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Study on the Layout of Ecological Space and the Integrated Management Mechanism of the Yangtze River Delta Urban Agglomeration

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Abstract: The urban agglomeration at the Yangtze River Delta is one of the six most developed and populated urban agglomerations in the world. In recent years, with accelerating urbanization, the land use has changed significantly. Excessive construction aggravates ecological fragility. In this context, this paper first investigates the evolutionary processes and layout of the ecological space in the Yangtze River Delta. The root causes of various problems are then analyzed. Finally, suggestions for further improvement in both detailed tasks and governance aspects are proposed. The applied methods included use of remote sensing (RS), geographic information system (GIS) and statistical analysis. Main results indicate that from 1990 to 2018, the ecological space of the Yangtze River Delta shrank, especially in the city of Shanghai. Ecological space is insufficient in the area, unevenly distributed and fragmented. The major root causes include rapid urbanization without overall planning, regional population surge and improper industrial structure. Suggestions for improvement include overall planning and integrated management, control of population size, active industry structure upgrade, land-use efficiency balanced with ecological indicators, and multiple integrated strategies encouraging application of new energy technologies.

Keywords: ecological space; ecosystem service; remote sensing; urban agglomeration; the Yangtze River Delta

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1. Introduction

Ecological space refers to non-construction lands. It can be classified into green and other ecological space. Green ecological space includes grasslands, forests, wetlands and water bodies, while other ecological space includes bare land, sand, saline-alkali land and deserts. As important carriers of biodiversity and a source of ecosystem services, ecological space is important for the sustainable development of human beings and should be well protected.

In recent decades, changes to ecological space and the corresponding consequences have become a research focus [1–4]. Some research concentrates on indicators describing the quantified consequences of worsened ecological spaces [5–7]. For example, Sun et al. selected eight representative cities in China to carry out research between land-cover change (LCC) and air pollution based on MODIS data. The results showed that the correlation between particulate pollution and LCC is lower in coastal areas, but higher in inland areas [7]. Besides air pollution, other relevant indicators include structure and quality of vegetation, quantity and pattern of patches, functionalities of ecosystem services, quality of water and ecological risks [8–14]. Some research has attempted to set up a framework for recognition of critical ecological spaces and propose methodologies to approach optimized planning [15–17]. Along with patches, linear ecological spaces, such as ecological corridors, are considered as well. For example, targeting the identification of key ecological sources and corridors which play an important role in achieving regional sustainability, Xiao et al.

investigated ecological security patterns in regards to biodiversity, carbon storage, water yield and ecological sensitivity indicators. Then, a methodology framework to prioritize important ecological spaces, including ecological corridors, was built [18]. Combining new technologies such as biotelemetry, remote sensing (RS), network analysis, current analysis, trace investigation, corridor recognition and minimized accumulated resistance analysis, large-scale research has advanced in revealing a complete overview of ecological spaces [19,20]. Liao et al. proposed a multi-scale land-use optimization method. By examining the upper reaches of the Yangtze River in southwest China, it was found that the key to land-use optimization in hilly areas was to increase the area of ecological spaces and improve the capacity of regional ecosystem services [20]. Harini et al. examined the efficacy of multiscale assessments of biodiversity linking remote sensing on larger spatial scales with localized field sampling. Their conclusions suggest linking localized field investigations of biodiversity with remotely sensed information, permitting extrapolations at progressively higher scales [21].

In the field of ecological space governance, international academics value coordination mechanisms and integrated governance of ecological space across administrative regions. The integrated development mode is regarded as the most effective way to achieve sustainability [22]. For example, the integrated governance of the Mekong River Basin by the Mekong River Commission was successful in improving technical understanding, developing planning tools and improving cooperation between the four lower Mekong countries [23]. Another successful case is the integrated governance of ecological space in the Xin'an River Basin across Anhui and Zhejiang provinces. The integrated governance is realized by systematic clarification of property rights, special laws and regulations and wide public participation [24]. In general, it is a compensation mechanism with multiple participants including the government, market and society.

The urban agglomeration at the Yangtze River Delta is one of the six most developed and populated urban agglomerations in the world. Its integrated development has achieved remarkable results. At the end of 2018, the government promoted the regional integration of the Yangtze River Delta as a national strategy. This brought great opportunities. However, challenges such as unbalanced development of territorial space, industrial isomorphism, limited energy and resources, and tight ecological and environmental constraints are ahead. The region has especially experienced a rapid urbanization process, resulting in serious erosion and destruction of ecological space. Fragility and fragmentation problems of ecological space need to be solved [25–29]. Wang et al. analyzed spatial and temporal variations in the ecological spaces of the Yangtze River Delta and examined the comprehensive ecological carrying capacity based on available water resources, regulation of water and air quality and leisure and recreation. It was found that 73.1% of the ecological capacity was severely overburdened [29]. Some research provides methods from the perspective of natural resource management, including ecological compensation mechanisms, policy-linking, territorial space governance and natural resource performance management and assessment to improve the ecological space [30,31]. There is also research carried out from the perspective of development dynamics, mechanisms, demonstration zone construction and integrated development. Achievements cover many aspects, such as economy, urban construction, transportation and water conservancy, water resources and rural revitalization, contributing intelligent points to promoting the developmental potential of the region [32–35]. However, the maintenance of ecosystem integrity, landscape ecological process optimization and the construction of integrated ecological security patterns have not yet been discussed.

How to build a natural, structured, connected, efficient, diverse and self-regulating ecological space for the Yangtze River Delta is the focus of this study. Using RS, geographic information system (GIS) and statistical analysis, the ecological space of the Yangtze River Delta was investigated and visualized. The dynamic evolution from 1990 to 2018 was revealed. Next, ecological space problems and their root causes were analyzed. Finally, suggestions for improvement were proposed in regards to both practical tasks and governance

strategies. The conclusions can serve as an important clue for sustainable development and eco-city construction in the Yangtze River Delta.

2. Study Area and Methodology

2.1. Study Area

According to the Development Plan of the Yangtze River Delta Urban Agglomeration approved by The China State Council in May 2016, the Yangtze River Delta urban agglomeration (Figure 1) includes Shanghai, nine cities in Jiangsu Province, eight cities in Zhejiang Province and eight cities in Anhui Province. The total area covers around 21,700 km^2 and the total population is around 225 million. Shanghai, as the central city of the agglomeration, is the finance and economy center of China. All major cities in the urban agglomeration are within 1 h ride by high-speed train.

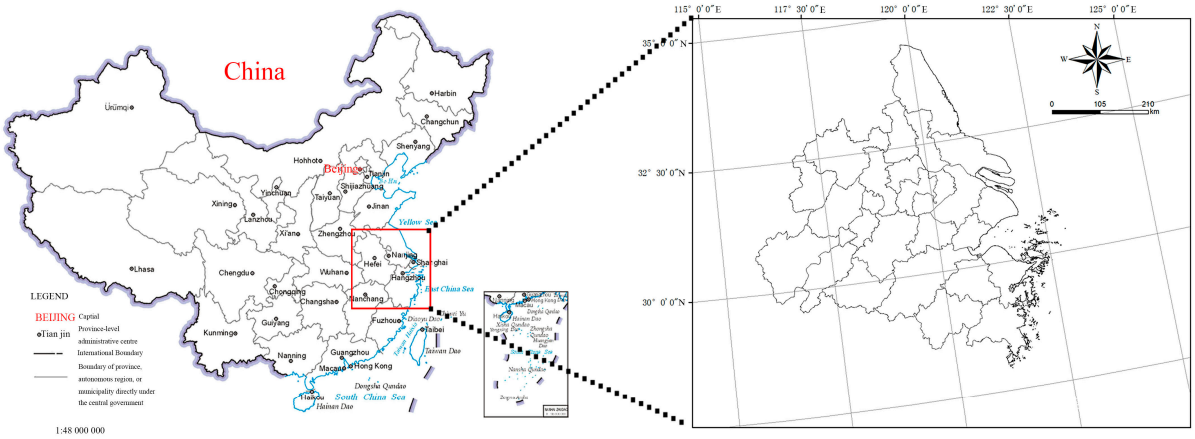


Figure 1. Location map of the Yangtze River Delta (source: http://bzdt.ch.mnr.gov.cn/ accessed on 18 November 2022).

2.2. Classification of Land-Use Based on Remote Sensing

Land-use classification (LUC) data can directly reflect the status of ecological spaces. In this research, through supervised classification of LandSat-8 RS images in ENVI 5.1 software, the LUCs of the Yangtze River Delta Urban Agglomeration in 1990, 1995, 2000, 2015 and 2018, with a spatial resolution of 30 m, were obtained. In order to improve the accuracy of the results, the LUC data was compared to the LUC obtained through manual visual interpretation based on high-resolution Google Earth images in ArcGIS software. Field trips were also conducted when the differences could not be manually corrected. The LUC in this research includes: Construction Land (CL), Green Land (GL), Wet Land (WL), Agricultural Land (AL) and Bare Land (BL). Descriptions of the classes are listed in Table 1.

Table 1. Descriptions of land-use classification.

Class of Land-Use	Description
Construction Land (CL)	land for residential areas, transportation facilities, special use, mining areas, etc.
Green Land (GL)	land covered by vegetation, including forests, parks, grasslands, etc.
Wet Land (WL)	Intersection of land and water
Agricultural Land (AL)	Land for agricultural activities
Bare Land (BL)	Land with no vegetation coverage and not used

2.3. Landscape Pattern Index Calculation

Landscape pattern refers to the distribution and integrated features of landscape combinations with different sizes, shapes and attributes. In this study, based on LUC data, landscape pattern index was calculated by Fragstats 4.2 software to support further analysis

of the quality of ecological spaces, especially the degree of fragmentation. Eight indicators of landscape pattern were selected to describe ecological spaces. They are listed in Table 2.

Table 2. Selected indicators of landscape pattern.

	Indicator	Description
Amount	Patch number (NP)	Describes the number of patches. Larger numbers indicate greater landscape fragmentation
	Patch density (PD)	The number of patches within every 100 ha
Shape	Landscape shape Index (LSI)	Shape complexity of a patch. For circle, LSI = 1, for square, LSI = 1.13
	Fractal dimension index (PAFRAC)	Indicates the complexity of landscape integration. Bigger values indicate greater fragmentation
Structure	Interspersion and juxtaposition index (IJI)	Reflects the distribution and combination of patches of different types. For each patch next to only one other type of patch, IJI approaches 0; otherwise IJI approaches 100
	Contagion index (CONTAG)	Indicates the degree of connection between patches. Low CONTAG indicates the landscape is formed by small patches. High values indicate superior patches have a good connection between each other
	Aggregation Index (AI)	Indicates the distribution feature, averagely distributed or aggregated

2.4. Linking Analysis with Public Statistical Data

Along with the data from LUC and landscape pattern analysis, statistical data from statistical yearbooks published by the government were also introduced in this study. The indicators included population, industrial structure, per capita greening area in the cities, etc. These data supported the analysis of the root causes of the ecological problems.

3. Results

3.1. Temporal Evolution of LUC and Ecological Space

The LUC data of the Yangtze River Delta are shown in Table 3. The spatial and temporal patterns of ecological space were then analyzed. The temporal evolution and spatial distribution characteristics are visualized in Figure 2.

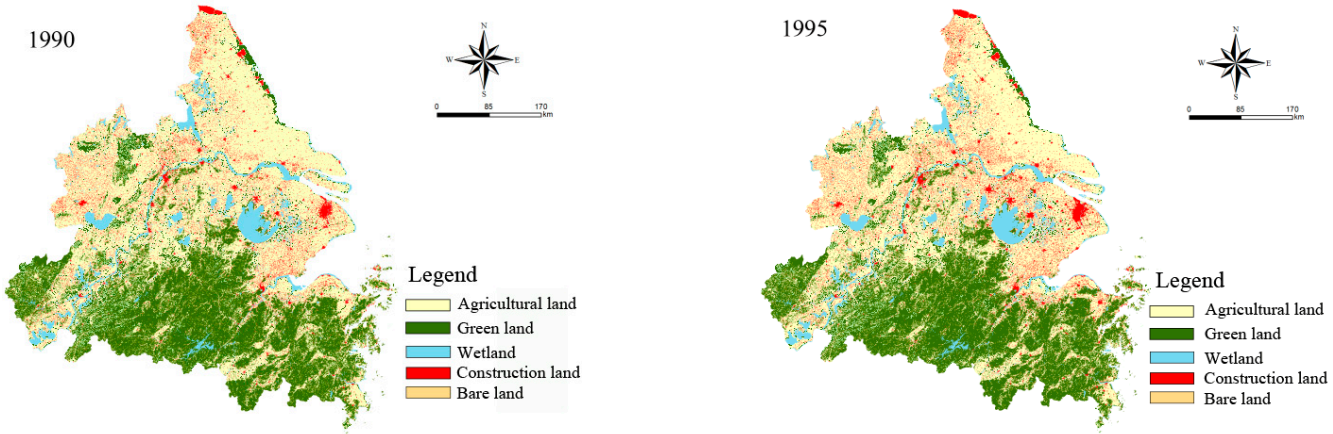


Figure 2. *Cont.*

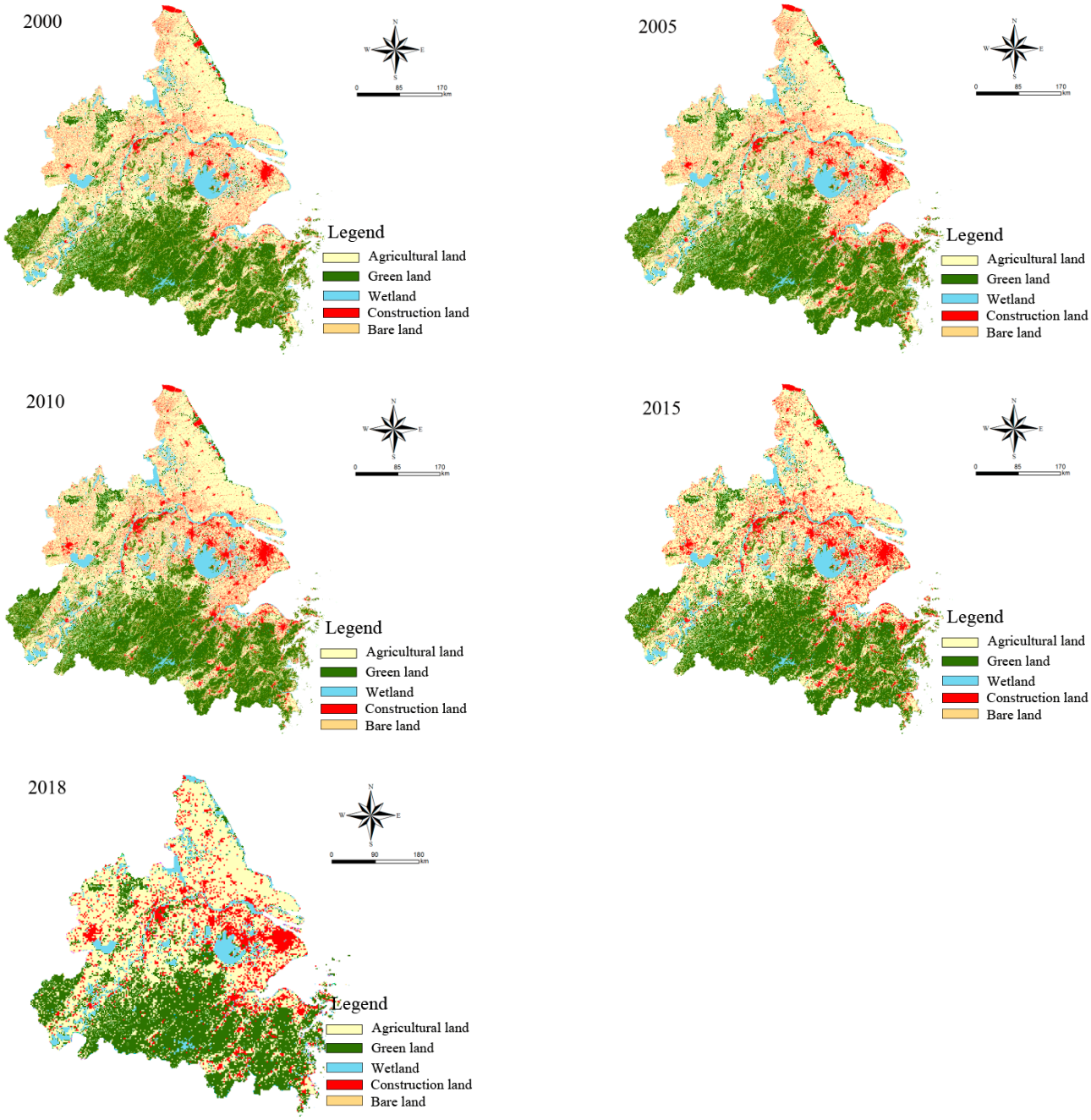


Figure 2. LUC result of the Yangtze River Delta from 1990–2018.

Table 3. LUC classification data 1990–2018(Unit: km^2).

Year	CL	GL	WL	AL	BL
1990	11,950.53	73,297.59	16,436.98	116,575.31	43.50
1995	14,118.22	73,692.1	16,458.03	113,851.71	48.93
2000	15,402.53	73,351.57	16,433.12	113,081.59	32.50
2005	18,639.63	73,508.16	16,393.44	109,744.98	33.96
2010	21,204.14	73,498.82	16,365.13	107,234.12	33.57
2015	22,012.21	73,324.34	16,286.14	106,704.45	31.56
2018	22,785.56	73,360.74	16,274.24	106,107.69	27.93

According to Table 3, from 1990 to 2018, CL increased from 11,950.53 km^2 to 22,785.56 km^2, doubling in 25 years; meanwhile, AL decreased around 10,000 km^2 in 25 years, from 116,575.31 km^2 to 106,107.69 km^2. A large amount of AL was converted into CL. The ecological space area decreased from 89,778 km^2 to 89,662 km^2. The breakdown shows GL, WL and BL decreased from 73,297.59 km^2, 16,436.98 km^2 and 43.5 km^2 to 73,360.74 km^2, 16,274.24 km^2 and 27.93 km^2, respectively. The change curves of all LUC are shown in Figure 3.

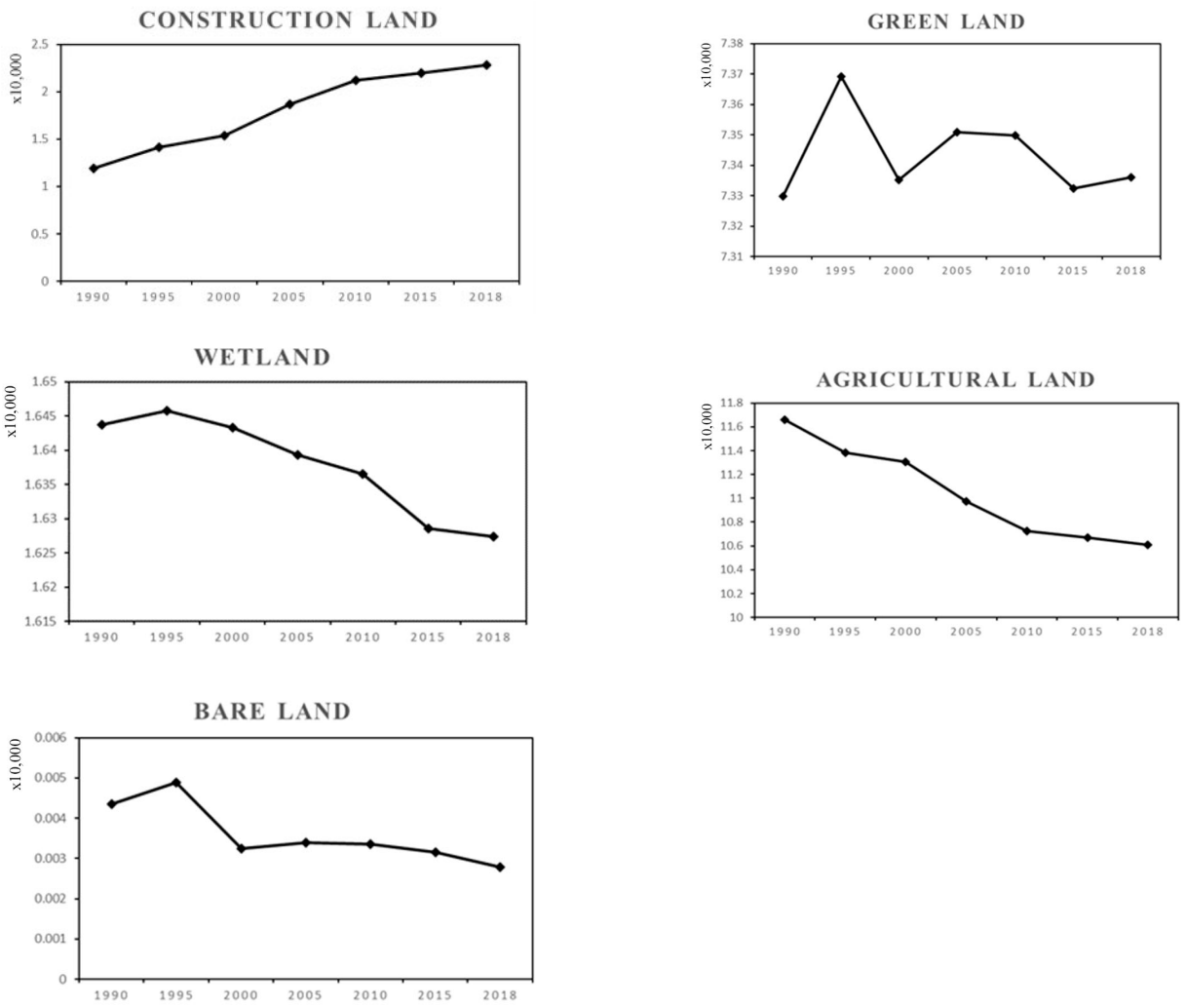


Figure 3. Change curves of land-use areas in the Yangtze River Delta from 1990 to 2018.

The LUC data of different provinces are listed in Table 4. The data change is visualized in Figure 4.

Table 4. LUC data of different provinces in the Yangtze River Delta Urban Agglomeration (Unit: km^2).

Province	Year	AL	GL	WL	CL	BL
Anhui	1990	40,617.64	32,926.42	5417.5	3517.24	4.5
	1995	40,560.99	32,910.94	5431.77	3571.55	4.5
	2000	40,181.26	32,907.66	5450.39	3937.05	4.49
	2005	39,955.83	32,910.41	5497.4	4122.74	4.49
	2010	39,437.41	32,873.66	5533.04	4631.87	4.87
	2015	39,398.97	32,826.16	5365.61	4487.31	3.39
	2018	39,267.81	32,477.19	5304.08	5229.49	2.87

Table 4. *Cont.*

Province	Year	AL	GL	WL	CL	BL
Jiangsu	1990	48,063.3	3246.18	7888.31	5169	12.37
	1995	46,535.47	3245.44	7985.22	6602.67	12.05
	2000	45,988.82	2952.36	8237.46	7197.03	12.37
	2005	44,851.45	2880.03	8518.89	8125.73	12.35
	2010	43,530.76	2843.13	8539.42	9463.71	11.97
	2015	43,452.19	2799.47	8288.05	9577.62	10.96
	2018	43,120.78	2772.55	8165.58	10,321.8	8.28
Shanghai	1990	4994.42	160.93	550.34	1102.91	0
	1995	4759.58	130.25	564.39	1335.75	0
	2000	4580.26	129.09	582.92	1415.8	0.14
	2005	4260.31	143.1	489.07	1822.27	0.14
	2010	3944.3	137.19	486.16	2149.66	0.14
	2015	3919.02	123.17	445.88	2202.08	0
	2018	3856.21	134	437.26	2290.1	0
Zhejiang	1990	23,288.03	36,933.48	2166.07	2259.3	26.59
	1995	22,384.31	37,649.8	2061.41	2606.17	13.01
	2000	22,319.73	37,337.84	2147.32	2850.35	15.61
	2005	20,666.21	37,153.25	2272.46	4575.77	16.94
	2010	20,310.65	37,123.83	2290.37	4955.24	16.54
	2015	19,417.19	37,244.63	2139.06	5681.66	10.65
	2018	19,038.35	37,340.82	2067.97	6240.1	9.39



Figure 4. Visualization of the LUC change in different provinces.

According to Table 4, the ecological space of Anhui and Shanghai decreased continuously. Figure 4 shows that the rapid urbanization process led to a surge of CL, encroaching on a large amount of ecological space and AL. However, the ecological space of Jiangsu Province and Zhejiang Province increased slightly from 2000 to 2005. This was because the state implemented a policy of returning farmland to forest in 2002; thus, woodland in the two provinces increased.

The population data and calculated per capita ecological space data are listed in Table 5. The change curves of per capita ecological space of the provinces are visualized in Figure 5. The per capita ecological space decreased from 50.46 m^2 in 1990 to 36.09 m^2 in 2018. The main reason was the large population inflow driven by economic development. The population increased from 178 million to 225 million from 1990 to2015. Figure 5 shows that the decreasing per capita ecological space trend applies to all provinces.

Table 5. Population and per capita ecological space of each Province in the Yangtze River Delta Urban agglomeration (population data from: http://www.stats.gov.cn/ accessed on 01 November 2022).

	Year	Ecological Space Area (km^2)	Population (Million)	Per Capita Ecological Space Area (m^2/Person)
Anhui	1990	38,348.42	56.18	68.26
	1995	38,347.21	60.13	63.78
	2000	38,362.54	59.86	64.09
	2005	38,412.3	61.20	62.77
	2010	38,411.57	59.57	64.48
	2015	38,212.16	61.44	62.19
	2018	37,784.14	63.24	59.74
Jiangsu	1990	23,094.20	67.06	34.31
	1995	11,242.71	70.66	15.91
	2000	11,202.19	74.38	15.06
	2005	11,411.27	74.75	15.27
	2010	11,394.52	78.69	14.48
	2015	11,112.48	79.76	13.93
	2018	10,946.41	80.51	13.59
Shanghai	1990	711.27	13.34	5.33
	1995	694.64	14.15	4.91
	2000	712.15	16.74	4.25
	2005	632.31	17.78	3.56
	2010	623.49	23.03	2.71
	2015	579.05	24.15	2.40
	2018	571.26	24.24	2.35
Zhejiang	1990	39,126.14	41.45	94.39
	1995	39,724.2	43.99	90.30
	2000	39,500.77	46.77	84.46
	2005	39,442.65	48.98	80.53
	2010	39,430.74	54.47	72.39
	2015	39,394.34	55.39	71.12
	2018	39,418.18	57.37	68.70

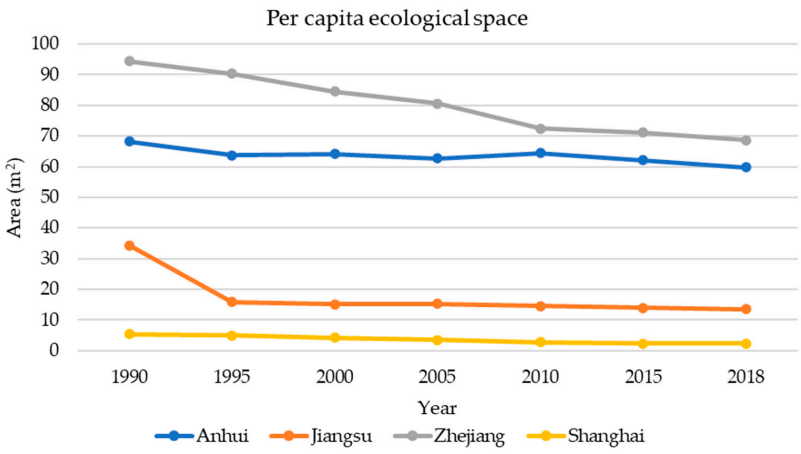


Figure 5. Change curves of per capita ecological space of each Province in the Yangtze River Delta Urban agglomeration.

3.2. Spatial Distribution Characteristics of Ecological Space

According to Table 4, the distribution pattern of ecological space in the Yangtze River Delta is high in the south and low in the north. The majority of ecological spaces are in Zhejiang (39,000 km^2) and Anhui Province (38,000 km^2). Shanghai (0.07 km^2) and Jiangsu (11,000 km^2) have a small number of ecological spaces. The spatial pattern characteristic is determined by the natural topography. The south of Zhejiang and Anhui Province is dominated by mountains where urban development and construction are difficult. Thus, the LUC is mainly GL and the ecological space is well-maintained. Shanghai and the northern part of Jiangsu Province are mainly flat terrain. They are suitable for urban development and construction, resulting in small ecological space.

According to Table 5 and Figure 5, the per capita ecological space area of each province in the Yangtze River Delta decreased continuously. From 1990 to 2018, the per capita ecological space of Anhui decreased from 68.26 m^2 to 59.74 m^2, Jiangsu from 34.31 m^2 to 13.59 m^2, Shanghai from 5.33 m^2 to 2.35 m^2 and Zhejiang from 94.39 m^2 to 68.70 m^2. The per capita ecological space of Zhejiang and Anhui (in the southern part of the Yangtze River Delta) is large, while of Jiangsu (in the north) and Shanghai (in the center) is small. Therefore, the ecological spatial distribution in the Yangtze River Delta is uneven.

3.3. Landscape Pattern of Ecological Space

Landscape pattern indicators of the ecological spaces are listed in Table 6. The table shows that from 1990 to2015, the NP and LSI increased, with a reduced total area; the increased number of patches indicates significant increase in fragmentation.

Table 6. Landscape pattern indicators.

Year	NP	PD	LSI	PAFRAC	CONTAG	IJI	COHESION	AI
1990	148,377	0.6797	230.1842	1.448	56.3583	50.4698	99.8669	90.3633
1995	147,264	0.6744	234.9447	1.4486	58.9591	51.0277	99.8636	90.1594
2000	150,136	0.6877	240.507	1.4477	54.9689	57.3636	99.8628	89.9199
2005	157,887	0.7231	248.0004	1.4293	53.8139	57.8674	99.8547	89.6003
2010	163,079	0.7469	253.3171	1.4222	53.0491	57.9474	99.8458	89.3751
2015	174,990	0.7658	256.4332	1.4153	52.3418	58.8954	99.3224	89.1655
2018	184,620	0.7679	256.8921	1.4068	51.5729	59.3506	99.1087	89.0068

3.4. Industrial Structure Data

The industrial structure data summarized from statistical yearbooks are listed in Table 7. The change curves are shown in Figure 6. According to Table 7, from 1990 to 2018, a portion of Shanghai primary industry decreased from 4.3% to 0.32%; secondary industry decreased from 64.69% to 29.78%; and tertiary increased from 30.70% to 70%. One can observe that the service industry is now the Shanghai economy's main driver. As for the other three provinces, the secondary industry is still a major component. However, the dynamic trend differs. In Anhui province, the secondary and tertiary industry portions increased over time. This indicates the province is still in the industrialization stage. For Jiangsu and Zhejiang, except for the increase in tertiary and decrease in primary industries, the secondary industry increased in the period from 1990 to2005, decreasing after 2005. This indicates the two provinces are in the process of transitioning from industrialization towards tertiary.

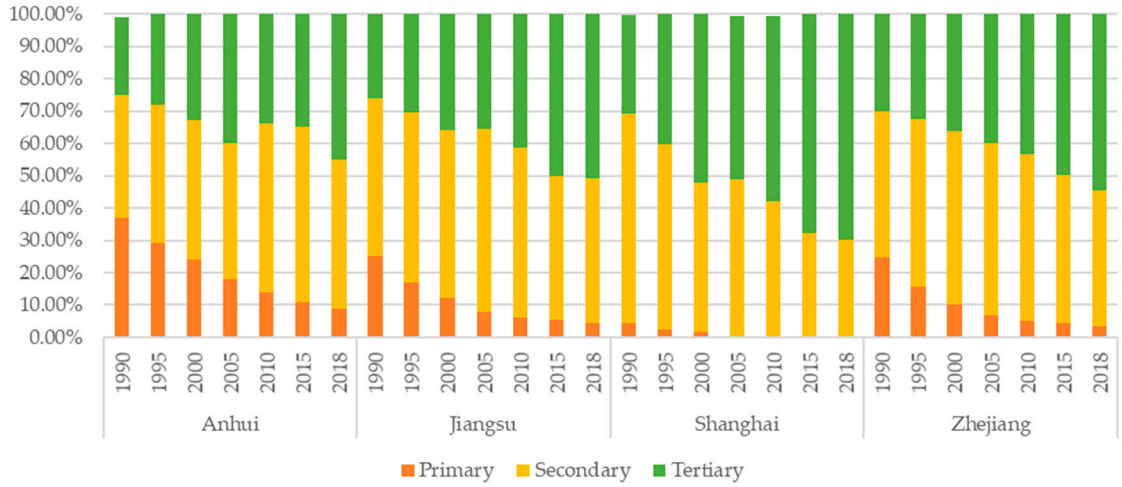


Figure 6. Change curves of the industrial structure of the Yangtze River Delta Urban agglomeration.

Table 7. Industrial structure of the Yangtze River Delta (source: http://www.stats.gov.cn/ accessed on 15 October 2022).

Province	Year	Primary	Secondary	Tertiary
Anhui	1990	37.00%	38.00%	24.00%
	1995	29.00%	43.00%	28.00%
	2000	24.00%	43.00%	33.00%
	2005	18.00%	42.00%	40.00%
	2010	14.00%	52.00%	34.00%
	2015	11.00%	54.00%	35.00%
	2018	8.79%	46.13%	45.08%
Jiangsu	1990	25.10%	48.90%	26.00%
	1995	16.80%	52.67%	30.53%
	2000	12.20%	51.90%	35.90%
	2005	7.86%	56.59%	35.55%
	2010	6.13%	52.50%	41.37%
	2015	5.27%	44.73%	50.00%
	2018	4.47%	44.54%	50.99%
Shanghai	1990	4.38%	64.69%	30.70%
	1995	2.50%	57.30%	40.20%
	2000	1.61%	46.27%	52.12%
	2005	0.09%	48.64%	50.48%
	2010	0.07%	42.05%	57.28%
	2015	0.43%	31.80%	67.76%
	2018	0.32%	29.78%	70.00%
Zhejiang	1990	24.87%	45.12%	30.01%
	1995	15.46%	52.12%	32.42%
	2000	10.28%	53.31%	36.41%
	2005	6.65%	53.40%	39.95%
	2010	4.91%	51.58%	43.51%
	2015	4.27%	45.96%	49.77%
	2018	3.50%	41.83%	54.67%

4. Ecological Space Problems

4.1. Insufficient Ecological Space

According to the above results, the ecological space of the Yangtze River Delta is insufficient. In particular, both the total and per capita numbers are significantly decreasing. The per capita area decreased from 50.45 m^2 in 1990 to 36.09 m^2 in 2018. According to the statistical yearbook, the per capita greening area of Shanghai is 8.8 m^2, which is much

lower than that of global cities such as New York (19.2 m^2), London (22.8 m^2) and Paris (24.7 m^2). Even in Hangzhou, the top green city in the agglomeration, the per capita greening area is 17.32 m^2, which is much lower than in developed countries (25–40 m^2). Insufficient ecological space leads to a threatened biodiversity. The livability and urban thermal environment are also impacted.

4.2. Uneven Spatial Distribution

According to Table 5 and Figure 2, the distribution of ecological space is uneven. Ecological space is high in the south while low in the middle and north. The two provinces in the south, Zhejiang and Anhui, have ecological spaces of 39,000 km^2 and 38,000 km^2, respectively, taking up 87% of the total available area. Shanghai in the center and Jiangsu in the north have ecological spaces of 700 km^2 and 11,000 km^2, taking up 0.7% and 12.3% of the total amount, respectively. This distribution pattern impedes the development of the Yangtze River Delta.

4.3. Quality Decrease

According to Table 6, the degree of fragmentation of ecological space increased. Fragmentation leads to a decrease in the quality of ecological service functions. One example is that heat island intensity and area increased significantly during the period from 2000 to 2015 [36]. Ecological space is losing the ability to mitigate heat islands. Other service performances are also weakened, including environmental purge, noise reduction, water conservation, soil activation, nutrient cycling, maintaining biodiversity, improving health, disaster prevention and providing recreational spaces [37–40].

5. Root Cause Analysis of Ecological Space Problems

The Yangtze River Delta is one of the most developed regions in China. The ratio of urbanization reaches 64.7%. The rapid urbanization, population increase and industrial structural change leads to ecological space problems. The fragility of regional ecosystems increases.

The most obvious root cause of the current state of ecological space is urban expansion. Along with the rapid urbanization is the low efficiency of land use due to the disorderly expansion of cities. CL significantly increased (by 9900 km^2) while AL decreased (by 10,300 km^2). The degree of fragmentation of urban landscape increased. Meanwhile, the strength of land development is excessively high, which harms the potential for sustainable development. According to statistical data, the unified strength of land development in the downtown area is 36%. This is much higher than in most iconic cities including Paris (21%) and London (24%). With the current strength of development, all available construction land would soon be consumed.

Another key factor is the population surge. The well-developed economy attracts massive labor resources. According to Table 5, the population of the Yangtze River Delta increased from 178 million in 1990 to 221 million in 2015. The region supports 15.78% of the total population of China with 2.18% of the total area. As a result, the ecological footprint had increased and the ecological space is compressed. The available ecological space per capita is very limited.

The industrial structure stands in the way of ecological space protection. The service industry is now the major driver of the Shanghai economy. As for the other three provinces, the main component is still secondary industry. Anhui is still in the industrialization stage. Jiangsu and Zhejiang are in the process of transitioning from industrialization to tertiary. However, the portion of traditional industry with high pollution and low efficiency is still high, including papermaking, printing, brewing and other chemical industries. The high-tech industry portion is relatively low. This threatens the environment and harms ecological space. Research by [35] also indicated that secondary industry is moving southwest (Anhui) of the Yangtze River Delta. This move brings greater air and water pollution. The ecological space is significantly compressed and the fragility increases.

6. Discussion

6.1. Urban Planning towards Optimized Balance between Land-Use Efficiency and Ecology

In recent decades, most of the cities in the Yangtze River Delta agglomeration experienced a period of rapid urbanization. Most cities promoted the construction of new districts rather than renovation of downtown areas. With the economic growth came the rapid consumption of land resources. The land-use efficiency is relatively low [41,42]. As indicated by the research data, such rapid urbanization is one of the root causes of ecological space problems.

To avoid such conditions, comprehensive planning should be applied to balance land-use efficiency and ecology. It is necessary to evaluate whole life-cycle benefits from multiple factors. The factors should include not only economic indicators such as economic stimulation and occupant number, but also ecological indicators such as carbon emissions, green industry involvement, per capita available ecological spaces and intensity of heat island effects. Comprehensive evaluation and optimization algorithms such as dynamic programing should be introduced [43].

With such processes, the expansion of city construction areas can be slowed down. The renovation of constructed areas by introducing low emission industry can become mainstream urbanization. Thus, ecological spaces can be well preserved.

6.2. Population Size Control and Structure Optimization

According to Table 5, the population of the Yangtze River Delta agglomeration increased from 178.03 million to 225.36 million. This adds to the high requirement for ecological resources and spaces. This is the main reason why the per capita ecological space decreased from 50.46 m^2 in 1990 to 36.09 m^2 in 2018, even though the total area of ecological space slightly decreased. Considering the population carrying capacity, the population size should be controlled. This method includes administrative order, industry structure upgrade and cost adjustment [44,45]. Meanwhile, the population structure should be optimized to match with industries.

6.3. Optimization of Industrial Structure

Currently, the industrial structure of the Yangtze River Delta urban agglomeration is transitioning from industrialization to service economy [46,47]. However, the portion of traditional industry with high pollution and low efficiency is still high. The secondary industry needs further upgrades to achieve better ecological performance. This is also necessary for high-quality economic growth with controlled population size. A circular chain economy should be developed to increase the efficiency of ecological resources. This is realistic for such a society background with a developed modern service industry and major high-level educational institutes.

6.4. Integrated Governance

The Yangtze River Delta is a complicated estuary ecosystem. The ecological environments are closely connected. Any point-source pollution can diffuse rapidly to the whole region and cause serious regional environmental consequences [48]. It is essential for high-quality development that the governance of ecological spaces in the Yangtze River Delta be integrated. This integrated governance requires an overall planning of ecological spaces targeted at changing the deterioration trend, a coordination mechanism that overcomes both administrative and geographical boundaries and wide public involvement [23,24,49].

It is recommended to form a committee with integrated administrative resources. The relevant departmental supervisors in the different provinces should take turns to lead the committee. Then, the administrative resources brought in can properly support the activities. The responsibility of all related departments in different provinces should be defined for the overall planning and clarified. A compensation mechanism can motivate different stakeholders.

6.5. Operational Tasks

Strategies for energy-saving and emissions reduction should be discussed and agreed upon. A unified mechanism of carbon trading can be proposed, including ecological capital investigation, cross-regional carbon trading platforms and forming fair and standardized assessment indicators. All local governments should encourage and lead industrial upgrade, actively optimize industrial structure, enhance overall planning of industry divisions, and value technical creation. A unified strategy for new energy industries should be published to promote the application of new energy. This includes defining unified standards and overall funding solutions for new energy vehicles. The collaboration of scientific research institutes to develop technical methods for environmental protection and governance should be encouraged.

7. Conclusions

The rapid development of the Yangtze River Delta urban agglomeration and large-scale construction activities bring huge pressure to the environment. Through RS, GIS and statistical analysis, this study reveals that the region's ecological space fragmentation is continuously increasing. It is urgent that measures and actions proceed immediately in order to protect, recover and improve the quality, quantity and functionality of ecological spaces. The main conclusions of this research are as follows.

From 1990 to 2018, the total area of ecological space reduced continuously from 89,778 km^2 to 89,662 km^2 and the total amount and per capita ecological space was seriously insufficient. The current ecological space distribution pattern in the Yangtze River Delta is high in the south and low in the north, which is significantly uneven. The ecological space fragmentation is high and still increasing, while the quality and ecological service functionality is degenerating.

The root cause of such an ecological situation is mainly due to rapid urbanization of the region, including the population explosion, improper industrial structure and dramatic change of land use. To solve the ecological space problems, it is recommended to proceed with urban planning aimed at optimizing the balance between land-use efficiency and ecology, controlling the population size, and optimizing population and industrial structure. From the governance perspective, it is recommended to proceed a long-term top-level design of integrated governance aimed at improving the amount and quality of ecological space, including overall planning, mechanisms for cooperation between environmental management and space planning departments and improvement on cross-region coordination.

This research can provide supporting materials for authorities to proceed with the above tasks and push forward the building of a harmonious living environment that enhances the region's potential.

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