Analysis of spatiotemporal changes and driving factors of blue-green space in six metropolitan areas of the Yangtze River Delta based on the PLUS model

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Abstract. This study aims to examine the evolution of blue-green space and urban development in the Yangtze River Delta region using Arcgis spatial analysis, landscape pattern index, and PLUS model to inform urban planning and environmental protection efforts. The results indicate that:1) Blue space in the region's six metropolitan areas initially increased, then decreased significantly from 2000-2020, while green space continued to decline. However, recent environmental policies have mitigated this trend. 2) Improved living standards have led to increased green space within cities, but construction land occupation has reduced green space outside of cities. 3) Blue-green space is becoming more fragmented, scattered, and homogenized in shape, and that economic development influences green space, while different regional development patterns impact blue space. 4) Socioeconomic and natural factors both drive blue-green space to change. There is a "dual desirability" between blue-green space protection and urban development. In conclusion, the scale and landscape pattern of blue-green space have changed significantly in the last 20 years, which are greatly influenced by urban development, and the blue-green space differences among metropolitan areas are obvious. Therefore, it is necessary to protect and optimize the blue-green space pattern of the metropolitan areas.

Keywords: blue-green space; spatiotemporal changes; driving factors; landscape pattern; six metropolitan areas in the Yangtze River Delta.

1. Introduction

The Yangtze River Delta region is the most economically developed region in China and has an extremely important strategic position, but it is also one of the typical regions in China where the contradiction between urbanization and ecology is prominent.[1] In 2016, the National Development and Reform Commission released The Yangtze River Delta City Cluster Development Plan, which states that the Yangtze River Delta region aims to build a spatial development pattern of "one core and five circles", promoting the formation and development of six metropolitan areas: the Shanghai Metropolitan Area, the Nanjing Metropolitan Area, the Su-Xi-Chang Metropolitan Area, the Hangzhou Metropolitan Area, the Hefei Metropolitan Area and the Ningbo Metropolitan Area. With the rapid development of metropolitan areas, the implementation of the strategy of ecological civilization construction also requires that the national territorial spatial planning should constantly strengthen the construction of ecological space development and protection pattern. In 2019, the Notice of the Ministry of Natural Resources on the National Territorial Spatial Planning Work mentioned that the review points of the municipal territorial spatial master plan should include "The scope of control and balanced distribution requirements for open spaces such as structural green areas and water bodies within the development boundary of cities and towns".[2] The blue space composed of rivers and wetlands, and the green space composed of parks and green corridors, have received wide attention. [3-5] With the development of the Yangtze River Delta region, urban construction land has continuously encroached upon ecological land, leading to an increasing pressure on the ecological environment.

In the context of municipal and county-level territorial spatial planning, the term "blue-green space" refers to the open spatial system of green areas, water areas and wetlands within the development boundaries of cities and towns.[2] Some scholars believe that blue-green space is a closely related organic whole in the urban and rural ecological system.[6] While some scholars define blue-green space as the specific space of the community of life of mountains, water, forests, fields, lakes and grasses.[7] At present, blue-green space plays an important role in mediating urban climate[8, 9], enhancing biodiversity[10, 11], reducing carbon emissions[12, 13] and promoting human health.[14, 15] In order to understand the change pattern of regional blue-green space, some scholars have also used GIS and remote sensing techniques combined with dynamic degree, information entropy , transfer matrix and landscape index to further study the spatiotemporal and landscape change characteristics of blue-green space. Xu Hao et al.[16] used dynamic change models and landscape pattern index to analyze the evolution of blue-green spatial scale and landscape pattern in the Su-Xi-Chang metropolitan area and its member cities over a 15-year period; Cui Jie et al.[17] made a dynamic analysis of the blue-green spatial scale and landscape pattern in Xuzhou metropolitan area based on landscape dynamic degree, landscape transfer matrix method and landscape index; Chen Ziyi et al.[18] analyze the trends and characteristics of the temporal evolution of blue-green space within the urban development zone of Wuhan under the influence of continuous urban expansion. Relevant research levels mainly cover urban agglomeration and municipal space, and no multi-scale research system has been formed yet. In terms of the driving mechanisms of structural and quantitative changes in blue-green space, most studies have analyzed the driving factors in terms of social and natural factors. Song Shuang et al.[19] explored the spatial change characteristics and evolutionary mechanisms of blue-green spatial change in the central city of Harbin from 1981 to 2020 by using spatial measurement methods; Gong Yingbi[20] used a coupled principal component-grey correlation approach to investigate the impact of four years of wetland landscape patterns in Changsha; He Sicong et al.[21] made a multi-scale quantitative analysis of the drivers of lake evolution in Wuhan city circle during 1994-2015 using multivariate statistical methods.

In terms of the analysis method of the driving mechanism, studies on the simulation of national land spatial changes at different regions and scales, both domestically and internationally, have mainly used various spatial simulation models such as CLUE-S[22-24] , FLUS model[25, 26] and SLEUTH[27, 28] to analyze driving factors.. PLUS is a new type of land use simulation model[29], it can describe the non-linear relationship between land use type changes and driving factors based on time-series patch changes, which has a higher simulation accuracy for uncovering the factors of land use changes. PLUS has been applied to land use simulations domestically and internationally in the latest research, and is conducive to the next step of research on blue-green spatial development of national land space.

In summary, although the existing studies have analyzed the characteristics of blue-green space changes in some urban areas, whether there are differences in ecological space development between different cities, what is the relationship between blue-green space and urban development, and whether there is conflict between the expansion of metropolitan area and the protection and expansion of blue-green ecological space, are questions that need to be further studied. Taking into account the definition of blue-green space by existing studies[16], this study defines "blue-green space" as green space represented by all vegetated areas and blue space represented by all natural and artificial water bodies. The six metropolitan areas in the Yangtze River Delta, which have rapid economic development and prominent conflicts between urban development and ecological and environmental problems, are taken as the study area. This study investigates the quantity, spatiotemporal distribution, characteristics of plaque changes and the rate of change of blue-green space in the Yangtze River Delta urban agglomerations. On the basis of these methods, the driving mechanisms of regional urban development and blue-green ecological spatial change characteristics in a long time series is analyzed by combining the PLUS model with natural environmental and socio-economic factors, providing a theoretical basis and decision-making reference for the optimization of the spatial structure of the Yangtze River Delta metropolitan area, promoting regional sustainable development.

2. Research methodology and data sources

2.1 Overview of the study area

According to The 2019 Yangtze River Delta Regional Integrated Development Plan Outline, the planning scope of the Yangtze River Delta is officially set as the entire region of Suzhou, Zhejiang, Anhui and Shanghai, with Shanghai as the main core, Nanjing and Hangzhou as the secondary core, radiating 13 prefecture-level cities such as Wuxi, Suzhou and Changzhou, covering a total area of 358,000 km^2 . The Yangtze River Delta has a good foundation for economic development. By the end of 2021, the total GDP of the Yangtze River Delta reaches 27.6 trillion, accounting for 24.1% of the national GDP. The Yangtze River Delta has excellent natural conditions, with a dense network of rivers and a predominantly plain topography. The northern and central regions of the Yangtze River Delta are dominated by construction land and arable land, and the southern region is dominated by forest and grassland. In parallel with the rapid economic development, the ecological space in the Yangtze River Delta has been gradually destroyed, where habitat fragmentation has increased and environmental problems have become increasingly prominent.

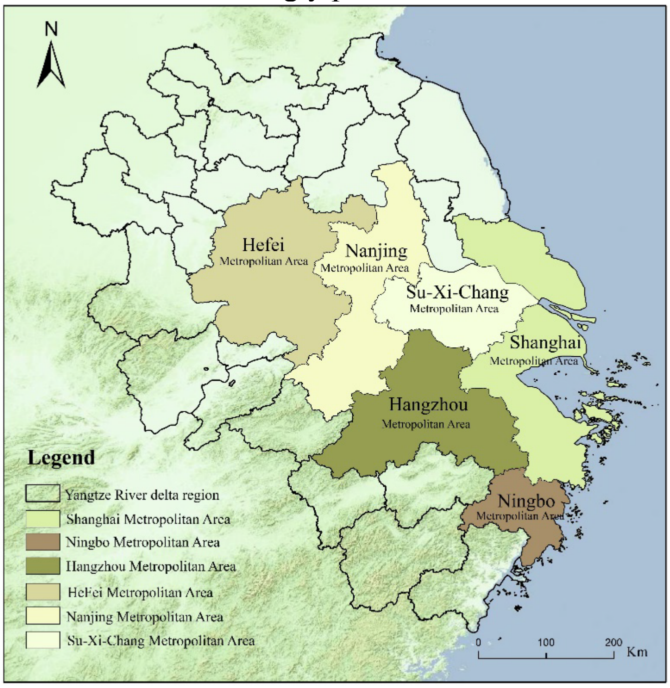

Fig. 1 Distribution of the six metropolitan areas in the Yangtze River Delta

2.2 Data sources and processing

The land use type data of the Yangtze River Delta region used in this study is obtained from the National Land Use Classification Data Product of the Resource and Environment Science and Data Centre of Chinese Academy of Sciences (https://www.resdc.cn/), with a spatial resolution of 30 m. The land use types are divided into six primary categories: arable land, forest land, grassland, water and construction land. The overall land use classification accuracy is above 90%. Data sources and basic information are indicated in the following table.

Table 1 Three Scheme comparing

Type	Data attribute	Year	Spatial resolution	Data source
Land use data	Land use status	2000-2020	30m	Resource and Environment Science and Data Center
Climate and environmental	Elevation	-	150m	www.rivermap.cn
	Slope	-	500m	-

data	Mean annual precipitation	2000, 2010, 2020	1km	National Earth System Science Data Center
	Annual average temperature	2000, 2010, 2020	1km	
	Spatial distribution of soil types in China		1km	
	Ecological reserve	2020	-	
Socioeconomic data	nighttime lighting	2020	500m	Resource and Environment Science and Data Center
	Spatial distribution of population	2000, 2010, 2019	1km	
	Gross domestic product	2000, 2010, 2019	1km	
	Highway network	2020	-	www.rivermap.cn

In the selection of driving factors, driving factors can be divided into natural environment factors and socio-economic factors. Combined with the existing literature on the driving mechanisms of land use change[30-32], the driving factors are selected as shown in the following table. Among them, "Nighttime lighting" can effectively reflect human social activities and the level of urbanisation.[33, 34]

Table 2 Indicators of driving factors for change

category	Driving factor
Natural environmental factor	Elevation Precipitation Temperature Slope Soil Distance to ecological reserve
Socioeconomic factor	GDP Nighttime lighting Population Distance to highway network

Among the various drivers, "Distance to highway network" includes urban roads, highways, national highways and railways. Arcgis is used to pre-process the data: 1) Euclidean distance calculation for the highway network and ecological reserve data; 2) Mean value calculation for population, GDP, temperature and precipitation data; 3) Using elevation data to calculate slope data; 4) The above data resolution is uniformly resampled to 100m to ensure the consistency of the raster data row numbers for subsequent analysis.

2.3 Research Methodology

2.3.1 Land use dynamic degree

Land use dynamic degree can be used to indicate the overall trend of change in a landscape type within a certain time frame in the study area, including changes in direction and rate. The positive and negative values indicate the direction of change in the landscape type, and the larger the absolute value of the dynamic degree is, the more dramatic the change is.

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

Where:K is the magnitude of change for a landscape type , U_a and U_b represent the area of a landscape type at the beginning and end of the study respectively, and T represents the duration of the study.

2.3.2 Land use transfer matrix

The land use transfer matrix is a two-dimensional matrix based on the transformation relationship between the current state of land cover in different phases of the same area, and is able to represent the value and direction of change of each land type in a simple and intuitive way during the study period. The expression is as follows.

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix} \quad (2)$$

Where:*n* is the number of land use types; *i,j* (*i,j* = 1,2,3 ......n) represent the land use types before and after the transfer respectively.S_{ij} denotes the area of land use type *i* at the beginning of the study transferred to land use type *j* at the end of the study.

2.3.3 Landscape Pattern Index

The landscape pattern index is an effective tool for analysing changes in landscape ecological patterns.The ecological stability of urban landscape patterns can be judged in order to deduce the appropriate scale for ecological pattern research.[35] In this paper, parameters are selected at the patch type level and landscape level(Table 3).

Table 3 Landscape pattern index table

Type	Index	Name	Unit	Meaningful description
Plaque type level	NP	Number of patches	#	Represents the total number of patches in the landscape area
	LPI	Largest patch index	%	Represents the dominant type of landscape and reflects the change of human activity interference intensity.
	COHESION	Patch Cohesion Index	\	It represents the spatial linkage degree of landscape in the landscape area.
Landscape level	PD	Patch density	#/km^2	It represents the number of patches per unit area.
	LSI	Landscape shape index	\	Represents the complexity of plaque shape
	AI	Aggregation index	%	It represents the degree of aggregation between patches.
	SHDI	Shannons diversity index	\	It represents landscape heterogeneity.

2.3.4 PLUS model

The PLUS model integrates the Land Expansion Strategy Analysis module (LEAS) and the meta-cellular automata model (CARS) , which is based on multi-class random patch seeds for future land use change simulation model, solving the problems of the complexity of the transformation analysis strategy and the lack of temporal concept and the ability to mine the driving mechanism of land use change in the pattern analysis strategy. The land expansion strategy analysis module is able to extract the portion of each type of land use expansion between the two periods of land use change and use the Random Forest algorithm (RCF) to obtain the development probability of each type of land use and the contribution of the driving factors to the expansion of each type of land use in that time period. The expression of the RCF is as follows.

$$P_{i,k}^{d}(\mathrm{x}) = \frac{\sum_{n=1}^{M} I(h_n(\mathrm{x}) = \mathrm{d})}{M} \quad (3)$$

Where: *k* is the land use type; *i* is the tuple in which *k* is located; *M* is the total number of decision trees; *x* is a vector consisting of multiple drivers; *d* is 0 or 1 (1 means there are other land use types converted to k,0 means none);$P_{i,k}^{d}$ is the probability of land expansion; I is the set of decision trees; $h_n(x)$ is the prediction type of the nth decision tree of vector x.

3. Results and analysis

3.1 Dynamic degree of blue-green space in the metropolitan areas of the Yangtze River Delta

During the period 2000-2020, the spatial variability of blue-green spatial dynamic degree in the Yangtze River Delta was large among metropolitan areas and between different time periods. Overall, the Su-Xi-Chang metropolitan area had the highest rate of blue-green space change, followed by the Shanghai, Ningbo, Nanjing, Hangzhou, and Hefei metropolitan areas. From 2015 to 2020, the blue-green spatial change rate decreased in all metropolitan areas except for Hangzhou. The scale of green space in each metropolitan area showed a negative growth trend at all stages, with the rate of reduction of green space in Su-Xi-Chang and Shanghai metropolitan areas significantly greater than that in other metropolitan areas; Blue space in each metropolitan area showed significant dynamic changes in stages, generally showing positive growth between 2000 and 2010, and negative growth between 2010 and 2020. The overall change of blue space was greater than that of green space, and the differences between metropolitan areas were also greater.

Table 4 Dynamic changes of blue-green space in the six metropolitan areas of Yangtze River Delta

		Hangzhou	HeFei	Nanjing	Ningbo	Shanghai	Su-Xi-Chang
Blue-green space	2000-2005	-0.46	-0.08	-0.12	-0.71	-0.89	-0.82
	2005-2010	-0.23	-0.39	-0.60	0.52	-0.85	-1.92
	2010-2015	-0.28	-0.36	-0.25	-0.39	-0.52	-0.28
	2015-2020	-0.33	-0.03	-0.12	-0.17	-0.48	-0.44
Green space	2000-2005	-0.52	-0.11	-0.23	-0.80	-1.07	-1.35
	2005-2010	-0.25	-0.46	-0.72	-0.19	-1.67	-3.20
	2010-2015	-0.27	-0.44	-0.30	-0.18	-0.45	-0.42
	2015-2020	-0.29	0.00	-0.10	-0.04	-0.27	-0.34
Blue space	2000-2005	0.61	0.31	1.01	1.59	-0.05	0.41
	2005-2010	0.09	0.29	0.57	16.25	2.80	0.79
	2010-2015	-0.61	0.51	0.16	-2.83	-0.76	-0.04
	2015-2020	-0.87	-0.42	-0.27	-1.98	-1.25	-0.61

3.2 Changing characteristics of blue-green spatial transfer dynamics in the Yangtze River Delta

In 2000, there were many lakes in the Yangtze River Delta study area, and blue space was generally distributed more in the north than in the south, with the largest area of blue space in the Taihu Lake basin in the Suzhou-Xi-Chang metropolitan area and the Chaohu Lake basin in the Hefei metropolitan area. The Shanghai and Ningbo metropolitan areas were bordered by the sea on one side. Green space covered a wide area, with the most concentrated construction land in the Shanghai metropolitan area. During the period 2000-2020, the expansion of construction land was evident and spread rapidly from the coast to the interior, resulting in a continuous decay of green space. In addition to the Shanghai metropolitan area, the Su-Xi-Chang and Nanjing metropolitan areas also experienced a significant expansion of construction land.

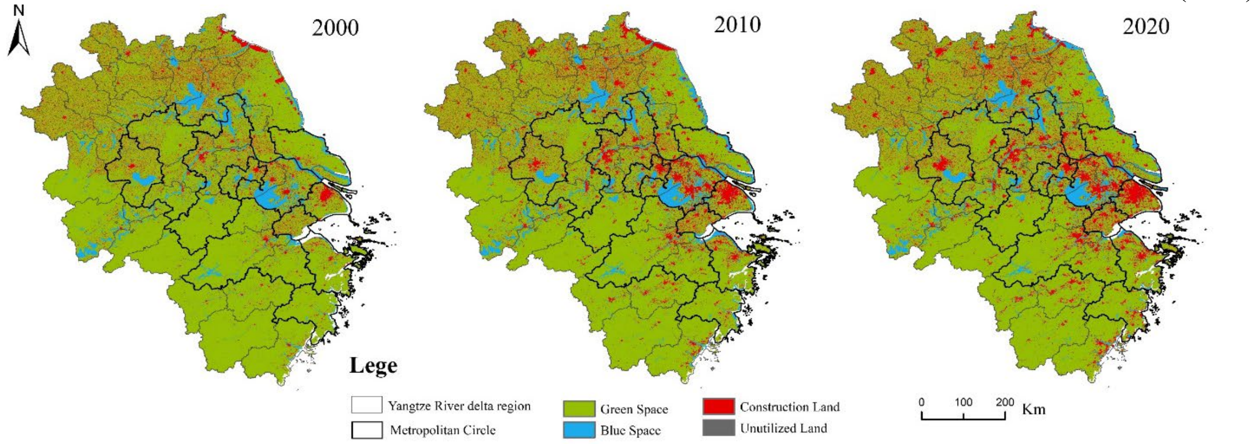

Fig. 2 Distribution of blue-green space in the Yangtze River Delta from 2000 to 2020

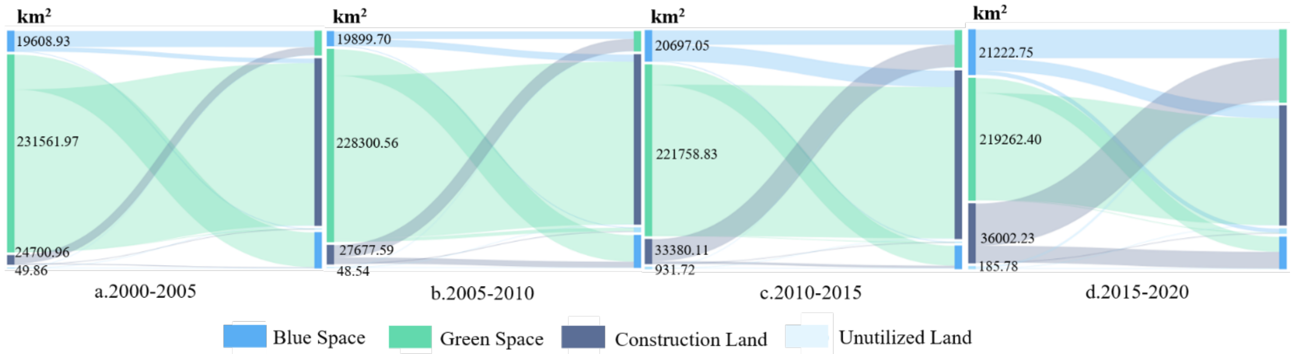

Fig. 3 Land use transfer from 2000 to 2020

Table 5 Blue-green Space Land use Transfer Matrix in the Yangtze River Delta from 2000 to 2020

Change direction	Type	2000-2005		2005-2010		2010-2015		2015-2020		2000-2020	
		Area /km²	Propor-tion	Area /km²	Propor-tion	Area /km²	Propor-tion	Area /km²	Propor-tion	Area /km²	Propor-tion
Green space increase	B to G	154	33.50%	470.6	62.80%	593.6	64.90%	1438.8	58.00%	828.5	46.60%
	L to G	302.4	65.80%	276.6	36.90%	272.8	29.80%	972.4	39.20%	944	53.10%
	U to G	2.9	0.60%	2.2	0.30%	48	5.30%	71.2	2.90%	5.9	0.30%
	Total	459.3	100.00%	749.4	100.00%	914.3	100.00%	2482.3	100.00%	1778.3	100.00%
Green space decrease	G to B	3060.9	82.20%	6149.5	84.40%	2955.6	87.50%	3630.8	87.30%	13892	87.40%
	G to L	658.3	17.70%	1000.8	13.70%	416.5	12.30%	509.8	12.30%	1922.2	12.10%
	G to U	5	0.10%	133.1	1.80%	5.1	0.20%	19.8	0.50%	73.1	0.50%
	Total	3724.2	100.00%	7283.4	100.00%	3377.1	100.00%	4160.4	100.00%	15888	100.00%
Blue space increase	B to L	17.2	2.50%	227	18.50%	51.6	4.90%	580.2	52.60%	622.8	24.50%
	G to L	658.3	97.30%	1000.8	81.50%	416.5	39.60%	509.8	46.20%	1922.2	75.50%
	U to L	1.3	0.20%	0.8	0.10%	583.1	55.50%	12.4	1.10%	1.6	0.10%
	Total	676.8	100.00%	1228.5	100.00%	1051.2	100.00%	1102.4	100.00%	2546.6	100.00%
Blue space decrease	L to B	84.5	21.80%	268	48.60%	193.6	41.30%	424.4	27.70%	641.5	37.30%
	L to G	302.4	78.20%	276.6	50.20%	272.8	58.10%	972.4	63.50%	944	54.90%

L to U	0.1	0.00%	6.9	1.20%	2.9	0.60%	134.2	8.80%	133.9	7.80%
Total	386.9	100.00 %	551.5	100.00 %	469.2	100.00 %	1530.9	100.00 %	1719.4	100.00 %

Note: G stands for green space; L stands for blue space; B stands for construction land; U stands for unutilized land.

From 2000 to 2020, the total green space in the study area showed a decreasing trend, with a decrease of 14109.2613 km^2, while the blue space showed an increasing trend, with an increase of 827.20 km^2. From 2000 to 2010, due to the influence of economic development and urban expansion, the construction land occupied more arable land and forest land. The change in land use was mainly reflected in a large decrease in green space and an obvious increase in construction land, with the amount of green space transferred to construction land being 9210.38 km^2.From 2010 to 2020, due to the influence of ecological protection policies, the amount of green space transformed into blue space and construction land, while the amount of blue space and construction land transformed into green space was also greatly increased (Figure 3).

As can be seen from Table 5, construction land was mainly converted from green space, with a net transfer of 5678.97 km^2, from 2005 to 2010, which was about twice that of other periods, indicating the most obvious expansion of construction land in this period, which was closely related to the rapid development of cities in the Yangtze River Delta region. Blue space was dominated by the conversion relationship with green space. From 2000 to 2020, a total of 1922.17 km^2 of blue space was transferred from green space, accounting for 12.1%, while 943.99 km^2 of blue space was transferred out to green space, showing an overall trend of increasing blue space. The proportion of blue-green space decreased from 91.03% to 86.11% between 2000 and 2020, with 13,082.55 km^2 of blue-green space encroached upon by construction land.

In terms of spatial distribution (Figure 4), the most obvious conversion of green space to construction land was concentrated in the southern part of Jiangsu Province and the Shanghai region. This was followed by the conversion of green space to blue space, mainly in the Taihu Lake basin in the Su-Xi-Chang metropolitan area and the Qiantang River basin in the Hangzhou metropolitan area. In addition, there were frequent changes in land types along the coast, mainly between green land and blue land conversion, with a certain amount of unused land development and construction land returned to blue-green space. The conversion of construction land to green space occurred mostly in inner-city areas, and there was a gradual upward trend in the amount of transfer, indicating that with the improvement of urban construction and living standards, people also had further requirements for their living environment. Look at it in stages, the expansion of construction land into green space was obvious from 2000 to 2010, and was mainly concentrated in the Shanghai metropolitan area, Su-Xi-Chang metropolitan area and Nanjing metropolitan area. While from 2010 to 2020, the overall occupation of green space in the Yangtze River Delta urban agglomeration improved, and the metropolitan areas tended to be balanced. On the whole, the transformation of land use types in the study area during the period 2000-2010 is more pronounced than in the period 2010-2020, with a larger area of transformation.

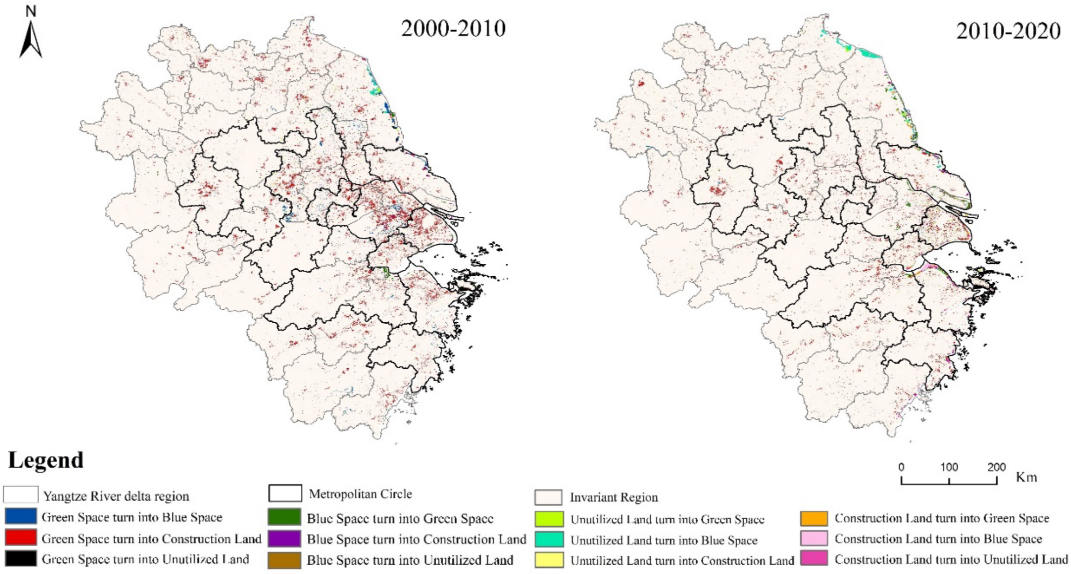

Fig. 4 Spatial distribution of blue-green spatial changes in the Yangtze River Delta during 2000-2010 and 2010-2020

3.3 Blue-Green Spatial Landscape Pattern Index Plaque type level

3.3.1 Changing characteristics of blue-green spatial patch types

Table 6 Horizontal landscape index of green space and blue space types in Yangtze River Delta metropolitan area from 2000 to 2020

		Green space			Blue space		
		NP	LPI	COHESION	NP	LPI	COHESION
HeFei Metropolitan Area	2000	223	71.0166	99.9839	3267	2.4588	98.2282
	2005	237	70.66	99.9837	3267	2.4642	98.2664
	2010	426	69.3165	99.9823	3277	2.4712	98.2834
	2015	444	67.7785	99.9812	3698	2.4687	98.112
	2020	495	67.7987	99.9811	3230	2.4707	98.3004
Hangzhou Metropolitan Area	2000	380	60.5641	99.9757	3031	3.1318	99.0701
	2005	586	59.1093	99.9735	3434	2.9907	98.9505
	2010	711	57.8314	99.9723	3494	2.433	98.7223
	2015	768	57.1166	99.9712	3471	2.2996	98.6817
	2020	884	56.0278	99.9696	3514	2.5436	98.7876
Ningbo Metropolitan Area	2000	380	60.5641	99.9757	1126	0.4047	95.4014
	2005	586	59.1093	99.9735	1326	0.258	94.7096
	2010	711	57.8314	99.9723	1370	2.7357	97.5819
	2015	768	57.1166	99.9712	1355	1.6472	96.5669
	2020	884	56.0278	99.9696	1540	1.2542	96.2322
Nanjing Metropolitan Area	2000	592	43.1251	99.9653	6646	2.7985	98.7417
	2005	620	42.3202	99.9647	6728	2.8482	98.7284
	2010	903	39.3909	99.9593	6781	2.9126	98.7463
	2015	972	38.9402	99.9593	7129	2.9465	98.778
	2020	1160	38.5088	99.958	6694	2.9161	98.8068
Shanghai Metropolitan Area	2000	1022	28.6084	99.9365	4062	5.9263	99.0979
	2005	1367	25.8289	99.929	4433	5.9532	99.0637
	2010	1723	16.5074	99.8727	4394	5.9572	99.1444
	2015	1825	15.9863	99.8677	4483	5.7477	99.0486
	2020	1995	15.7917	99.8349	5574	5.4064	98.8721
	2000	416	57.3908	99.9674	2564	14.1702	98.8476

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	2005	522	52.9381	99.9609	2665	14.2322	98.8543
Su-Xi-Chang Metropolitan Area	2010	739	37.9036	99.9042	2519	14.366	98.8331
	2015	758	37.2567	99.904	2513	14.2928	98.8434
	2020	859	20.3888	99.8408	2522	14.034	98.7463

From 2000 to 2020, the Largest patch index(LPI) and the Patch cohesion index(COHESION) of green space in each metropolitan area of the study showed a continuous decreasing trend, while the Number of patches(NP) increased, which showed the degree of green space affected by human influence gradually increased, the degree of connectivity gradually decreased，and the degree of fragmentation increased. Among them, the overall change of LPI and COHESION in Shanghai metropolitan area and Su-Xi-Chang metropolitan area was relatively large.

In the Hefei, Nanjing, and Su-Xi-Chang metropolitan areas, the number of blue space patches remained relatively stable from 2000 to 2020, while in the Hangzhou, Ningbo, and Shanghai metropolitan areas, the number of blue space patches increased, with the highest increase in the Shanghai metropolitan area. From 2010 to 2020, the blue space of Hefei and Nanjing metropolitan areas first presented fragmentation, and then presented concentrated contiguous. The fragmentation in the Shanghai metropolitan area increased significantly from 2015 to 2020. The COHESION and LPI of blue space tended to be stable except for Ningbo metropolitan area. The LPI and COHESION of Ningbo metropolitan area fluctuated greatly, with connectivity and patch dominance reaching the maximum in 2010.

Overall, the indicators for green space change more significantly, which means green space is more affected by human activities than blue space during urban development. The faster a city develops, the more damage is done to the green space landscape, while changes in the blue space landscape are influenced by different urban development patterns.

3.3.2 Landscape change characteristics of blue-green space

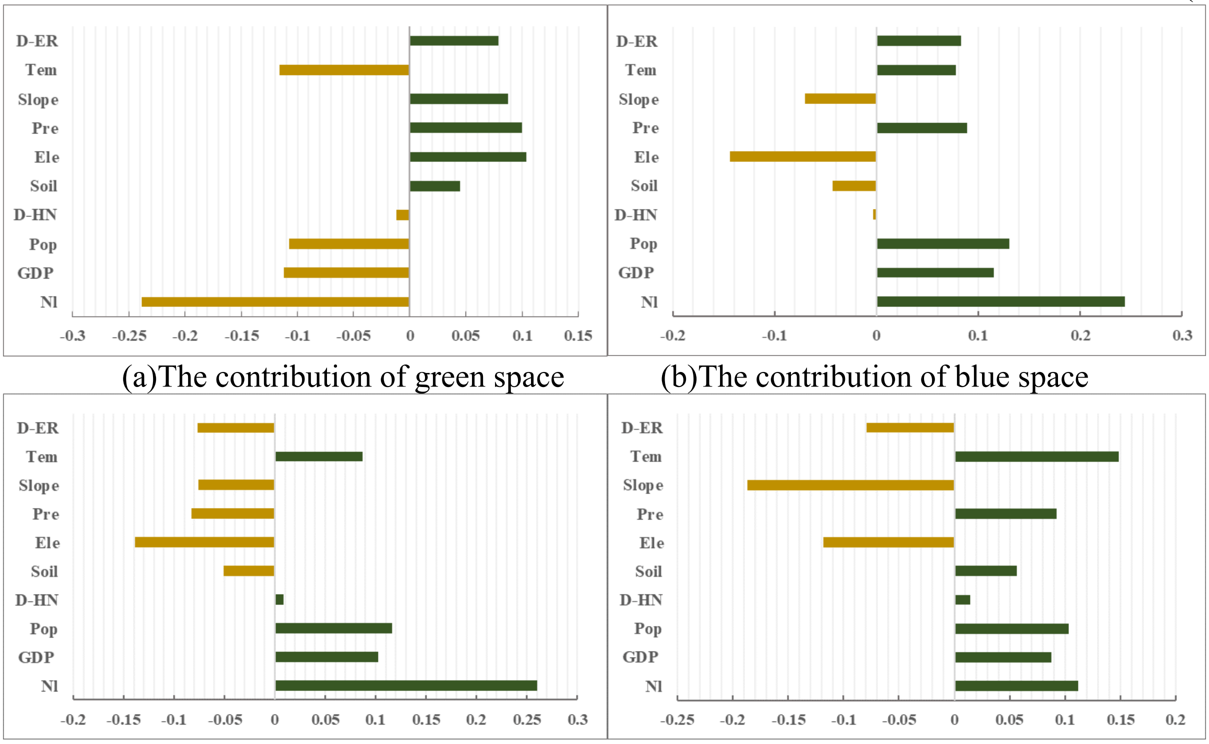
Table 7 Landscape index of blue-green space landscape in Yangtze River Delta region

	PD	LSI	AI	SHDI
2000	4753250902	152.3463	94.8399	0.3018
2005	4695464750	156.5713	94.6931	0.3261
2010	4528688708	164.417	94.4296	0.3696
2015	4493603106	168.2734	94.297	0.3877
2020	4451101120	170.6686	94.2255	0.4027

Table 7 shows that the study areas patch density declined gradually between 2000 and 2020, indicating increasing landscape fragmentation. During this period, the landscape shape index showed a gradual increase, showing that all landscape types became more discrete and irregular in shape. The Agglomeration Index declined by 0.6144, indicating that blue-green spaces were less aggregated in their layout. The Shannons diversity index increased by 0.1009, indicating a ba lanced distribution of patch types and a richer variety of land use types.

3.4 Analysis of the contribution of PLUS model driving factors

The blue-green spatial raster data and the processed data of elevation (Ele), precipitation (Pre), temperature (Tem) , distance from ecological reserve (D-ER) , Slope, Soil , GDP , Nighttime lighting(Nl) , Population (Pop), Distance to highway network (D-HN) were imported into the PLUS model. The LESA module of the Markov-PLUS model was applied to the development probability of each land use category Calculations, and the extent to which each driving factor contributed to the change in expansion of each category as shown in the figure.



(a)The contribution of green space (b)The contribution of blue space

(c)The contribution of construction land (d)The contribution of unutilized land

Fig. 5 The contribution of land use type

For green space, the most significant driving factors are nighttime lighting, temperature and GDP. Among natural environment factors, temperature and elevation have a greater impact on green space change, with average of 0.116 and 0.104 respectively. The southern part of the Yangtze River Delta is mostly hilly, while the northern part is mostly plain, and vegetation change is more influenced by light, heat and temperature conditions. Building in areas with high elevation and low temperature can greatly increase the production costs of development operators, so green space tends to be stable. As elevation continues to decrease, suitable temperatures are more conducive to human life and production activities, which gradually increases its influence on green space, leading to a higher percentage of arable land being converted to construction land. Among the factors of social conditions, the degree of regional development represented by nighttime lights has the most obvious influence on green space, with a contribution of 0.238 in the overall probability of change. The areas where green space decreases are mostly located around areas with high values of nighttime lights, especially around big cities such as Shanghai, Hangzhou, Nanjing and Hefei. It can be interpreted as the green space in the suburbs of towns is mostly influenced by urban expansion, indicating that the transformation of green space is to a large extent linked to the degree of regional development. In addition, GDP and population are also play crucial roles in green space change. As the economy rises, urban industries require more land for expansion, and the growing population demands more space for housing, leading to a reduction in green space.

Nighttime lighting is the most significant factor affecting the transformation of blue space, followed by elevation and population. Urban development and human living needs are the primary causes of the transformation of blue space, as seen in the Taihu Lake basin, where areas with higher development and population experience significant increases in blue space. Elevation plays a critical role in the transformation of blue space, with naturally expanding waters found mainly in areas with lower elevation. Regions with abundant precipitation or close to ecological reserves are also more prone to change, leading to a positive effect on water area.

Since 2000, approximately 14,533.80 km^2 of blue-green space has been transferred to construction land in the total transfer amount of blue-green space. Therefore, the study of the factors influencing the increase of construction land is an indirect analysis of the drivers of the reduction of blue-green space. For construction land, the degree of regional development represented by "Nighttime lighting" is the first contributor to the increase in construction land. This indicates that the urban development has regional continuity, with areas of higher development level being further driven to convert blue-green space into construction land. Since the distribution of construction land is consistent with the distribution of Nighttime lighting, after excluding Nighttime lighting, elevation, population, GDP and precipitation are the main driving factors of the increase in construction land. The urban economic development attracts the gathering of population and industry. The more frequent human activities are, the less conducive ecological restoration is. As a result, the expansion of construction land is accompanied by a decrease in blue-green space. Among the natural factors for the increase of construction land, elevation and temperature are the two natural environmental factors with higher contribution, indicating that the protection of blue-green space and urban development have "dual desirability" characteristics, so the key to solve the contradiction between them is the reasonable coordination and utilization of space.

In addition, in terms of the mechanisms driving change from unutilized land, the limiting effects of natural influences such as slope, temperature and elevation make land use more difficult and more expensive to maintain or develop, also leading to some blue-green space being abandoned as unutilized land.

4. Conclusion and Discussion

4.1 Conclusion

(1) During the period of 2000-2020, the dynamic degree of blue-green space in the six metropolitan areas of the Yangtze River Delta showed obvious phased characteristics. Blue space increased first and then decreased, changing dramatically, while green space continued to grow negatively. The Su-Xi-Chang metropolitan area had the highest rate of blue-green space change, followed by the Shanghai, Ningbo, Nanjing, Hangzhou, and Hefei metropolitan areas, which has a clear characteristic of the decline trend from coastal to inland. In the last five years, the rate of blue-green space change in each metropolitan area has decreased, showing that the regional ecology is gradually being restored.

(2) Land use changes in the Yangtze River Delta region are mainly manifested by a significant decrease in green space and a great increase in construction land. The occupation of construction land is the main reason for the decrease in blue-green space, which is closely related to urban expansion. In recent years, influenced by the policies of arable land protection and forest land protection, blue space and construction land have also been gradually transformed into green space. The conversion of green space to construction land is concentrated in the more economically developed areas of Jiangsu and Shanghai and the conversion of green space to blue space is mainly in the Taihu Lake and Qiantang River basins, while the conversion of construction land to green space occurs mostly in inner-city areas due to peoples pursuit of a higher quality of life. The overall of green space in the study area has improved since 2010, and the metropolitan areas have become more balanced.

(3) Urban development has a greater impact on the green spatial landscape, while blue spatial change is influenced by different urban development patterns. At the patch level, the dominance and the connectivity of the largest green space patches in the study area continue to diminish, resulting in a high degree of fragmentation. The more developed metropolitan areas of Su-Xi-Chang and Shanghai suffer greater human disturbance. The blue space patches of Hangzhou, Ningbo and Shanghai metropolitan areas have significantly increased, while the blue space patches of Hefei and Nanjing metropolitan areas have gradually shifted from fragmentation to concentrated contiguity since 2015. The Patch cohesion index and the Largest patch index of blue space have stabilized except for Ningbo metropolitan area. At the landscape level, with the urban development in the Yangtze River Delta, the blue-green space landscape in the Yangtze River Delta has become more fragmented, less clustered, more complex in shape, and the landscape types in the region are regionally balanced and evenly distributed.

(4) Spatiotemporal changes in blue-green space in the Yangtze River Delta metropolitan area are driven by multiple factors. Socio-economic factors are the direct driving factors, while natural factors

are relatively insignificant driving factors of blue-green spatial change due to their long-term fixed characteristics. Overall, the level of urban development, population volume and economic level are the main socio-economic driving factors, while temperature, elevation and precipitation are the main natural driving factors. Areas with a high level of development will continue to drive the expansion of construction land, as a result the layout and scale of blue-green space should be appropriately configured for the " dual desirability " of blue-green space protection and urban development.

4.2 Discussion

The spatiotemporal characteristics of blue-green space in the Yangtze River Delta metropolitan areas show certain commonalities as well as major differences. In terms of commonality, from 2000 to 2010, the rapid urbanization of the Yangtze River Delta attracted an agglomeration of population and capital, and a large amount of green space was occupied by construction land in the form of spreading from urban areas to suburban areas, resulting in drastic changes in blue-green space. From 2010 to 2020, except for Hangzhou metropolitan area, metropolitan areas showed a decrease in the rate of change of blue-green space, indicating that the policy and the region have entered a stage where there is a greater emphasis on ecological protection after experiencing rapid economic development. The relevant policies on returning farmland to forests, lakes and wetland protection have been further improved, and the trend of shifting from incremental development to sustainable development has become mainstream, with signs of improvement in regional ecology. However, for a long time in the actual construction of the city, blue-green space has been divided into different governance and waterfront has been built separately, resulting in many problems such as blue-green space fracture and waterfront division. The blue-green spatial landscape pattern in the Yangtze River Delta tends to be fragmented and complicated and the connectivity has weakened, which exacerbates the evolution of the ecological pattern of blue-green space, failing to manifest the ecological effect and ecological synergistic service functions.

In terms of differences, the demand for blue space and green space varies between each metropolitan area due to their different development directions. The Shanghai metropolitan area has always been at the forefront of economic development in the Yangtze River Delta, with a highly developed modern service industry. The Su-Xi-Chang metropolitan area received the spillover effect of Shanghais manufacturing industry earlier, with manufacturing as the leading industry. This has led to a large conversion of green space to construction land in the two metropolitan areas during the urban expansion process, resulting in more fragmented green space. The change in blue space varies according to different urban development patterns. The Yangtze River Delta region took the lead in promoting the river chief system and carrying out ecological compensation. So the treatment of the Taihu Lake basin in the Su-Xi-Chang metropolitan area and the Qiantang River basin in the Hangzhou metropolitan area has achieved significant results, with rapid expansion of blue space.

The PLUS model analysis reveals that blue-green spatial changes in the Yangtze River Delta result from a combination of natural and socio-economic factors. Natural factors such as elevation, temperature, and precipitation determine the distribution of blue-green space patterns. The main factor driving blue-green space is nighttime lighting, indicating that rapid urbanization is the main cause of blue-green spatial transformation in the region. Urban sprawl has led to a significant decrease in green space around large cities, while population concentration and economic development have also impacted blue-green space. On the one hand, the expansion of construction land has reduced ecological land. On the other hand, with the economic development and improvement of living standards, peoples need for a beautiful ecologica l environment is growing. Therefore, the protection of blue-green space must be coordinated with urban development.

Based on the analysis of spatiotemporal changes and driving factors of blue-green space in the Yangtze River Delta metropolitan areas, the following recommendations are made.

(1) To strengthen the ecological control of blue-green space in the Yangtze River Delta, there should be an emphasis on implementing and managing blue-green space planning while ensuring land use scale, adhering to arable land and ecological protection, and providing targeted protection for

blue-green space. It's necessary to link the increase and decrease of urban construction land, regulate new construction land, and balance blue-green space protection and urban development. Building ecological protection zones around cities and maximizing their role in protecting blue-green space and regulating urban ecology is also important.

(2) To optimize blue-green space in the Yangtze River Delta metropolitan areas, zone-based protection should be implemented to integrate blue-green space resources. Coastal and lake-ring areas, urban parks, and artificial ponds should be managed for water environment. Highly urbanized areas should have increased landscapes, and an ecological network of blue-green space should be formed to create an ecological corridor of mountains, water, forests, fields, lakes and grasses. This will improve the urban landscape while promoting sustainable ecological development, meeting human needs, and regulating blue-green space.

(3) When changing the structure and land use type of blue-green space, it is significant to evaluate the ecological benefits before and after the change to avoid the loss of ecological benefits caused by unreasonable use. By incorporating the quantified results of ecological restoration of blue-green space into the performance assessment of the main body responsible for the implementation of ecological protection and restoration, problems in the process of ecological protection and restoration can be identified so that countermeasures can be taken in a timely manner to ensure the long-term effectiveness of ecological restoration.

Blue-green space is a complex ecological mechanism that involves multiple disciplines and layers of influencing factors. Therefore, there are certain professional limitations in the depth of knowledge involved in this study, and there may be some inadequacies. The spatiotemporal characteristics of blue-green spatial changes in the metropolitan areas based on higher resolution images need to be studied, the interaction of blue-green spatial driving factors in the metropolitan areas needs to be further verified, and the trend of blue-green space changes in the metropolitan area needs to be further modelled and predicted, with a view to giving better play to the positive role of blue-green space ecological land use in the future land use planning and design process. The final aim is to plan and construct the metropolitan area in a scientific and reasonable manner, so as to achieve the harmonious development of economic development and ecosystem.

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