.2. Study area landscape pattern index

3.2.1. Changes in the landscape pattern index of the study area landscape levels

In this study, with the help of the landscape pattern index analysis method, the landscape rank landscape pattern index (Table 5) was calculated for the three periods (2000, 2010, and 2020) in the study area, and quantitative analysis was conducted on the landscape index to determine the overall change characteristics of the study area landscape, and the results shown below.

From the viewpoint of the spreading index of the landscape classes in the study area, the overall dominant landscape connectivity of the Yangtze River Delta experienced two processes: a slow decline from 2000 to 2010 and a rapid decline from 2010 to 2020. The integrity of the overall pattern continues to decline, and the restriction and diffusion of landscape systems on landscape flows such as non-point source pollution in the region decreases. Although the overall trend of the spreading index of the provinces and cities in the study area is the same as that of the Yangtze River Delta landscape, Shanghai experienced a dominant landscape turnover between 2010 and 2020. The expansion and filling development of urban areas in 2000–2010 increased the connectivity of the dominant landscape of cropland, while the expansion and development of satellite cities for built-in land in 2010–2020 decreased significantly in the corresponding spread index, the overall index showed an increase and then a decrease. Jiangsu had the highest spreading index, which was related to the high proportion of dominant landscape types in the region. Although the dominant landscape of woodland in Zhejiang Province had less degree of dynamics, the spreading index decreased between 2010 and 2020, partly indicating that human activities were cutting woodland landscape systems in the area and that biological habitats were in a tendency to fragment. Anhui Province has the highest overall landscape motility similar to the Yangtze River Delta. However, the spread index is the smallest in the study area, this phenomenon and Anhui Province across the Qinling-Huaihe River dividing line, climate and vegetation system north-south differentiation correlation, spread index first rise and fall, and the integrity of the dominant landscape fluctuates significantly.

From the aggregation and division indices, the overall aggregation index of the Yangtze River Delta accelerated the decline, and the division index accelerated rise. The connectivity of the overall landscape system in the study area experienced a slow decline from 2000 to 2010 and an accelerated decline from 2010 to 2020, with an overall increase in landscape plaques or a decrease in the size of large plaques. The landscape layout of built-in land and cropland in Shanghai is more compact, and the

Table 5 | Landscape level landscape index of the study area in 2000, 2010, and 2020

Research Scope	Year	CONTAG	AI	DIVISION	SHDI	SHEI
The Yangtze River Delta	2000	63.7872	87.8904	0.8517	1.2071	0.5242
	2010	63.0079	87.7342	0.8594	1.2355	0.5366
	2020	60.9686	87.0675	0.8817	1.3002	0.5647
Shanghai	2000	61.2934	89.7258	0.8060	1.1378	0.5847
	2010	62.8367	90.1718	0.8844	1.1734	0.5643
	2020	59.0226	88.4720	0.9206	1.2598	0.6058
Jiangsu	2000	73.4194	91.3026	0.7043	0.8913	0.3871
	2010	70.7047	90.9461	0.7216	0.9384	0.4271
	2020	67.3726	89.7119	0.7820	1.0391	0.4729
Zhejiang	2000	63.7174	85.1235	0.8958	1.1446	0.4971
	2010	63.0449	85.1215	0.8985	1.1754	0.5105
	2020	58.7177	83.9212	0.9028	1.2423	0.5654
Anhui	2000	59.7396	87.3413	0.7502	1.1005	0.5655
	2010	61.7309	87.1768	0.7609	1.1184	0.5378
	2020	58.1591	87.4109	0.7781	1.1549	0.5935

proportion of cropland in Jiangsu is the highest and the continuity is good in each research area, so the aggregation index of the two places is higher. However, the proportion of cropland and built-in land in Shanghai is homogeneous, so the division index continues to rise, while the dominant landscape area of Jiangsu Province is high, so the division index is low. Zhejiang Province has complex terrain, misplaced woodland distribution and cropland, the lowest aggregation index, high division index, and no obvious change. Anhui Province, because the proportion of various types of landscape is similar to the overall structure of the Yangtze River Delta, the evolution is similar to the Yangtze River Delta, although the overall landscape aggregation in 2020 rebounded, but the change is not obvious.

From the diversity index, the SHDI diversity index of the Yangtze River Delta as a whole and the three provinces and one city in the interior gradually increased between 2000 and 2020, which indicates various types of landscape plaques were tended to be evenly distributed in space. This phenomenon is related to the transformation of cropland to built-in land implied by urban expansion in various regions, which also reflects the decrease of the area of large natural patches such as the Taihu Lake, the Gaoyou lake, the Hongze Lake, and its surrounding wetland and forest area. The SHEI evenness index shows fluctuating growth in each region, and the dominant type of dominant landscape in each region decreases with the advancement of urban construction process, but the capacity of landscape diversity increases. In addition, the diversity index of Jiangsu province is significantly lower than other regions in each data set, which is closely related to the high proportion of dominant landscape of cropland in Jiangsu province, and likewise affects the spreading index, aggregation index, etc. Regional native large-scale natural plaques often play an important regulatory role in the local climate environment, playing the role of ecological source, so in the development of urbanization need to strengthen the protection of large-scale natural plaques (Jiang *et al.* 2006; Zhao *et al.* 2007).

3.2.2. Changes in the landscape pattern index of the category levels in the study area

On the basis of interpreting the overall landscape change characteristics of the study area, due to the great difference in ecological service values of each type of landscape, in order to analyze the spatial and temporal change characteristics of each type of landscape, the study then calculates the category level landscape pattern index of the study area for three periods (2000, 2010, and 2020) (Tables 6–10), the analysis results shown below.

From two types of landscapes with human-led changes, cropland, and built-in land, there is a high degree of similarity in the evolution patterns of each region. As extreme weather disasters deepen the contradiction between limited land resources and rapidly increasing population, arable land reclamation and urban expansion have caused great damage to the regional ecological environment, climate-policy-reclamation often forms an organic chain (Gao & Yi 2012; Shi & Shi 2015). The spatial distribution of cropland shows the characteristics of dense north and sparse south, with a continuous decrease in the area of

Table 6 | Category levels landscape indices in the Yangtze River Delta in 2000, 2010, and 2020

Year	Landscape type	NP	PD	ED	AREA_MN	COHESION
2000	Cropland	72,529	0.2037	19.2067	272.2061	99.9602
	Woodland	62,813	0.1764	11.3599	153.7455	99.9135
	Grassland	198,374	0.5572	4.9214	3.7626	81.0884
	Wetland	3,212	0.009	0.3400	63.7718	96.0650
	Waters	103,825	0.2916	4.3237	23.0230	98.8361
	Built-in land	108,664	0.3052	7.7900	23.4963	93.1434
2010	Cropland	81,403	0.2286	19.4719	234.7975	99.9573
	Woodland	78,831	0.2214	11.5891	121.6619	99.9107
	Grassland	209,759	0.5891	5.1256	3.7030	81.4584
	Wetland	2,669	0.0075	0.2801	64.5399	95.2765
	Waters	79,126	0.2222	3.8609	30.8530	98.8291
	Built-in land	106,945	0.3004	8.2615	30.7255	95.0410
2020	Cropland	97,456	0.2737	20.3110	179.5692	99.9494
	Woodland	69,683	0.1957	11.2715	137.6158	99.9096
	Grassland	200,261	0.5625	4.9073	3.8690	81.3086
	Wetland	2,907	0.0082	0.2708	52.2122	94.0639
	Waters	71,937	0.2020	4.5782	36.5075	99.2289
	Built-in land	104,327	0.2930	9.9303	45.9155	96.9836

Table 7 | Shanghai category levels landscape index for 2000, 2010, and 2020

Year	Landscape type	NP	PD	ED	AREA_MN	COHESION
2000	Cropland	1,153	0.1426	19.0305	388.0338	99.8481
	Woodland	135	0.0167	0.0893	1.6074	34.3117
	Grassland	99	0.0122	0.1637	18.2929	92.3895
	Wetland	43	0.0053	0.6030	293.3953	98.0697
	Waters	1,883	0.2328	4.5492	78.8030	99.1289
	Built-in land	2,195	0.2714	16.3821	82.3390	99.0847
2010	Cropland	1,504	0.1859	17.7908	244.8078	99.7179
	Woodland	225	0.0278	0.2762	4.5067	73.2815
	Grassland	241	0.0298	0.4199	8.5477	82.4177
	Wetland	55	0.0068	0.7388	419.2182	98.1125
	Waters	1,810	0.2238	4.7472	75.9238	98.9399
	Built-in land	1,419	0.1754	15.1174	192.9803	99.3559
2020	Cropland	982	0.1214	18.7298	316.3534	99.6061
	Woodland	214	0.0265	0.9898	47.0841	91.8845
	Grassland	398	0.0492	1.4054	27.9673	86.4043
	Wetland	119	0.0147	1.0924	209.9748	96.8928
	Waters	2,462	0.3044	6.2346	53.6747	98.8226
	Built-in land	1,910	0.2361	17.5117	166.9639	99.3335

Table 8 | Jiangsu category levels landscape index in 2000, 2010, and 2020

Year	Landscape type	NP	PD	ED	AREA_MN	COHESION
2000	Cropland	5,129	0.0500	15.8634	1464.1400	99.9753
	Woodland	3,223	0.0314	1.0458	68.3183	98.1173
	Grassland	4,304	0.0419	0.6234	10.0606	89.1995
	Wetland	1,201	0.0117	0.3840	67.7935	95.9674
	Waters	38,941	0.3793	6.4807	34.4002	99.0930
	Built-in land	33,413	0.3254	10.1453	30.9148	92.6041
2010	Cropland	5,075	0.0494	16.2252	1426.0160	99.9739
	Woodland	7,001	0.0682	1.3316	30.1077	97.7842
	Grassland	11,348	0.1105	1.1620	6.4151	89.5967
	Wetland	703	0.0068	0.2962	87.3713	95.6936
	Waters	32,842	0.3199	5.9273	40.7575	98.8122
	Built-in land	33,894	0.3301	11.0259	38.8599	94.5914
2020	Cropland	10,543	0.1027	18.3207	613.1295	99.9656
	Woodland	4,891	0.0476	1.3330	50.0282	97.9754
	Grassland	8,633	0.0841	0.9709	7.7975	87.1697
	Wetland	1,046	0.0102	0.3101	55.8451	94.1277
	Waters	30,023	0.2924	7.1270	46.8816	99.2770
	Built-in land	30,928	0.3012	12.883	65.3163	97.2282

land shifted to built-in land. The increase in the number of arable land plaques led to a decrease in the binding index of the average plaque area. As edge density increases, the shape of the plaques tends to become more complex, which also indicates that cropland is the most severely fragmented among all types of landscapes. Built-in land, on the other hand, shows the opposite characteristics of change, with an increase in land area, a decrease in the number of plaques, and an increase in the average plaque area. The general increase in the bonding index and the simultaneous increase in edge density indicate that the expansion pattern of built-in land is a combination of infilling and spreading, which increases the resistance to the operation of some ecological flows in the region. Among them, the number of cropland plaques, the density of cropland plaques, the bonding index of built-in land in Shanghai shows a decreasing trend opposite to that of the region, indicating that the built-up area in the center of Shanghai experienced rapid urban development at the end of the last century continued to

Table 9 | Zhejiang category levels landscape index in 2000, 2010, and 2020

Year	Landscape type	NP	PD	ED	AREA_MN	COHESION
2000	Cropland	38,593	0.3668	20.2711	89.7692	99.5205
	Woodland	24,733	0.2350	21.7073	232.1348	99.9272
	Grassland	121,720	1.1567	9.8457	3.3469	69.7051
	Wetland	525	0.0050	0.1310	47.7848	96.0539
	Waters	20,405	0.1939	2.8345	13.4336	96.9586
	Built-in land	12,871	0.1223	3.3523	28.3564	93.3087
2010	Cropland	43,875	0.4170	20.5860	75.4179	99.3988
	Woodland	22,774	0.2164	21.6461	251.2802	99.9268
	Grassland	119,623	1.1368	9.5906	3.2992	68.7521
	Wetland	148	0.0014	0.0964	236.4662	97.5681
	Waters	14,808	0.1407	2.4538	19.2271	97.2955
	Built-in land	12,675	0.1205	3.8431	46.6043	96.086
2020	Cropland	53,131	0.5049	21.8127	52.1951	98.8668
	Woodland	21,108	0.2006	21.1859	271.1688	99.9275
	Grassland	116,049	1.1029	9.3086	3.3248	68.6851
	Wetland	135	0.0013	0.0507	109.6593	95.5711
	Waters	15,150	0.1440	3.8774	27.8554	97.9202
	Built-in land	18,040	0.1714	6.7738	57.8268	97.4856

Table 10 | Anhui category levels landscape index in 2000, 2010, and 2020

Year	Landscape type	NP	PD	ED	AREA_MN	COHESION
2000	Cropland	28,190	0.2013	20.8400	295.2214	99.9650
	Woodland	34,695	0.2477	11.7873	106.5044	99.8792
	Grassland	72,494	0.5176	4.6577	4.0638	87.2993
	Wetland	1,476	0.0105	0.4484	58.2276	95.5643
	Waters	43,270	0.3090	3.8347	14.5223	97.8107
	Built-in land	60,178	0.4297	8.8931	16.1989	83.1397
2010	Cropland	31,690	0.2263	21.1003	258.7286	99.9622
	Woodland	48,746	0.3481	12.1866	75.0129	99.8760
	Grassland	79,053	0.5644	4.9553	3.8931	87.0423
	Wetland	1,761	0.0126	0.3762	30.0557	92.5594
	Waters	30,210	0.2157	3.3398	22.5491	97.7445
	Built-in land	59,288	0.4233	9.1616	18.6268	87.2757
2020	Cropland	32,718	0.2336	20.6543	243.0433	99.9592
	Woodland	43,283	0.3090	11.6775	83.4425	99.8741
	Grassland	74,731	0.5336	4.6884	4.1569	88.0172
	Wetland	1,649	0.0118	0.3614	32.7253	92.3129
	Waters	24,962	0.1782	3.1238	26.6230	98.1379
	Built-in land	53,596	0.3827	9.6763	26.2748	92.3783

develop in the form of landscape enclaves to the peripheral range after the infill expansion. The number of arable land and built-in land plaques in Zhejiang Province has increased greatly, which indicates that the expansion and development of built-in land is also restricted to a certain extent by the mountainous landscape of Zhejiang Province, so urban development is more concentrated in the northern plains of Zhejiang.

From the viewpoint of the main component landscapes of woodland and grassland systems, the number of plaques of grassland landscapes is the highest among all types of landscapes, and the floating changes of connectivity index are large, while woodland landscapes have more stable landscape changes compared to woodland landscapes. In addition to other provinces and cities outside Zhejiang Province, the number of plaques and patch density of grassland landscape have been increased, but the total area of woodland, grassland landscape in Zhejiang Province is much higher than other provinces and cities, indicating that the total amount of natural plaques in these two types of landscape is still reduced under the interference of human activities, while the increase of the two types of landscapes are mostly derived from the urban green space system or the implementation of the policy of returning farmland to forest. However, the spatial distribution of these two types of landscapes is strongly influenced by climate, and a large number of them are distributed in the southern part of Anhui and Zhejiang Province within the subtropical monsoon climate zone, and the regional variation of the landscape is strong, and the plaque density and edge density of such landscapes in Zhejiang and Anhui are significantly higher than those in Shanghai and Jiangsu. The number of plaques and the average plaque area growth ratio of these two types of landscapes in Shanghai are higher. However, the native woodland and grassland landscape in Shanghai are scarce, the park urban planning and riverside green space transportation plan in Shanghai promote the increase of these two kinds of landscapes. Zhejiang Province grassland landscape integration index is the lowest, where this type of landscape often occurs simultaneously with woodland landscape and exists in a smaller plaque form in another landscape, and such mixed landscapes in southern Anhui also have the same pattern characteristics.

In terms of watershed and wetlands, the distribution of these two types of landscapes is mainly concentrated in the lower reaches of the Yangtze River and the related watersheds of the Taihu Lake, the Gaoyou Lake, and the Hongze Lake, while wetland landscapes are often distributed around large-scale watershed plaques or at river crossings and sea inlets. While the area of watershed landscapes increases and the number of plaques decreases year by year, wetland landscapes are the most decreasing landscape type in the study area. Jia *et al.* (2020)'s research shows that although the overall water ecosystem area has increased, the landscape types with high ecological service values are decreasing rapidly. Wetland landscape, as one of the most sensitive land types to basin hydrological systems, often has an impact on hydrological water resources and hydro-ecological interaction processes in basins in the context of global climate change (Dong & Zhang 2011; Li *et al.* 2013). The density of wetland landscape boundaries is the lowest among all types of landscapes and shows a decreasing trend, the shape of plaques tends to be simpler in the process of landscape reduction, and the overall landscape bonding also shows a decreasing trend, the surrounding ecosystem between the ecological flow is affected to varying degrees. In each province and city, except for Shanghai, where the number of plaques is increasing, the number of plaques in the waters of the other three provinces is decreasing while the total area is increasing, and the connectivity of plaques is increasing, and the landscape expansion process is linking multiple plaques of waters, which may be related to the frequent flooding disasters in the lower reaches of the Yangtze River under the influence of climate (Jiang *et al.* 2005). The number of wetland plaques in Jiangsu and Anhui provinces, where wetland landscapes are more distributed, decreased instead of increasing, and the average plaque area and bonding index decreased significantly. The natural wetland landscape is reduced in continuity under the disturbance of human activities, and the wetland landscape such as the National Wetland Park of the Caizi Lake in the north of Anqing City, Anhui Province, and the ShiJiu Lake in southern Jiangsu Province deteriorate rapidly, and there is an obvious phenomenon of wetland plaque shrinking or disappearing during the study period.

4. CONCLUSION

Changing climatic conditions and increasingly drastic human activities have had a significant impact on the regional environment, and it is, therefore, necessary to develop targeted strategies for regional development. This paper studies the land use dynamics and landscape pattern changes in the Yangtze River Delta as a whole and its constituent provinces and cities for 20 years, and presents the main analytical conclusions in terms of the category landscape dynamics and the spatial and temporal evolution of the regional landscape, with a view to providing targeted suggestions and strategies for regional urbanization development.

During the study period, the landscape area of three categories, namely cropland, woodland and wetland, declined, and the landscape area of grassland, waters, and built-in land increased. Although cropland has always been the dominant landscape in the Yangtze River Delta, the dominance of non-natural landscapes in the region has gradually increased, mainly manifested by the accelerated transformation of the cropland landscape to the built-in land landscape, with the area share of the former decreasing by 7% and the area share of the latter increasing by 6%, and the transformation area exceeding 20,000 km^2, with built-in land having replaced cropland as the dominant landscape in Shanghai in 2020.

The dominant landscape connectivity of the Yangtze River Delta and its internal constituent provinces and cities in the overall landscape perspective shows a slow decline from 2000 to 2010 and a rapid decline from 2010 to 2020. Similarly, the decrease of aggregation index and the general increase of fragmentation index indicate that the overall landscape system tends to be scattered and uniformly distributed, the degree of habitat fragmentation increases, the degree of aggregation of similar landscape plaques in all regions except Anhui Province decreases, the indeterminate information content increases, the complexity of the overall landscape increases, and regional environmental risks increase.

The spatial characteristics of the distribution of various landscape types in the study area are obvious, with woodland, grassland distributed in large numbers in Zhejiang Province and southern Anhui Province in the subtropical climate zone, and wetlands often appearing in the lower Yangtze River basin together with waters. Cropland is severely fragmented and fragmentation increases due to urban expansion, while built-in land expands mainly in the form of a combination of infilling and spreading. The landscape integrity of woodlands among the landscape types with high ecological service value is significantly higher in Zhejiang and Anhui than in Shanghai and Jiangsu. The area of wetland landscape and the number of plaques tend to decrease in all regions, and the wetland landscape in Anhui Province deteriorates at the fastest rate among all regions.

The landscape pattern index used in this study can evaluate the overall ecological characteristics of regional landscape for surface cover or land use information, thus further guiding the land use development plan of the research area and coordinating the issue of land use for construction and development and the protection of various ecological areas. Based on the above study, it is considered that the Yangtze River Delta regional development and urbanization process should pay attention to maintaining the integrity of regional dominant landscapes of cropland, while protecting the diversity and connectivity of natural landscapes with high ecological service value, and maintaining the ecological service value of various kinds of landscapes. While strictly implementing the red line of ecological protection and the red line of cropland protection, the regional landscape pattern should be optimized according to the spatial distribution characteristics and development level of different regions, so as to improve the land utilization rate and maximize the landscape value to coordinate the common development of humans and nature.

There are some limitations in this study, mainly in terms of data continuity and land use data accuracy. This study used three phases of surface cover data over a 10-year span for computational study, the interpretation of continuous changes in regional ecosystems still has some limitations, in the future, a larger time range, and a shorter year frequency of time panel data can be developed to systematically assess the regional urban process for decades. Because the landscape system has a scale effect, the surface coverage data of 100 m $\times$ 100 m used in the study still lack the ecological characteristics of small- and medium-scale areas, and further research on municipal scale can be carried out in the future to further reveal the relationship between the overall and local landscape patterns of the region under various scales. In addition, this study only cares about the ecological characteristics of landscape pattern at the land use data level, the influence of urban development on regional ecosystems is still limited, and further research can be carried out in the future in the light of regional socio-economic data to guide the urbanization development and ecological protection of different developed regions.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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