

Research Article

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Spatial and temporal changes in ecosystem services value and analysis of driving factors in the Yangtze River Delta Region

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Abstract: Based on land use classification data for the Yangtze River Delta region in 2000, 2015, and 2020, this study aims to explore the spatial and temporal evolution of ecosystem services value (ESV) in the region. By analyzing the land use structure and its dynamic changes, an ESV model is constructed. Furthermore, the study utilizes a geodetector to analyze the driving factors of ESV in the Yangtze River Delta region. The findings are as follows: (1) From 2000 to 2020, arable land was the predominant land use type in the Yangtze River Delta region. (2) The ESV in the region showed an upward trend followed by a decline from 2000 to 2020. Regulating services and supporting services have always been the core functions of ecosystem services in the region, with hydrological regulation contributing the most. (3) From a spatial perspective, there were significant differences in the spatial distribution of AESV (aggregated ecosystem services value) in the Yangtze River Delta region. The AESV changes in various cities within the region were evident, with a decreasing trend observed in most cities. (4) The sensitivity index of each land use type was less than 1, with forest land exhibiting the highest sensitivity and having the greatest impact on ESV. (5) Geodetector analysis revealed that the AESV in the Yangtze River Delta region is influenced by a combination of regional natural factors, economic factors, and social factors, and the interaction among different driving forces significantly enhances the spatial heterogeneity of AESV in the region.

Keywords: Yangtze River Delta, ecosystem services value, geodetector analysis, land use change

1 Introduction

Ecosystem services refer to the various benefits provided by natural ecosystems and their support to human societies. They are generated by the interactions among biodiversity, ecological processes, and natural resources [1]. Ecosystem services play a crucial role as a bridge between human society and natural ecosystems, serving as an important link in maintaining the harmony of the human–nature community [2,3]. Ecosystem services can be categorized into four main types: provisioning services, regulating services, cultural services, and supporting services [4]. Provisioning services encompass materials and energy directly obtained from ecosystems, including food, water, timber, fiber, and medicine. Regulating services involve activities such as water resource regulation (e.g., flood control and water purification), climate regulation (e.g., temperature regulation and climate stability), disease control (e.g., control of disease vectors), and natural disaster mitigation (e.g., storm protection and dust storm prevention). Cultural services include aesthetic landscapes, recreational and leisure activities, mental well-being and spiritual satisfaction, as well as the preservation of natural and cultural heritage. Supporting services include ecosystem productivity, material cycling, biodiversity maintenance, and soil formation. These services meet basic human needs and provide a crucial foundation for economic development [5]. However, the rapid economic development has led to an increasing demand for natural resources, and the increase in one type of ecosystem service often leads to the decline of another [6]. Therefore, it is of great significance to clarify the trade-offs and synergies among ecosystem services for sustainable human development, aiming to maximize human well-being and promote the harmonious development of the economy and nature [7].

With the rapid socioeconomic development and accelerated urbanization process, significant changes have occurred in land use patterns [8]. These changes have negatively impacted the functionality of ecosystems, thereby affecting

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people's quality of life and the sustainable development of socioeconomic systems [9]. Consequently, the research scope of ecosystem services value (ESV) is gradually shifting from single ecosystems to broader scales and spatial ranges [10]. In the past, the research mainly focused on the service value of specific ecosystems, such as forests and wetlands [11,12]. However, more and more studies are now focusing on ESVs at different scales and spatial ranges, such as regions, urban clusters, and watersheds [13,14]. For example, Qiao *et al.* [15] assessed the spatial-temporal characteristics of five ecosystem services: water production, soil conservation, carbon storage, food provision, and net primary productivity of vegetation in the Huaihe River Basin from 1995 to 2020, using the InVEST model and GIS spatial analysis methods. They also employed principal component analysis to assess the trade-offs and synergies of ecosystem services at the pixel, county, and city scales. The results showed that the relationships among ecosystem services exhibited certain consistency at different scales and also demonstrated scale-related differences and dynamics. Huang *et al.* [16] analyzed the spatial-temporal changes in ecosystem services on Hainan Island from 1980 to 2020 and explored the driving factors of the spatial distribution of ecosystem services using a random forest model. They also investigated the response patterns of different ecosystem services to human activities and natural factors over the past 40 years. The results indicated that rainfall, soil moisture, actual evapotranspiration, maximum temperature, and minimum temperature were the main driving factors influencing the spatial distribution of ecosystem services on Hainan Island. Zhi and Zhang [17] focused on the Yellow River Basin and used land use and socioeconomic data, combined with a modified ESV calculation method, to estimate ecosystem service supply.

With the acceleration of urbanization, natural ecosystems in the vicinity of cities are being disrupted and transformed, leading to a reduction in the supply of ecosystem services and negative impacts on human society [18]. However, under the implementation of environmental protection and restoration measures, the value of ecosystem services may be restored or increased [19]. Therefore, studying the relationship between the value of ecosystem services and spatiotemporal changes is of great significance for environmental protection and sustainable development.

Since Costanza *et al.* [2] proposed the principles and methods for estimating ESVs in 1997, the concept and research on ecosystem services have received widespread attention in China. In recent years, there has been an increasing focus on studying the impact of regional land use changes on ESV, making it a research hotspot in disciplines such as ecology, geography, and environmental science. Zou *et al.* [20] conducted research and analysis

on the relationship between landscape pattern changes and ESV changes in the Songhua River Basin (Harbin section) using the correlation coefficient method. The study showed that ESV is mainly related to landscape type area, landscape fragmentation, and landscape diversity. When there are significant changes in landscape type area, reduced fragmentation, and increased diversity, it is favorable for the increase in ESV. Chen *et al.* [21] calculated and analyzed the total amount and composition of ESV in Henan Province for the years 2000, 2010, and 2018 based on land use data. They also explored the spatial pattern and evolution characteristics of ESV in Henan Province using GIS spatial analysis tools at the grid scale. Mou and Feng [22] identified land use/cover change as an important factor influencing regional ESV. They analyzed the impact of land use changes on ESV within the framework of sustainable development, providing scientific references for regional ecological civilization construction. By using the land use status maps of Beijing in 2010 and 2020, they simulated the land use patterns under three development scenarios for the year 2030 using the Markov-CLUE-S coupling model and discussed the impact of land use changes on the total amount of ESV in line with Sustainable Development Goal 15 (SDG 15) indicators. However, previous studies have mostly focused on overall assessments of ESVs in different regions, with relatively limited quantitative analysis of ESV spatiotemporal changes within urban agglomerations. Furthermore, systematic analysis of spatial variations in the intensity of ESV influencing factors is rarely seen.

The Yangtze River Delta region, as a typical area representing the current and future economic vitality and potential in China [23], is also a region where environmental challenges are highly concentrated and exacerbated [24]. This rapidly urbanizing region is characterized by rapid economic and social development and dramatic changes in land use patterns [25]. With the deepening implementation of the Yangtze River Delta urban agglomeration development strategy, urban construction land continues to encroach upon ecological land, placing increasing pressure on the environment [26]. This has led to significant changes in the structure of ecosystems, resulting in challenges related to regional human–environment relationships and imbalances in ecosystem service provision. These challenges manifest in issues such as air pollution, water resource scarcity, and declining water quality [27]. The emergence of these problems is attributed to the competition and conflicts between human activities and natural factors [28].

In summary, to elucidate the impact of rapid regional economic development and urbanization on ecosystem services, the author believes that understanding the evolutionary patterns and influencing mechanisms of the trade-offs and synergies in the Yangtze River Delta urban

agglomeration's ecosystem services holds significant theoretical and practical significance. Therefore, this article selects the Yangtze River Delta urban agglomeration as the research focus and utilizes land-use data from 2000 to 2020, along with fundamental data related to socio-economic factors, soil, hydrology, meteorology, and more. The study employs a geographic detector to analyze the spatial variations in the strength of various influencing factors in the Yangtze River Delta region, with the aim of providing valuable insights for land-use planning, environmental restoration, and protection in this region.

2 Methods

2.1 Study area overview

The Yangtze River Delta region is located between 114°5' to 123°10' east longitude and 27°1' to 35°20' north latitude, and it is part of the Yangtze River Economic Belt. The total area of the region is approximately 358,000 km², including Shanghai municipality, as well as Jiangsu, Zhejiang, and Anhui provinces. The Yangtze River Delta region is a floodplain and has a long history of agriculture. It is one of the most developed and densely populated industrial zones in China, while also possessing abundant ecological resources [29]. In recent years, rapid urbanization has had a significant impact on the land use and land cover patterns in the Yangtze River Delta region, leading to a decline in ecosystem service capacities such as water purification, flood control, and erosion regulation, as well as a decrease in ecological environment quality [30]. This study focuses on the Yangtze River Delta region to explore its ESVs, providing important reference significance for ecological environmental governance in this region and even nationwide.

2.2 Data sources and processing

The land use data for the Yangtze River Delta region were sourced from the Resource and Environment Science Data Center of the Chinese Academy of Sciences, accessible at <https://www.resdc.cn>. This dataset comprised three temporal phases of Landsat TM satellite images, capturing the years 2000, 2015, and 2020. To align the data with the research objectives, we undertook a comprehensive reclassification of the land use information based on the classification system utilized by the Resource and Environment Information Database of the Chinese Academy of Sciences.

This process aimed to standardize and harmonize the data, resulting in the identification of six primary land use categories: cropland, forestland, grassland, built-up land, water bodies, and unused land.

To address any potential concerns regarding missing data or data inconsistencies, we implemented a multi-faceted approach. First, as previously mentioned, we reclassified the data to ensure it was in line with our research objectives. Following this, we subjected the land use classification to rigorous quality and reliability assessments. Statistical techniques, including the application of Kappa coefficients, were employed to gauge the accuracy of the land use classification. In addition, visual validation utilizing Google Earth imagery was undertaken, contributing to a more robust and precise interpretation of the land use classifications. The results of these assessments affirmed the high quality and compliance of the land use data with the requisite research standards.

In tandem with the land use data, we collected grain yield data from the statistical yearbooks of the respective provinces (or cities) corresponding to the study years. Concurrently, grain prices were determined utilizing information sourced from the "China Agricultural Product Price Survey Yearbook (2020)." These supplementary datasets underwent meticulous scrutiny to identify and rectify any inconsistencies or missing information. To enhance their reliability, we cross-referenced these datasets with multiple sources, ensuring data quality and accuracy.

Among the indicators related to driving factors, digital elevation model (DEM) data were acquired from the Geographic Spatial Data Cloud Platform. Precipitation and soil erosion intensity data were sourced from the Resource and Environment Science Data Center of the Chinese Academy of Sciences. Indicators such as GDP, per capita net income of rural residents, total retail sales of consumer goods, per capita arable land area, and population density (PD) were extracted from the statistical yearbooks of the respective provinces (or cities). In instances of missing data, we employed appropriate statistical methods, such as interpolation or extrapolation, tailored to the specific data type, to mitigate any gaps and enhance the reliability of our analysis.

2.3 Research methods

2.3.1 Land use dynamic analysis method

To quantitatively analyze land use changes in the Yangtze River Delta region, the method of land use dynamic analysis is employed, which includes the calculation of single land use type dynamics and comprehensive land use dynamics [31]. The formulas are as follows:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\%, \quad (1)$$

$$LC = \left(\sum_{i=1}^n \Delta U_{i-j} / 2 \sum_{i=1}^n U_i \right) / T \times 100\%. \quad (2)$$

In the aforementioned formulas, K represents the dynamics of a specific land use type, expressed in percentage (%); U_a and U_b represent the area of the land use type at the beginning and end of the study period, respectively, measured in hectares (hm^2); T represents the duration of the study period; LC represents the comprehensive land use dynamics, expressed in percentage (%); ΔU_{i-j} represents the area of land use type i converted to other land use types during the study period, measured in hectares (hm^2); and n represents the number of land use types.

2.3.2 Calculation of ESV

To begin with, we utilized the ESV coefficients proposed by Costanza *et al.* [2] and Han *et al.* [32]. From their recommendations, we selected 11 ecosystem service functions, encompassing food production, raw material production, gas regulation, climate regulation, hydrological regulation, soil retention, biodiversity maintenance, and aesthetic landscape provision. These functions were carefully chosen to represent ESVs within our research context. Taking into account the unique characteristics of the Yangtze River Delta region, we introduced appropriate adjustments to the equivalent factors associated with ESVs. This allowed us to establish parameters tailored to the specific conditions of our study area. It is important to note that, due to the intricate nature of built-up land and its relatively lower

ecological value, it was not factored into our research. Furthermore, as part of our methodology, we adopted a standardized equivalent factor, equating to 1/7 of the per-unit area grain yield production value, as a reference for ESVs [33].

By consulting statistical yearbooks, the average grain yield per unit area in the Yangtze River Delta region for the years 2000, 2015, and 2020 is calculated to be $5,253 \text{ kg}/\text{hm}^2$. The average price of grain in the Yangtze River Delta region is determined by referring to the *China Agricultural Product Price Survey Yearbook (2020)* and found to be 2.53 yuan/kg. The coefficient of ESV per unit area for the Yangtze River Delta regions is determined (as shown in Table 1). Based on this information, the ESV for the Yangtze River Delta region is calculated using equation (3).

Taking into account the varying sizes of cities in the Yangtze River Delta region, we introduce the per unit area ESV (equation 4) and the rate of change of per unit area ESV (equation 5) to analyze the spatiotemporal evolution of ESVs in the region [34]. We also employ sensitivity indices to analyze the degree of dependency of ESVs on ecosystem value coefficients [35,36] (equation 6).

$$ESV = \sum_{i=1}^n (U_i \times VC_i), \quad (3)$$

$$AESV = \frac{\sum_{i=1}^n (U_i \times VC_i)}{\sum_{i=1}^n U_i}, \quad (4)$$

$$C = \frac{(AESV_{t2} - AESV_{t1})}{AESV_{t1}} \times 100\%, \quad (5)$$

$$CS = \left| \frac{(ESV_{h2} - ESV_{h1})/ESV_{h1}}{(VC_{ih2} - VC_{ih1})/VC_{ih1}} \right|, \quad (6)$$

Table 1: Coefficients of ESV per unit area in the Yangtze River Delta region

Ecosystem function		Land use type				
Level 1	Level 2	Cropland	Forest	Grassland	Water bodies	Unused land
Provisioning services	Food production	20.78	99.46	65.96	36.04	54.33
	Raw material production	52.90	25.08	22.22	13.16	12.73
	Water resource supply	10.07	55.12	37.38	13.03	47.16
Regulatory services	Gas regulation	50.71	334.17	194.56	24.42	100.18
	Climate regulation	51.13	118.89	76.70	13.69	43.98
	Pollution abatement	370.00	369.93	420.97	5318.85	448.52
Supporting services	Hydrological regulation	10.29	232.83	175.97	2.79	44.96
	Soil conservation	20.99	125.32	80.22	19.29	84.26
	Maintenance of nutrient cycling	8.05	11.69	10.22	1.80	4.26
Cultural services	Biodiversity	9.56	34.87	23.53	3.09	12.24
	Aesthetic landscape	20.22	28.75	36.81	428.81	36.09
Total		56.79	130.56	104.05	534.09	80.79

where ESV represents the ESV in currency (in yuan); U_i represents the area of the i -th ecosystem (land use type) in square meters (hm^2); VC_i represents the ESV coefficient of the i th ecosystem in yuan per square meter (yuan/hm^2); aggregated ecosystem services value (AESV) denotes the per unit area ESV in yuan per square meter (yuan/hm^2); C represents the rate of change of per unit area ESV in percentage (%); t_1 and t_2 represent different time periods; CS represents the sensitivity index; and h_1 and h_2 represent the initial value coefficient and the adjusted coefficient, respectively.

2.3.3 Geographic detector model

The geographic detector is a method used to detect spatial variations of geographic elements and reveal the driving factors behind these elements. The geographic detector model is employed to investigate the natural, social, and economic factors that influence the spatial variation of ESV in the Yangtze River Delta region [37]. The formula is as follows:

$$q = 1 - \frac{1}{N\sigma^2} \sum_{h=1}^L N_h \sigma_h^2. \quad (7)$$

In the formula, q represents the influence of a factor on the spatial variation of ESV, with a value ranging from 0 to 1. A larger q indicates a stronger impact of the factor on

the spatial variation of ESV. σ_h^2 and σ^2 refer to the variances of ESV for the evaluation unit h and the entire study area, respectively. N represents the number of evaluation unit samples in the study area.

3 Results

3.1 Dynamics of land use changes

In terms of land use structure (Figure 1), the dominant land use types in the Yangtze River Delta region from 2000 to 2020 were cropland, forestland, and built-up land. In 2000, the proportions of these three land types were 52.46, 27.31, and 7.75%, respectively, accounting for a total of 87.52%. In 2020, the proportions were 46.08, 26.92, and 13.93%, respectively, accounting for a total of 86.93%. From 2000 to 2020, the land area with the largest changes was built-up land, followed by cropland. The area of built-up land increased by 13,218 km^2 , while the area of cropland decreased by 12,730 km^2 . The changes in the areas of forestland, grassland, water bodies, and unused land showed relatively small variations. The dynamics of land use changes in the Yangtze River Delta region from 2000 to 2020 are presented in Table 2. Looking at the individual dynamics of land use, from 2000 to 2015, unused land experienced the most significant change, followed by built-up land and

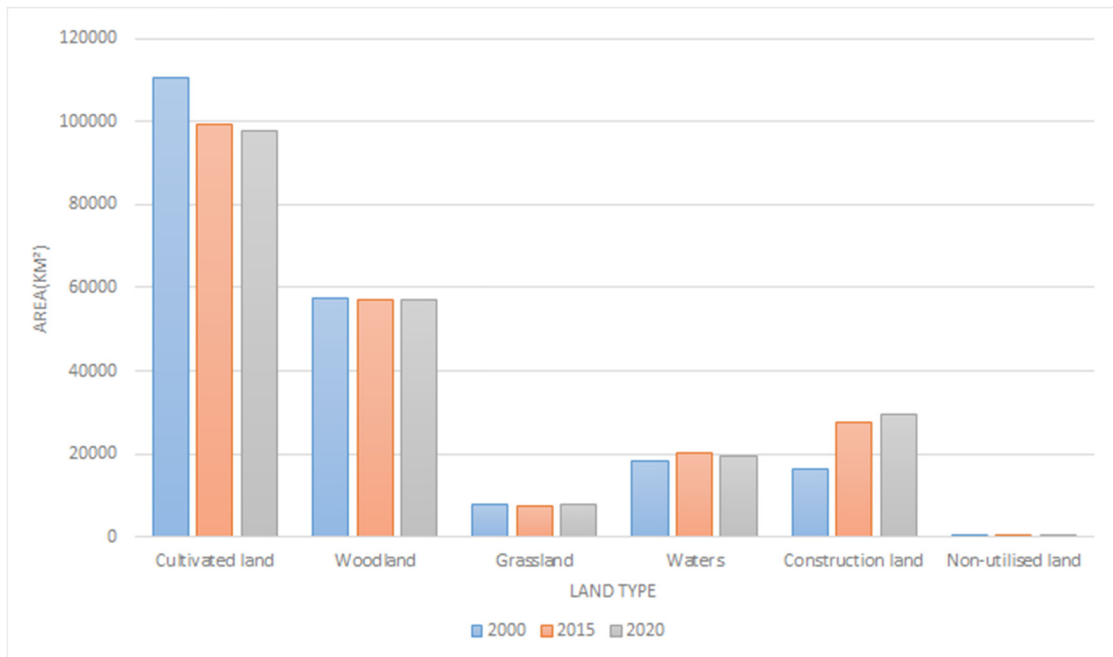


Figure 1: Illustrates the changes in land area for different land use types in the Yangtze River Delta region from 2000 to 2018.

cropland, with dynamics of -0.31 , -0.05 , and 0.01% , respectively. From 2015 to 2020, unused land still exhibited the largest change, followed by built-up land and grassland. Notably, the dynamics of unused land increased significantly, built-up land showed an increasing trend, and the reduction in cropland area intensified compared to the previous period. Overall, over the past two decades, the Yangtze River Delta region has experienced substantial changes in land use, particularly in unused land and built-up land, with dynamics exceeding 0.1% .

During the period from 2000 to 2020, the overall land use dynamics in the Yangtze River Delta region was 1.34% . Specifically, from 2000 to 2015, the land use dynamics was 0.9% , but from 2015 to 2020, it decreased to only 0.06% . This indicates that prior to 2015, the rate of land use change in the Yangtze River Delta region was accelerating, while afterward, the rate of change significantly slowed down. This also suggests that the impact of regional socio-economic activities on land became more pronounced. Land use dynamics are closely related to the intensity of human activities, such as encroachment on cropland, expansion of built-up areas, and gradual development of unused land. In addition, the implementation of ecological restoration projects, such as returning farmland to forests and grasslands, also influences land use dynamics. These factors have led to varying degrees of land use dynamics in different cities of the Yangtze River Delta region during different time periods.

3.2 Changes in ESV

3.2.1 Time series analysis of ESV in the Yangtze River Delta region

Based on equation (3), ESVs in the Yangtze River Delta region for the years 2000, 2015, and 2020 were calculated to be 10,853.454 billion yuan, 21,123.134 billion yuan, and 1,842.89 billion yuan, respectively. The ESV showed an increasing trend from 2000 to 2015, followed by a decrease.

Overall, there was a decrease of 10,669.165 billion yuan. Specifically, the ESV increased by 10,269.68 billion yuan from 2000 to 2015 and by 20,938.845 billion yuan from 2015 to 2020 (Table 3). In terms of the primary components of ecosystem functions, regulatory services and supporting services remained the core functions of ecosystem services in the Yangtze River Delta region. Analyzing the proportion, there was a relatively small variation in the proportion of different service categories from 2015 to 2020, indicating a relatively stable distribution of ecosystem services during this period. The proportion of regulatory services consistently remained around 45% , followed by supporting services at approximately 50% . Cultural services and provisioning services had smaller proportions. Examining the secondary components of ecosystem function composition, hydrological regulation had the highest contribution rate, consistently exceeding around 39% from 2000 to 2020.

3.2.2 Spatial and temporal variation of per capita ESV

In this detailed study, urban areas with an AESV greater than 2 million yuan per hectare were classified as high-value areas. Those with AESV ranging from 1 to 2 million yuan per hectare were considered medium-value areas, while regions below 1 million yuan per hectare were categorized as low-value areas. This classification provided a clear demarcation for assessing the spatial evolution of AESV in the Yangtze River Delta region, as depicted in Figure 2.

From the data presented in Figure 2, significant spatial variations in AESV across the Yangtze River Delta region become evident. The high-value areas predominantly include southern parts of Jiangsu Province, Hefei in Anhui Province, and Zhoushan in Zhejiang Province. In the year 2000, these high-value areas were mainly concentrated in cities like Suzhou, Wuxi, Changzhou, Zhenjiang, Nanjing, Hefei, and Zhoushan. However, the low-value areas encompassed regions primarily in the surrounding locales of the Yangtze River Delta, such as northern Jiangsu Province,

Table 2: Presents the dynamics of land use changes in the Yangtze River Delta region from 2000 to 2020

Year interval	Single land use dynamics						Overall land use dynamics
	Cropland	Forest	Grassland	Water bodies	Built-up land	Unused land	
2000–2015	0.0066	0.0007	0.0048	-0.0065	-0.0458	-0.3108	0.9020
2015–2020	0.0034	-0.0006	-0.0102	0.0050	-0.0146	-0.1827	0.0584
2000–2020	0.0058	0.0003	0.0013	-0.0035	-0.0405	-0.4917	1.3380

Table 3: Individual service values of ecosystem functions in the Yangtze River Delta region, 2000–2020

Ecosystem function		2000		2015		2020	
Level 1	Level 2	Value (in 100 million yuan)	Percentage (%)	Value (in 100 million yuan)	Percentage (%)	Value (in 100 million yuan)	Percentage (%)
Provisioning services	Crop production	2741.53	2.53	2813.68	1.33	36.58	1.98
	Raw material production	1003.18	0.92	1032.15	0.49	15.54	0.84
	Water resource supply	−3328.79	−3.07	−3445.19	−1.63	54.32	2.95
	Subtotal	415.92	0.38	400.63	0.19	106.43	5.78
Regulatory services	Gas regulation	4219.46	3.89	4322.86	2.05	63.09	3.42
	Climate regulation	8045.92	7.41	8261.65	3.91	126.44	6.86
	Pollution abatement	3836.09	3.53	3935.84	1.86	43.56	2.36
	Hydrological regulation	79552.16	73.30	82443.75	39.03	740.55	40.18
Supporting services	Subtotal	95653.63	88.13	98964.10	46.85	816.63	44.31
	Soil conservation	6689.50	6.16	6924.96	3.28	76.08	4.13
	Maintenance of nutrient cycling	534.31	0.49	548.33	0.26	7.92	0.43
	Biodiversity	3474.70	3.20	3615.34	1.71	49.69	2.70
Cultural Services	Subtotal	10698.51	9.86	110052.73	52.10	897.04	48.68
	Aesthetic landscape	1766.48	1.63	1813.88	0.86	22.79	1.24
Total		108534.54	100.00	211231.34	100.00	1842.89	100.00

Shanghai, Jinhua, Taizhou, and others. By the years 2015 and 2020, there was a noteworthy expansion of high-value areas to include Chuzhou, indicating a trend toward a more contiguous distribution of high-value ecosystem services. Conversely, the low-value areas witnessed a decline in size, with cities like Jinhua and Taizhou no longer falling under this category.

The shift in AESV holds significant implications for these specific urban centers. For instance, the cities that exhibited a decrease in AESV, particularly Suzhou and Wuxi, have faced substantial environmental and ecological challenges. The decline in ESV in these cities, primarily due to urban expansion and land-use changes, might lead to diminished capacity for crucial ecosystem functions. This reduction could adversely affect air and water quality, diminish biodiversity, and reduce green spaces vital for urban ecological balance. Moreover, the conversion of natural areas into urban land can exacerbate the urban heat island effect and increase the vulnerability to extreme weather events, posing significant risks to urban sustainability and the health of residents.

The increasing trend observed in other cities, such as Zhoushan, Yancheng, and Taizhou, suggests a different set of challenges and opportunities. While the increase in AESV in these cities is a positive indicator of healthy ecosystem services, it also necessitates sustainable urban planning to maintain this balance [38,39]. The growth in ESV is often accompanied by increasing pressures from urban development and population growth, requiring careful management to ensure that the ecosystem services are not overexploited or degraded.

According to equation (5), we obtained the spatial distribution of AESV change rates in cities at and above the prefectural level in the Yangtze River Delta region, as demonstrated in Figure 3. The analysis reveals that the majority of the cities experienced a decrease in AESV over the last two decades, indicating significant pressure on the regional ecosystem. From 2000 to 2010, approximately 26.92% of the cities showed a declining trend in AESV, albeit with minimal reductions. However, during the period from 2010 to 2020, the trend reversed in 69.23% of the cities, showing an increase in AESV, while 30.77% continued to experience a decline. The cities with the most significant reductions, such as Suzhou and Wuxi, saw decreases exceeding 15% during this latter period. Conversely, cities like Zhoushan, Yancheng, and Taizhou exhibited an upward trend in AESV compared to the previous decade.

The fluctuations in AESV in these cities can be attributed to various factors, including land-use changes, urbanization, and environmental policies. In Suzhou, for example,

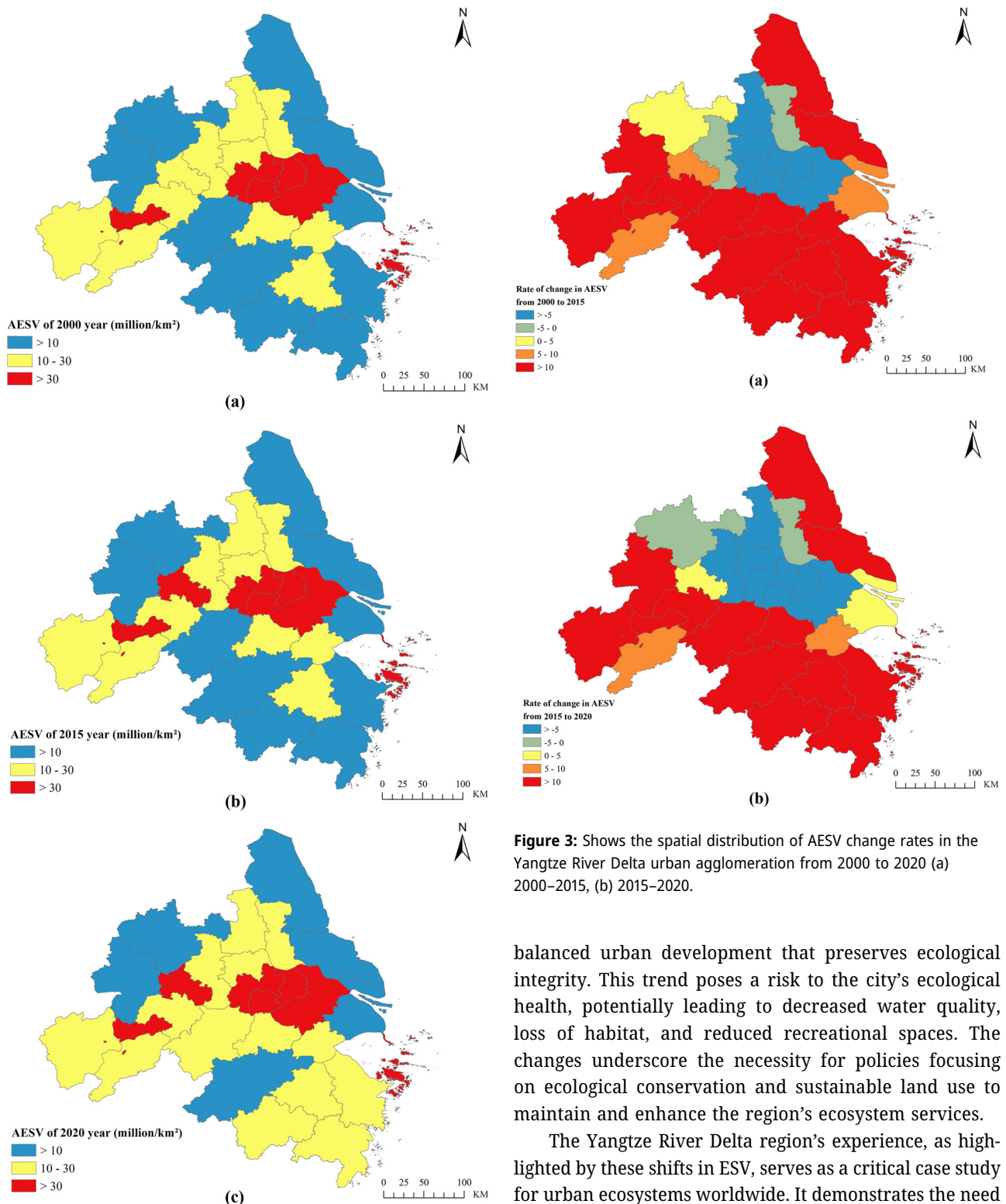


Figure 3: Shows the spatial distribution of AESV change rates in the Yangtze River Delta urban agglomeration from 2000 to 2020 (a) 2000–2015, (b) 2015–2020.

balanced urban development that preserves ecological integrity. This trend poses a risk to the city's ecological health, potentially leading to decreased water quality, loss of habitat, and reduced recreational spaces. The changes underscore the necessity for policies focusing on ecological conservation and sustainable land use to maintain and enhance the region's ecosystem services.

The Yangtze River Delta region's experience, as highlighted by these shifts in ESV, serves as a critical case study for urban ecosystems worldwide. It demonstrates the need for integrated environmental and urban planning strategies that consider the long-term sustainability of ecosystem services. As urban areas continue to grow and evolve, maintaining and enhancing ecosystem services will be crucial for ensuring sustainable urban living conditions and environmental resilience.

the transformation of water areas into urban land has led to a substantial decrease in AESV, highlighting the need for

3.3 Sensitivity analysis of ESV to value coefficients

In our analysis, we utilized equation (6) to calculate the sensitivity index for the Yangtze River Delta region, adjusting the ESV coefficients by $\pm 50\%$. The results, presented in Table 4, show notable variations in the sensitivity index among different land use types for the years 2000, 2015, and 2020.

Table 4 indicates that in 2000, the sensitivity index ranked from highest to lowest was forest land, grassland, cropland, water bodies, and unused land. By 2015 and 2020, the order changed. In 2015, the sequence was forest land, cropland, water bodies, grassland, and unused land, while in 2020, it became forest land, water bodies, cropland, grassland, and unused land. This shift highlights the changing dynamics of land use types' influence on the region's ESV. The sensitivity index for each land use type remained below 1, suggesting a relative stability of ESV in response to value coefficient changes. This stability is indicative of the appropriateness of the value coefficients used in this study for the Yangtze River Delta region.

A critical observation from Table 4 is the consistently high sensitivity index of forest land across all years, indicating its significant impact on ESV. For instance, the sensitivity index for forest land peaked at 0.6899 in 2020, revealing its increasing responsiveness to ESV. This high sensitivity can be attributed to the extensive area covered by forests and their substantial ESV coefficient. It underscores the vital role of forests in providing key services like carbon sequestration and biodiversity conservation. Water bodies also demonstrated a rising trend in their sensitivity index, especially notable in 2020 with an index of 0.1414. Despite their smaller area, water bodies play a crucial role in the ecosystem, providing services such as water purification and flood control. The increasing sensitivity of water bodies suggests that changes in their value coefficients can significantly affect the region's overall ESV.

These findings emphasize the importance of effective land management and conservation strategies, particularly for forests and water bodies, in maintaining and enhancing the ESV in the Yangtze River Delta region. The results

highlight the need for policies that protect and sustainably use these critical ecosystems. Targeted interventions in forest and water body management are likely to result in considerable improvements in ecosystem services, contributing to the ecological stability and resilience of the region.

3.4 Analysis of driving factors of ESV

To explore the driving factors of ESV in the Yangtze River Delta region, we carefully selected a set of indicators that are both theoretically relevant and supported by available data. These indicators were chosen with the goal of capturing the diverse natural, economic, and social factors that could potentially influence ESV in the region [40–43]. Three natural factors, including annual precipitation (AP) [44], DEM [45], and soil pH (PH) [46], were included in our analysis. These factors were selected due to their known ecological significance and the availability of reliable data. AP is a key climatic variable that can impact vegetation growth and water availability, which are essential components of ecosystem services. The DEM represents the topographical variation, which can influence hydrological processes and land use patterns. Soil pH is a critical soil characteristic that affects nutrient availability and plant health, thereby influencing the provision of ecosystem services. In addition to these natural factors, we considered four economic factors: total GDP, per capita GDP (PCGDP), per capita net income of farmers (PCNIF), and retail sales of consumer goods (RSCG) [47]. These economic indicators were chosen because they reflect the economic activity and development in the region, which can have a significant impact on land use and ecosystem services. Higher economic activity may lead to changes in land use and resource utilization, affecting the overall ESV. Furthermore, we included two social factors, namely, per capita arable land area (PCALA) and PD [48,49]. These social indicators were selected based on their relevance to land use and human influence on ecosystems. Per capita arable land area reflects the availability of land for agricultural purposes, which can affect the extent of cropland and, consequently, food production services. PD is an important sociodemographic factor that can influence land use patterns, urbanization, and resource consumption, all of which have implications for ESV.

Based on the research scale of the Yangtze River Delta region, using AESV as the dependent variable and the aforementioned influencing factors as independent variables, quantitative analysis of the driving factors and their

Table 4: Sensitivity index of ESV in the Yangtze River Delta region

Year interval	Cropland	Forest	Grassland	Water bodies	Unused land
2000	0.1206	0.4658	0.1616	0.1026	0.0007
2015	0.1237	0.4638	0.1000	0.1056	0.0007
2020	0.1217	0.6899	0.1118	0.1414	0.0005

Table 5: Driving factors of ESV in the Yangtze River Delta region

	AP	DEM	pH	GDP	PCGDP	PCNIF	RSCG	PCALA	PD
<i>q</i> statistic	0.236	0.030	0.131	0.149	0.443	0.240	0.565	0.129	0.328
<i>p</i> value	0.450	0.970	0.629	0.533	0.148	0.415	0.329	0.759	0.183

Table 6: Cross-detection results of GeoDetector

	AP	DEM	pH	GDP	PCGDP	PCNIF	RSCG	PCALA	PD
AP	0.236								
DEM	0.448	0.030							
pH	0.445	0.281	0.131						
GDP	0.521	0.432	0.366	0.149					
PCGDP	0.646	0.536	0.831	0.768	0.443				
PCNIF	0.592	0.712	0.563	0.484	0.757	0.240			
RSCG	0.802	0.634	0.806	0.695	0.731	0.731	0.565		
PCALA	0.360	0.359	0.409	0.297	0.674	0.328	0.831	0.129	
PD	0.651	0.418	0.489	0.499	0.521	0.824	0.652	0.558	0.328

interactions was conducted using the “factor detection” and “interaction detection” functions of the Geographic Detector (GeoDetector) tool. This analysis aimed to explore the dominant factors causing spatial differentiation of ESV in the Yangtze River Delta region and the characteristics of interaction among the driving factors. Finally, the results of factor detection (Table 5) and interaction detection (Table 6) by the Geographic Detector for the spatial differentiation of AESV in the Yangtze River Delta region were obtained.

Analysis shows that the spatial distribution differences of AESV in the Yangtze River Delta region are influenced by a combination of regional natural, economic, and social factors. In terms of the impact of driving factors on AESV, the retail sales of social consumer goods have the most significant explanatory power, accounting for 56.5%. Following that, per capita GDP and PD have an influence of around 30–40%, making them important factors affecting the spatial differentiation of regional AESV. In addition, factors such as AP and per capita net income of farmers have an impact of over 23% and are relatively important in influencing the spatial differentiation of AESV in the region. The explanatory power of factors such as soil erosion, total GDP, and per capita arable land area is above 10% but has a relatively smaller impact on the spatial differentiation of ESV. The cross-detection results are used to determine whether the two influencing factors act independently or interact with each other. From Table 6, it can be observed that the interaction between any two factors is greater than the influence of individual factors. Therefore, the spatial differentiation of AESV in the Yangtze River Delta region

is the result of the combined effects of different driving factors. Based on the results of interaction detection, the interactions between social consumer goods retail sales (RSCG) and AP, per capita GDP (PCGDP) and soil pH (PH), social consumer goods retail sales (RSCG) and soil pH (PH), PD and per capita net income of farmers (PCNIF), as well as arable land area (PCALA) and social consumer goods retail sales (RSCG) reach an level of approximately 80%. The interaction among different driving forces significantly enhances the spatial differentiation of AESV in the Yangtze River Delta region. The synergistic enhancement effect formed by the complex coupling of different factors collectively influences the spatial differentiation of AESV in the region. Therefore, in the practice of optimizing ecosystems and controlling ecological risks, the characteristics of different driving factors and the synergistic enhancement effects of their interactions should be considered in the Yangtze River Delta region. Differentiated and multidimensional regulatory strategies should be adopted. When choosing land use development models, they should be in line with the region's natural conditions and socio-economic development level to avoid undue or strong human-induced land use disturbances that increase pressure on natural and socio-economic factors and regional ecosystems.

4 Discussion

In our research, we conducted a comprehensive analysis of the spatiotemporal patterns of land use changes and the

resulting ESV in the Yangtze River Delta region from 2000 to 2020. Here, I will provide a more in-depth discussion of our main research findings.

To begin, we observed significant changes in land use within the Yangtze River Delta region during this 20-year period. Over this time frame, the area designated for construction land increased by 13,218 km², while arable land decreased by 12,730 km², marking the most prominent trends in land use dynamics. This trend is closely linked to urbanization and industrialization processes, posing a threat to agricultural land resources due to the continuous expansion of construction land. However, simultaneously, the areas of forests, grasslands, water bodies, and unused land underwent relatively minor changes, possibly reflecting the effectiveness of policies and protective measures for these critical ecosystems.

Furthermore, our study revealed distinct changes in ESV across the Yangtze River Delta region during the same 20-year period. The overall trend showed an initial increase followed by a subsequent decrease, resulting in a net decrease of 10,669.165 billion yuan. This trend encompasses various complex ecosystem service functions, with hydrological regulation consistently making the most significant contribution. Despite the overall declining trend, ESV exhibited notable variations across different regions. High-value areas were primarily concentrated in southern Jiangsu, Anhui's Hefei and Chuzhou, and the Zhoushan area, while low-value areas were mainly situated in the peripheral areas of the Yangtze River Delta. These research findings provide crucial insights.

Regarding the relationship between land use changes and ESV, it underscores the importance of sustainable land management. The expansion of construction land and the reduction of arable land have had adverse effects on ecosystem service functions, especially those related to water resource management and regulation services. This highlights the need for increased attention to sustainable land resource management during urbanization and industrialization processes to ensure the continued provision of essential ecosystem services in the Yangtze River Delta region.

Moreover, variations in ESV across different regions may be influenced by multiple factors, including geographical location, climate, and economic activities. This implies that policies and planning should be tailored to the specific needs of different regions to maximize the integrity of ecosystem services.

In summary, our study offers critical insights into land use changes and ESV in the Yangtze River Delta region. These insights not only deepen our understanding of sustainable development and environmental conservation in this region but also provide valuable references for future

policymakers and planners. Nevertheless, further research is needed to elucidate the mechanisms behind these trends and to propose more specific policy recommendations for achieving greater sustainability. While this study has made important discoveries, it also has some limitations. For example, data availability poses a challenge. We relied on existing land use data and ESV models, which may carry uncertainties and accuracy issues. In addition, our study focused on the period from 2000 to 2020, and future research could consider longer time spans to better capture trends in land use changes. Finally, the diversity of models and methods used to calculate ESVs may lead to variations in results between different studies. Future research can explore more precise estimation methods to enhance result reliability.

5 Conclusion

In this study, we conducted an in-depth analysis of the spatiotemporal patterns of ESV in the Yangtze River Delta region from 2000 to 2020, in response to changes in land use. We also provided relevant discussions. The following are our key findings:

- (1) Significant changes in land use were observed in the Yangtze River Delta region, with the expansion of construction land and the reduction of arable land being the most prominent trends. These land use changes have had a negative impact on ESV, particularly in areas related to water resource management and regulation services.
- (2) ESV in the Yangtze River Delta region exhibited a pattern of increase followed by a decrease from 2000 to 2020. While there was an overall declining trend, ESV displayed significant variations across different regions, closely associated with factors such as geographical location, climate, and economic activities.
- (3) The close link between land use changes and ESV underscores the importance of sustainable land management to ensure that the ecosystem in the Yangtze River Delta region continues to provide vital services.
- (4) Our study provides valuable insights into land use changes and ESV in the Yangtze River Delta region, contributing to a deeper understanding of sustainable development and environmental conservation in the region. This information serves as a valuable reference for future policymakers and planners.

It is important to note that while our research offers critical information about ecosystem services in this

region, further investigations are needed to elucidate the mechanisms behind these trends and to provide more specific policy recommendations for achieving greater sustainability.

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