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# Spatial–Temporal Divergence and Coupling Analysis of Land Use Change and Ecosystem Service Value in the Yangtze River Delta Urban Agglomeration

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**Abstract:** Land use changes (LUC) have exacerbated the evolution of ecosystem structure in the urban agglomeration of the Yangtze River Delta (YRDUA), significantly affecting ecosystem service functions and values. Although the impact of land use on ecosystem service value (ESV) has received significant attention, most existing studies explore the relationship between LUC and ESV at the national, provincial, or regional scales. Few studies focus on urban agglomerations, particularly in the YRDUA. Additionally, while many studies analyze the driving factors of ecosystem services and the trade-offs and synergies among them, there is a relative scarcity of research on the coupling coordination relationship between LUC and ESV. In this study, we used the ecosystem service assessment model to dynamically analyze the spatio-temporal changes of land use and ESV in the YRDUA from 2000 to 2020 and evaluated the dynamic relationship between the two using the coupled coordination model system. The results show the following: (1) Land use types within the YRDUA underwent significant changes during the study period, with a notable decrease in farmland and a substantial increase in construction land being the dominant trends. (2) ESV showed upward and downward trends over different periods, with water bodies having the highest value, followed by forested land and farmland, respectively. The ESV of water bodies showed a trend of first increasing and then decreasing. Higher ESVs were mainly concentrated around lakes such as Taihu Lake and coastal areas along the Yangtze River, radiating outward from these central points. (3) Currently, the coupling coordination degree (CCD) between land use intensity and ESV in the YRDUA is mostly reluctant coordinated or in the state of primary coordination. However, with time, the CCD trend has increased. In addition, variations between cities were more pronounced, showing a spatial pattern characterized by higher coupling levels in eastern/northern regions compared to western/southern regions. Our study can provide policy references for improving land planning, optimizing land use structures, and realizing high-quality, sustainable, green, and coordinated development in the YRDUA.

**Keywords:** land use; ecosystem services; coupling coordination; Yangtze River Delta urban agglomeration

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## 1. Introduction

Ecosystem services refer to all the benefits ecosystems provide to people, including cultural, regulatory, and supply services that directly affect human existence and support services necessary to maintain other services [1]. The value of ecosystem services (ESV) is a crucial indicator for measuring the condition of the local ecosystem, which is an essential bridge connecting the ecosystem with human well-being, health, and livelihood [2]. Academics generally understand that land use change (LUC) is the primary factor influencing the ESV [3]. Modifications to land use structures will affect ecosystems' functional processes and composition, altering the ESV directly [4]. Simultaneously, changes in ecological service functions will also impact human adjustments to land use structure and efficiency. China is a perfect case for research on the relationship between LUC and ESV. In recent years, the fundamentals of China's economy have undergone historical and substantive changes, and it has entered a new stage of economic development, that is, the stage of new normal development, with the growth rate shifting from a high speed to a medium speed, and the mode of development shifting from scale and speed to quality and efficiency [5]. Therefore, research on LUC and ESV is of great significance in this context. It is well known that the ongoing urban boundary expansion brings several ecological and environmental issues that significantly harm the ecosystem. Meanwhile, China's regional sustainable development and ecosystem stability are also severely challenged by high-intensity economic activities and unreasonable land use, resulting in problems like over-exploitation of resources, soil erosion, and habitat fragmentation [6,7]. Thus, for efficient territorial spatial planning and enhancing ecosystem service functions, a thorough investigation of the connection between urban land use change and environmental services is crucial [8,9].

More and more academic attention has been extensively paid to China's ecosystem services. Since Costanza et al. [10] divided the global ecosystem into 15 biological communities and 17 main service functions and systematically estimated the global ESV for the first time, a reasonable calculation method of equivalent value per unit area was obtained and has been recognized by most scholars. As the research has advanced, many academics have been interested in studying ESV and have started actively investigating the theory and methodology of measuring ESV in a way that is consistent with China's actual circumstances. For instance, Ouyang et al. [11] explored the methodologies for evaluating the ESV and its relationship to research on sustainable development, as well as a thorough analysis of the ecosystem service function's research trend and advancement. In addition, ESV is highly correlated with land use change, reflecting human activities' impact on ecosystems [12]. Moreover, this interconnection is dynamic and intricate, encompassing a variety of ecological, social, and economic dimensions. For example, land use change in rapidly urbanizing areas can significantly reduce ecosystem services, and ESVs in different regions show different trends in time and space [13]. Jiang et al. [14] have demonstrated that the supply and value of ecosystem services are directly related to the distribution of natural geographic elements and socio-economic development in the region. Currently, the synthesis approach model, the quantitative method of remote sensing, and the unit area value equivalent element approach utilizing land use data are standard techniques for evaluating ESV [15]. After Costanza et al. [10] proposed the equivalent factor method and estimation of the value of global ecosystem services, many Chinese scholars have conducted studies based on China's specific national conditions. For example, Xie et al. [16] proposed a revised factor of the value coefficient of ecosystem services that is more suitable for China's national conditions. This approach has been widely adopted by scholars in subsequent studies and applied to ESV assessment in various regions of China [17].

LUC is a major driver of changes in ecosystem functions and services. By studying the coupling relationship between LUC and ESV, we can identify the types of land use that are most conducive to maintaining ecosystem services and ecological integrity, as well as reveal the spatial–temporal dynamics of ecosystem service provision and help identify key areas that need to be prioritized for conservation and restoration. Currently, researchers generally adopt the coupling coordination degree (CCD) model to evaluate the coupling coordination relationship between LUC and ESV [18]. Pan et al. [19] utilized the CCD model to study the dynamic relationship between land use intensity and ecosystem services in the coalfields of Shanxi Province. Hu et al. [20] explored the CCD relationship between new-type urbanization and ecosystem services in Nanchang City. Taking Guiyang City as an example, Li et al. [21] explored the synergistic relationship and interaction intensity between land use intensity (LUI) and ESV using the coupling CCD model. In addition, some studies have incorporated multi-index comprehensive evaluation methods such as the entropy weight method. For example, Deng et al. [22] used the entropy weight method and the CCD model to study the land use and ecological resilience of the Dianchi Basin, highlighting the need for targeted land use planning and ecological protection measures based on regional characteristics.

As a critical component of the Belt and Road Initiative (BRI), the Yangtze River Delta urban agglomeration (YRDUA), a quickly urbanized area with the notable traits of fast social and economic growth, is leading China's reform and opening-up efforts [3]. However, as the YRDUA's integrated development strategy has advanced, urban construction has continuously occupied ecological land, increasing environmental pressure and causing drastic changes in ecosystem structure [23]. Moreover, the coupling intensity of land use change and ESV in different regions of the YRDUA is also significantly different [3], and the development degree of the coupling coordination relationship between ESV and land use is one of the critical factors affecting the high-quality development of the YRDUA. At the same time, considering the pressure of rapid urbanization in the YRDUA, more attention should be paid to the coupling and coordination between LUC and ESV. Consequently, to protect the region's ecological security and promote sustainable socio-economic growth, it is necessary to accurately estimate ESV and further explore the spatio-temporal differences and interlinkages between LUC and ESV.

This paper aims to develop an equivalent factor approach of the ESV in the YRDUA by constructing and applying advanced assessment models, examining their distribution patterns and interrelationships with land use changes between 2000 and 2020. This will be achieved by (1) constructing the YRDUA's ESV assessment model using the enhanced equivalent factor approach and computing and assessing the overall ESV; (2) examining the temporal and spatial distribution of ESV in the YRDUA between 2000 and 2020, and investigating the factors influencing this development; (3) applying the coupling coordination model to analyze the relationship between LUC and ESV in the YRDUA, extending this analysis to the temporal and spatial distribution traits of the coupling coordination among various cities, evaluated by established classification criteria for coupling coordination. In addition to providing specific policy recommendations for the YRDUA to improve land planning, optimize land use structure, realize the coordinated development of land use and ecosystem, and further promote sustainable ecological and economic development, this study can establish an appropriate land use type change and ecosystem service assessment system for the urban agglomeration.

## 2. Materials and Methods

### *2.1. Study Area*

The Yangtze River Delta urban agglomeration (YRDUA) is located in the alluvial plain before the Yangtze River enters the sea [24], which includes a total of 27 municipalities in the lower reach of the Yangtze area (Figure 1), with an administrative area of around 225,000 km$^2$. In the 21st century, the Yangtze River Delta region has undergone rapid economic development, establishing itself as one of China's most densely populated, economically active, and industrially significant areas. The YRDUA's combined gross domestic product (GDP) reached CNY 19.735 trillion in 2019, around 20% of the country's GDP. Compared to the national average of 2.78%, the GDP growth rate in 2018–2019 was 9.88% [23], and the total GDP of the YRD urban agglomerations even grew to CNY 30.51 trillion in 2023, representing about 24% of the GDP of the nation and continuously raising its standing economically. The natural setting of the YRDUA is characterized by fertile land and plenty of rivers and streams.

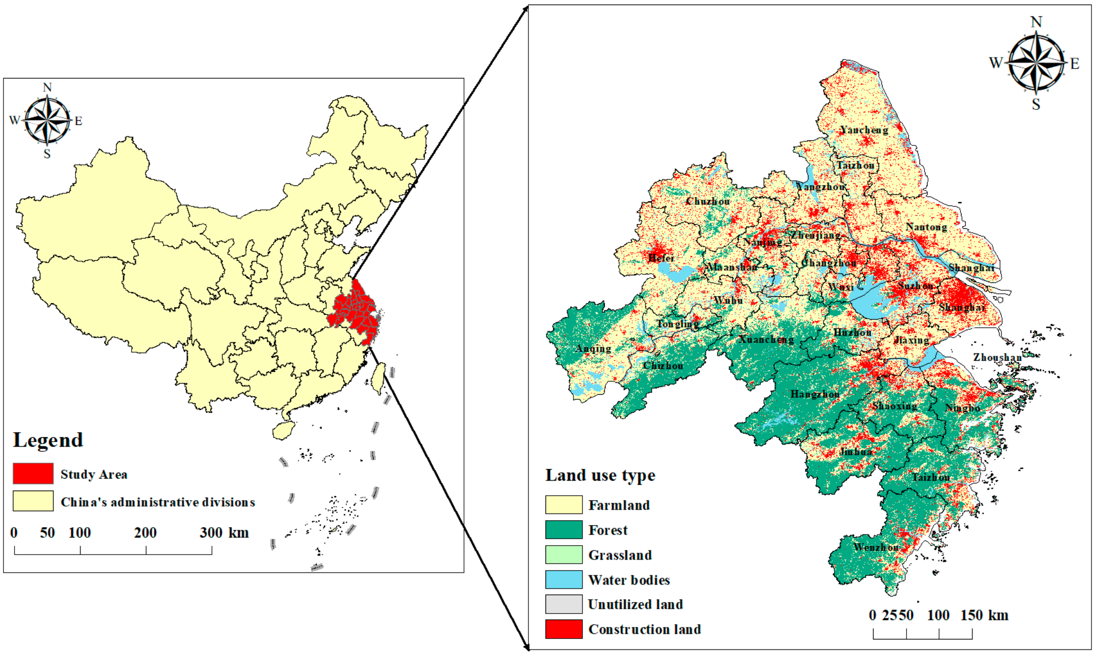


**Figure 1.** Location map of study area.

## 2.2. Data Sources

This paper selects the land use data of the YRDUA with a five-year interval from 2000 to 2020. The data are further preprocessed by projection, reclassified, and uniformly standardized into the WGS84 coordinate system. Land use types are divided into six first-level categories: farmland, forest land, grassland, water bodies, unutilized land, and construction land. The land use data are from the Zenodo open data repository (www.zenodo.org/, accessed 6 February 2024) [25] with a spatial resolution of 30 m × 30 m. The socio-economic data utilized in this research were sourced from multiple authoritative databases, including the Statistical Yearbooks of Jiangsu Province (2001–2021), Anhui Province (2001–2021), Zhejiang Province (2001–2021), and Shanghai Municipality (2001–2021), as well as the Cost-Effectiveness Compilation of Chinese Agricultural Products (2021).

## 2.3. Methods

In order to deeply analyze the spatio-temporal changes in land use status and ESV and their interaction in the YRDUA, our study initially investigates the spatio-temporal changes in land use in the YRDUA using land use dynamics, land use intensity, land type transfer matrix, and other variables. Secondly, the value equivalent factor method is used to revise the ESV table per unit area's equivalent factor table to calculate the YRDUA's ESV. In addition, this paper presents sensitivity analysis indicators to guarantee the validity of the evaluation outcomes. Finally, a CCD model between land use intensity and ESV is constructed to expose the complex interrelation between land use and ESV.

### 2.3.1. LUC Characteristics

#### Land Use Dynamic Degree

(1) Single land use dynamic degree

The change in land area types in different periods is the primary manifestation of land use change in the YRDUA. In order to better describe the change rate of land use and the intensity of mutual transformation of different land use types, this paper adopts the dynamic degree method of land use types to measure the change rate of land use [26], in which a certain land use type's changing rate is described by a single dynamic degree [27]. The calculation formula is as follows:

$$K = \frac{I_b - I_a}{I_a} \times \frac{1}{N} \times 100\% \tag{1}$$

where $K$ represents the change in the dynamic degree of a single land use type in the region, the areas of a particular land use type at the beginning and end of the research are represented by $I_a$ and $I_b$, and N represents the length of study period in years.

(2) Comprehensive land use dynamic degree

A single land use dynamic degree can only reflect the scale and speed of changes in the quantity of a particular type of land in a particular time frame in the study area. The dynamic degree of comprehensive land use can well reflect the speed of change of any land use type in the research area at a certain period, thus reflecting the comprehensive impact of social and economic activities on land use in the region [28]. Following is the calculation formula:

$$L_c = \frac{\sum_{i=1}^{n} \Delta LU_{i-j}}{2\sum_{i=1}^{n} LU_i} \times \frac{1}{N} \times 100\% \tag{2}$$

where $L_c$ denotes the comprehensive land use dynamics; $LU_i$ denotes the area (hm$^2$) of the $i$th land use type upon the study's inception; $\Delta LU_{i-j}$ denotes the absolute value of the area of the $i$th land transformed into the $j$th land use type during the whole study period; N denotes the number of years of the study.

Transfer Matrix for Land Use Types

The land use transfer matrix can comprehensively and concretely depict the structural characteristics of regional land use change and the direction of changes in different land use types [29]. The calculation formula is as follows:

$$A_{ij} = \begin{vmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{vmatrix} \tag{3}$$

where $A$ represents the area for land use, while $i$ and $j$ symbolize the land use types at the commencement and conclusion of the study period, respectively. Moreover, $n$ represents the total count of land use types involved.

#### 2.3.2. Ecosystem Service Value (ESV)

Assessing ESV serves as a pivotal indicator in ecological development, enhancing public awareness regarding biodiversity conservation and fostering comprehension of the significance of "valuable natural resources". This process facilitates exploration into enhancing regional ecological worth, ultimately offering insights to harmonize regional economic progress and ecological preservation efforts.

(1) Equivalent Factor of Standard Unit ESV Accounting

The standard unit ESV equivalent factor, commonly known as the standard equivalent, is defined as the average economic value of natural grain production per unit area of farmland per year. This measure is used to quantify how much different ecosystems could contribute to providing ecological services. The standard equivalent is one-seventh of the market value of grain produced per unit area of farmland [16]. To unify $ESV$s per unit area, the average grain prices of various provinces and cities in the YRDUA in 2020 were selected as the standard for calculation [27]. The formula is as follows:

$$E_\alpha = \frac{1}{7}\sum_{i=1}^{n} \frac{m_i p_i q_i}{N} \tag{4}$$

where $E_a$ represents the economic value of the production service function provided by the unit farmland ecosystem (CNY/hm$^2$); $i$ represents the types of crops. Since the planting area of rice, wheat, and corn accounts for more than 75% of the total grain crop planting area in the YRDUA, this paper selects rice, wheat, and corn as the main grain crops of the region. $p_i$ represents the average market price of the $i$ food crop (CNY/t); $q_i$ represents the yield per unit area of the $i$ food crop (t/hm$^2$); $m_i$ represents the area of the ith food crop (hm$^2$). N is the total area (hm$^2$) of nth food crops. By collecting the statistical yearbook of Jiangsu, Zhejiang, Anhui Province, and Shanghai City and the "Compilation of Cost and Income data of National Agricultural Products" and other data, the economic value of the unit standard equivalent of the Yangtze River Delta urban agglomeration is finally calculated as 2355.244 CNY/hm$^2$.

(2) Correction of the value coefficient of ecosystem services

Xie et al. (2015) revised the equivalent factor table of ecosystem service value per unit area based on the actual situation in China, which has been widely recognized by the academic circle in China [16,17]. Based on this, this paper revises the table of value equivalent factors, and the calculated ESV of the YRDUA is shown in Table 1.

**Table 1.** ESV coefficients in YRDUA (CNY/hm$^2$).

| Primary Classification | Secondary Classification | Farmland | Forest Land | Grassland | Water Body | Unutilized Land |
|---|---|---|---|---|---|---|
| Supply Services | Food production | 2602.54 | 594.70 | 549.56 | 1542.68 | 11.78 |
| | Raw material production | 577.03 | 1366.04 | 808.63 | 859.66 | 35.33 |
| | Water supply | −3073.59 | 706.57 | 447.50 | 12,812.53 | 23.55 |
| Regulatory Services | Gas regulation | 2096.17 | 4492.63 | 2841.99 | 3144.25 | 153.09 |
| | Climate regulation | 1095.19 | 13,442.56 | 7513.23 | 6936.19 | 117.76 |
| | purify the environment | 317.96 | 3939.15 | 2480.86 | 10,775.24 | 482.83 |
| | hydrological regulation | 3521.09 | 8796.84 | 5503.42 | 148,933.85 | 282.63 |
| Support Services | Soil conservation | 1224.73 | 5470.05 | 3462.21 | 3815.50 | 176.64 |
| | Nutrient maintenance | 365.06 | 418.06 | 266.93 | 294.41 | 11.78 |
| | Biodiversity | 400.39 | 4981.34 | 3148.18 | 12,270.82 | 164.87 |
| Cultural Services | Aesthetic landscape | 176.64 | 2184.49 | 1389.59 | 7795.86 | 70.66 |
| Total | - | 9303.21 | 46,392.42 | 28,412.09 | 209,180.99 | 1530.91 |

(3) Ecosystem service value (ESV) accounting

The YRDUA's overall ecosystem service value, as well as the value of each individual service function, were determined in this study using Costanza's ecological service value calculation approach. The following is the calculating formula:

$$\begin{cases} ESV_i = \sum_{j=1}^{m} A_i \times VC_{ij} \\ ESV_j = \sum_{i=1}^{m} A_i \times VC_{ij} \\ ESV = \sum_{i=1}^{m}\sum_{j=1}^{m} A_j \times VC_{ij} \end{cases} \tag{5}$$

where $ESV$ denotes the ecosystem service value (CNY); $ESV_i$ denotes the value of the ecosystem service of ith type of land (CNY); $ESV_j$ denotes the value of the $j$th ecosystem service function (CNY); $A_i$ denotes the area of the $i$th type of land (hm$^2$); and $VC_{ij}$ denotes the coefficient of the $j$th ecosystem service function of the $i$th type of land (CNY/hm$^2$).

### 2.3.3. Sensitivity Indicators Analysis

For the purpose of validating the accuracy and dependability of the assessment results, this article uses sensitivity analysis of $ESV$ to determine the sensitivity of $ESV$ to the ecosystem value coefficient across various types of land uses [30]. This paper further calculated and analyzed the sensitivity of $ESV$ to changes in the ecosystem value coefficient by adjusting the $ESV$ coefficient to ($\pm$) 50% of the original value [26]. The following is the calculating formula:

$$CS = \left| \frac{(ESV_{\mathrm{b}} - ESV_{\mathrm{a}})/ESV_{\mathrm{a}}}{(VC_{\mathrm{bi}} - VC_{\mathrm{ai}})/VC_{\mathrm{ai}}} \right| \tag{6}$$

where $CS$ is the sensitivity coefficient. $VC_{ai}$ and $VC_{bi}$ are the numerical coefficients of type $i$ land use before and after adjustment, respectively. The $ESV$ before and after the adjustment are denoted by $ESV_a$ and $ESV_b$, respectively [17]. After calculation, $CS < 1$ indicates that $ESV$ is inelastic relative to the value coefficient and the result is reliable, and when $CS$ is close to 0, it indicates that $ESV$ is less sensitive to the value coefficient and the result is more reliable. When $CS > 1$, it indicates that the evaluation results are not reliable [31].

### 2.3.4. Analysis of ESV Variation

The coefficient of variation is an indicator used to measure the degree of dispersion between a data set and its mean. The coefficient of variation is employed to ascertain the extent of spatial disparities in the $ESV$. If the coefficient of variation of $ESV$ in a region is significant, it indicates that the change in $ESV$ in the region is significant; that is, there are significant differences in ecosystem service functions between different locations. The following is the calculating formula:

$$CV = \frac{1}{ESV_{p0}} \sqrt{\frac{\sum_{i=1}^{n} \left(ESV_{pi} - ESV_{p0}\right)^2}{n}} \tag{7}$$

where ecosystem service value's coefficient of variation is known as $CV$; $n$ is the city's number in the study; $ESV_{pi}$ is the per capita ecosystem service value of the $i$th city; and $ESV_{p0}$ is the average per capita ecosystem service value in the YRDUA.

### 2.3.5. Coordination Analysis of LUC and ESV Couplings

The coupling relationship between land use intensity and the ecosystem stems from the degree of physical coupling, primarily denoting the positive dynamic interaction where two or more systems mutually influence and enhance each other [32]. In economics, coupled coordination analysis is often used to assess the orderliness of the variable development. In correlation analysis of $ESV$, land use, and other domains, the coupled coordination model has been frequently applied [33]. The following is the calculating formula:

$$D = \sqrt{C \times T} \tag{8}$$

$$C = 2 \times \sqrt{U_1 \times U_2/(U_1 + U_2)^2} \tag{9}$$

$$T = \alpha U_1 + \beta U_2 \tag{10}$$

where $D$ is the degree of coupling coordination between $LUC$ and $ESV$; $C$ is the degree of coupling of the system; $T$ is the system's degree of coordination. $U_1$ is the standardized total ecosystem service balance value ($0 \leq U_1 \leq 1$), and $U_2$ is the standardized comprehensive intensity of land use ($0 \leq U_2 \leq 1$). $\alpha$ and $\beta$ are the system weights of $ESV$ and land use, respectively. This paper assumes that $LUC$ and $ESV$ are equally important ($\alpha = \beta = 0.5$). Table 2 displays the CCD categorization. In addition, due to the different dimensions of $LUC$ and $ESV$, this paper adopts the MIN–MAX standardization method to standardize the data [34]. The specific formula is as follows:

$$x' = (x - x_{\min})/(x_{\max} - x_{\min}) \tag{11}$$

where $x'$ is the standardized index value. $x_{min}$ and $x_{max}$ are the minimum and maximum values of this index, respectively.

**Table 2.** Classification of CCD.

| D Value | Level | Stage |
|---|---|---|
| $0 \leq D < 0.1$ | Extremely disorder | |
| $0.1 \leq D < 0.2$ | Severely disorder | |
| $0.2 \leq D < 0.3$ | Moderately disorder | Disordered development stage |
| $0.3 \leq D < 0.4$ | Mildly disorder | |
| $0.4 \leq D < 0.5$ | Near-disorder | |
| $0.5 \leq D < 0.6$ | Reluctant coordination | |
| $0.6 \leq D < 0.7$ | Primary coordination | |
| $0.7 \leq D < 0.8$ | Intermediate coordination | Orderly development stage |
| $0.8 \leq D < 0.9$ | Good coordination | |
| $0.9 \leq D \leq 1.0$ | High-quality coordination | |

## 3. Results

### *3.1. Analysis of Land Use*

#### 3.1.1. Land Use Types between 2000 and 2020

Between 2000 and 2020, the land use landscape within the YRDUA underwent significant transformations, as shown in Figure 2 and Table 3. The land use type of the YRDUA has changed significantly during the study period. Among them, farmland has always been the largest and most extensively distributed land use type in the YRDUA, but its area has decreased from 2000's 121,080.376 km$^2$ to 2020's 109,813.774 km$^2$, with a total decrease of 11,266.602 km$^2$ in 20 years. Its share of the total land area also dropped from 54.432% to 49.367%. Concurrently, forest lands exhibited a dynamic trajectory, initially experiencing an expansion followed by a decline, in which the area decreased from 70,198.973 km$^2$ in 2000 to 67,893.856 km$^2$ in 2020, and its proportion also decreased by nearly 1% in 20 years. The grassland area decreased from 35.321 km$^2$ to 16.701 km$^2$. Moreover, the water bodies decreased from 2000's 17,857.528 km$^2$ to 2020's 17,052.607 km$^2$, and the percentage decreased from 8.028% to 7.666%, with a relatively stable overall change. The unutilized land within the YRDUA has historically constituted a minor fraction of the total land area, experiencing a decline from 11.482 km$^2$ in 2000 to merely 3.407 km$^2$ by 2020, which underscores the extensive utilization of land resources within the region, pointing towards an almost complete exploitation of available land for various purposes. Concurrently, the area designated for construction within the agglomeration has seen a consistent uptick, expanding from 13,258.102 km$^2$ at the turn of the century to 27,661.444 km$^2$ two decades later. The expansion translates to an increase in the construction land's share of the total land area from 5.961% to 12.435%, marking an approximate growth of 108.606% relative to the year 2000.

**Table 3.** Area of YRDUA's land use types (km$^2$).

| Type of Land Use | 2000 | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|
| Farmland | 121,080.376 (54.432%) | 116,097.105 (52.192%) | 111,896.552 (50.304%) | 110,022.670 (49.461%) | 109,813.774 (49.367%) |
| Forest land | 70,198.973 (31.558%) | 70,695.707 (31.782%) | 70,752.358 (31.807%) | 68,512.899 (30.800%) | 678,93.856 (30.522%) |
| Grassland | 35.321 (0.016%) | 47.661 (0.021%) | 64.267 (0.029%) | 31.218 (0.014%) | 16.701 (0.008%) |
| Water body | 17,857.528 (8.028%) | 18,849.230 (8.474%) | 18,953.175 (8.520%) | 18,699.046 (8.406%) | 17,052.607 (7.666%) |
| Unutilized land | 11.482 (0.005%) | 5.117 (0.002%) | 4.068 (0.002%) | 3.380 (0.002%) | 3.407 (0.002%) |
| Construction land | 13,258.102 (5.961%) | 16,746.962 (7.529%) | 20,771.369 (9.338%) | 25,172.575 (11.317%) | 27,661.444 (12.435%) |

Note: % represents the percentage of a certain land use type over the total land area.

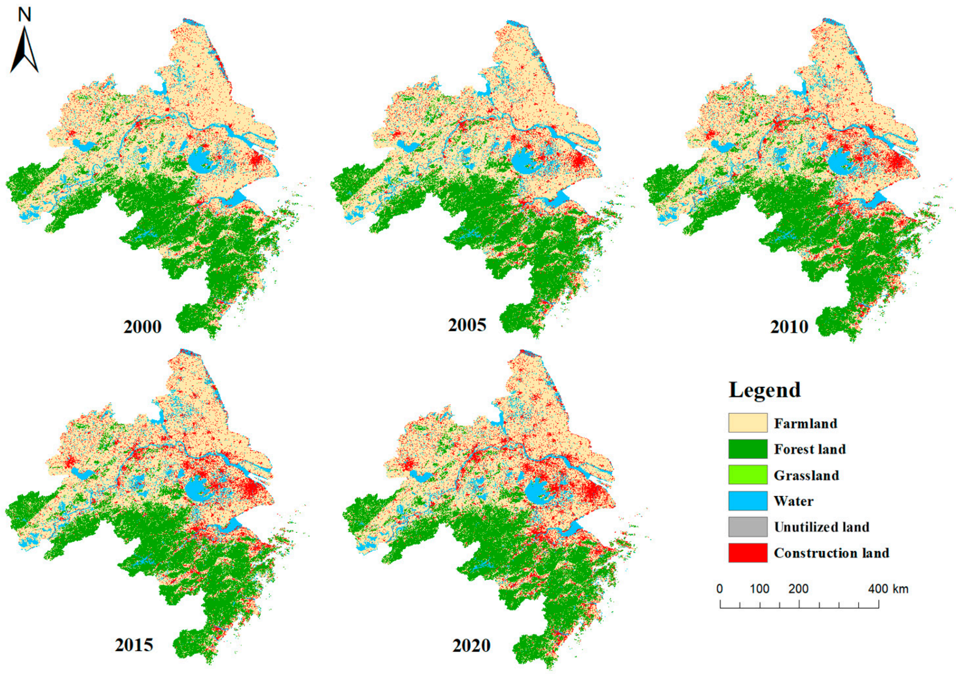


**Figure 2.** Land use types' spatial distribution within YRDUA.

### 3.1.2. Land Use Dynamics Degree Change

A region's pace of change in land use may be extrapolated from the dynamic degree of land use. Table 4 illustrates the dynamic degrees of single and comprehensive land use for each land use category.

**Table 4.** Changes in land use dynamics in YRDUA.

| Year Range | Single Dynamic Degree | | | | | | Comprehensive Dynamic Degree |
|---|---|---|---|---|---|---|---|
| | Farmland | Forest Land | Grassland | Water Body | Unutilized Land | Construction Land | |
| 2000–2005 | −0.823% | 0.142% | 6.988% | 1.111% | −11.086% | 5.263% | 0.449% |
| 2005–2010 | −0.724% | 0.016% | 6.968% | 0.110% | −4.101% | 4.806% | 0.378% |
| 2010–2015 | −0.335% | −0.633% | −10.285% | −0.268% | −3.381% | 4.238% | 0.396% |
| 2015–2020 | −0.038% | −0.181% | −9.300% | −1.761% | 0.154% | 1.977% | 0.224% |
| 2000–2020 | −0.465% | −0.164% | −2.636% | −0.225% | −3.517% | 5.432% | 0.324% |

The calculated dynamic changes in land use presented in the table demonstrate that urbanization and economic development have significantly impacted land use within YRDUA. From the comprehensive dynamic perspective, the YRDUA's overall growth rate of land use was 0.324% from 2000 to 2020, exhibiting fluctuating growth patterns. Notably, between 2000 and 2005, the comprehensive dynamic degree towards land use experienced its highest value at 0.449%. Subsequently, from 2005 to 2010, the comprehensive change rate of land use decreased to 0.378%, indicating a slowdown in the overall change rate. However, it rose again to reach 0.396% over the following five years before reaching its lowest point at 0.224% between 2015 and 2020. Therefore, considering the overall development speed, it can be observed that the YRDUA initially witnessed an increasing trend followed by deceleration—a phenomenon potentially linked to China's transition from rapid development to high-quality development through relevant policies and environmental factors. From the single land use dynamic perspective during the study period, farmland exhibited negative dynamics with continuous decline, and construction land displayed positive dynamics but with decreasing values and apparent slowing growth rates.

The area of specific farmland within the YRDUA has consistently decreased from 2000 to 2020, showing an overall reduction rate of 0.465% over these two decades. The decline of farmland areas, with an annual average change reduction rate of 0.48%, suggests a gradual transformation of farmland into other land use types. In particular, the decrease in farmland peaked in 2000–2005, which was −0.823%. The forestland area showed a slight increase first, then a gradual decrease, and the overall dynamic degree was −0.164%, which was still a downward trend on the surface. Among them, the decrease in forest area from 2010 to 2015 was the fastest, at 0.633%. With an overall drop rate of 2.636%, grassland area was the land type with the most significant shift in range in the YRDUA. The decline from 2010 to 2015 and 2015 to 2020 is the most significant, reaching 10.285% and 9.3%, respectively. The water bodies' changes are relatively stable, which may be related to the fact that the government attaches great importance to river and lake protection. The unutilized land in the YRDUA saw a more pronounced decline of −3.517% between 2000 and 2020, suggesting an enhanced efficiency in land utilization and its conversion into other land types. Among the various land use categories, construction land experienced positive growth, with a dynamic value of 5.432% during the same period, reflecting the YRDUA's rapid industrial and urban expansion in the 21st century. In summary, Table 4's data highlight a clear trend in land use dynamics: a persistent decrease in farmland and ecological lands (including grasslands and forests) and an increase in urban and construction lands throughout the study period.

### 3.1.3. Land Use Conversion Patterns

For the purpose of delving deeper into the interactions and transitions among land use types within the YRDUA region, we used ArcGIS 10.5 software to overlay the land use data in the region. The land use transfer matrix is shown in Table 5.

**Table 5.** Land transfer matrix (km$^2$).

| Type of Land Use (2000) | Type of Land Use (2020) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | Total | Loss |
| I | 102,578.429 | 2732.679 | 4.253 | 2465.454 | 1.130 | 13,298.432 | 121,080.376 | 18,501.947 |
| II | 4568.570 | 65,124.765 | 5.448 | 25.836 | 0.184 | 474.170 | 70,198.973 | 5074.208 |
| III | 14.555 | 6.894 | 6.899 | 1.136 | 0.217 | 5.620 | 35.321 | 28.421 |
| IV | 2504.709 | 29.021 | 0.042 | 14,241.466 | 1.256 | 1081.035 | 17,857.528 | 3616.062 |
| V | 3.155 | 0.002 | 0.052 | 3.326 | 0.519 | 4.428 | 11.482 | 10.963 |
| VI | 144.356 | 0.490 | 0.006 | 315.390 | 0.101 | 12,797.760 | 13,258.102 | 460.342 |
| Total | 109,813.774 | 67,893.850 | 16.700 | 17,052.607 | 3.407 | 27,661.444 | 222,441.782 | - |
| Gain | 7235.345 | 2769.085 | 9.801 | 2811.141 | 2.887 | 14,863.685 | - | 27,691.943 |

Note: I, II, III, IV, V and VI, respectively, represent farmland, forest land, grassland, water bodies, unutilized land, and construction land.

Between 2000 and 2020, the YRDUA experienced a total land transfer area of 12.449% of the agglomeration's overall area. During this period, farmland emerged as the category with the most extensive area transfer, with a net transfer area of 11,266.602 km$^2$. A significant portion of this transferred farmland, precisely 71.876%, was transformed into construction land, highlighting the substantial impact of urban expansion and infrastructure development on agricultural spaces within the region. Secondly, 2732.679 km$^2$ of farmland have been changed to forest land, representing 14.770% of the total area of farmland loss. The net transfer area of forest land is 2305.123 km$^2$, accounting for 3.28% of its total area, which is the second largest type of transferred land. Moreover, grassland has a transfer-out area of 28.421 km$^2$ and a transfer-in area of 9.801 km$^2$, with a relatively stable overall area. The total area of water area transferred out was 3616.062 km$^2$, and the total area transferred in was 2811.141 km$^2$, with a net transferred area of 804.921 km$^2$. As for unutilized land, the total area transferred out was 10.963 km$^2$, and the area transferred in was 3.407 km$^2$, with a net transferred area of 7.556 km$^2$. Regarding construction land, the highest transfer volume was recorded, with a transfer area of 14,863.685 km$^2$ and a net increase of 14,403.343 km$^2$, indicating a significant growth in urban construction within the agglomeration.

To sum up, between 2000 and 2020, the spatial and temporal evolution of land use within the YRDUA showcases the profound impact of socio-economic advancement and human interventions on land resources. The notable decline in farmland and the significant expansion of construction land underscores the region's swift growth, urbanization, and industrialization over the past twenty years.

### *3.2. ESV Change Characteristics*

By leveraging land use and socio-economic data covering the period from 2000 to 2020, our study applied the value equivalent factor method to revise the equivalent factor table for estimating ESV per unit area. This refined methodology facilitated the computation of ESVs at different developmental stages across the YRDUA, incorporating the latest spatial scale adjustments. The calculated ESVs at different phases are documented in Table 6.

The data reveals that over the last two decades, the ESV of the YRDUA experienced an initial rise followed by a subsequent decline. Specifically, the ESV increased continuously from 2000 until it peaked at CNY 830.408 billion in 2005 and then gradually decreased, settling at CNY 773.894 billion by 2020. In terms of individual land use types, among the six primary classified land use types, water bodies have the highest ESVs, comprising over 40% of the total ESV, followed by forest land and farmland, respectively. In contrast, the ESV of grassland and unutilized land is relatively small, partly attributable to their lesser extents within the designated study area. When analyzing the situation more granularly by land use type, the farmland's ESV declined from 2000's CNY 112.644 billion to 2020's CNY 102.162 billion. The forest's ESV initially exhibited an increase before a subsequent decline, culminating in a decrease from 2000's CNY 325.670 billion to 2020's CNY 314.976 billion. Due to the small size of grassland in the YRDUA, the data calculation leads to a large fluctuation in the ESV of grassland, with a rate of change of −52.69% from 2000 to 2020, and the value decreasing from 100.4 million in 2000 to 47.5 million in 2020, and this fluctuation is also highly correlated with the rapid decrease in grassland area. Furthermore, the total ESV of water bodies diminished from CNY 373.5456 billion to CNY 356.7081 billion, registering a 4.51% fall. This decline in water bodies' ESV was a key factor contributing to the overall decrease in the region's ESV. The ESV of unutilized land remained minimal, reflecting its limited actual ecosystem functions. Across the YRDUA, there was a gradual decline in total ESV from 2000's CNY 811.9613 billion to 2020's CNY 773.8942 billion, reflecting the negative repercussions of land use modifications, ecological degradation, and various anthropogenic activities on the ESV within the region since the turn of the 21st century.

From the perspective of different ESV, the supply service value of cropland remained relatively stable over the years, peaking at CNY 1.283 billion in 2000 and reaching its lowest at CNY 1.166 billion in 2015. The supply service value of forests slightly decreased but remained stable overall. Water bodies consistently exhibited the highest supply service value, while grasslands and unused lands contributed minimally to supply services across all years. Regarding regulatory services, the value of regulatory services for all land types decreased. Water bodies consistently showed the highest regulatory service value, starting at CNY 303.202 billion in 2000 and decreasing to CNY 289.535 billion by 2020. In terms of support services, forests were the main contributors, with their value declining from CNY 76.302 billion in 2000 to CNY 73.797 billion in 2020. For cultural services, the cultural service value of cropland slightly decreased from CNY 2.139 billion in 2000 to CNY 1.940 billion in 2020. The cultural service value of forests remained stable overall, while the cultural service value of water bodies decreased from CNY 13.922 billion in 2000 to CNY 13.294 billion in 2020.

In order to more effectively study the spatial distribution changes in ESV in the YRDUA, this study uses ArcGIS 10.5 software for visualization and divides ESV into five categories using the natural intermittent point classification method. The specific results are shown in Figure 3. As shown in Figure 3, water bodies are the primary source of ESV for the YRDUA; high ESV zones are primarily located around significant lakes, including Taihu Lake, West Lake, Gaoyou Lake, and Hongze Lake, with a radial distribution emanating from these aquatic centers. The ESV along the Yangtze River also showcases a zonal pattern, paralleling the river's course. Spatial analysis reveals a pronounced disparity in ESV between the northern and southern cities within the agglomeration, with the southern cities exhibiting higher ESV. In contrast, the northern cities are lower; the high values are primarily clustered in the region where western Jiangsu, northern Zhejiang, and eastern Anhui meet, underscoring the spatial variability and regional distinctions in ecosystem service contributions across the Yangtze River Delta.

**Table 6.** ESV changes in different land use types in YRDUA (unit: CNY one hundred million).

| Year | ESV | Type of Land Use | | | | | Total |
|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | V | |
| 2000 | Supply services | 12.833 | 187.243 | 0.064 | 271.700 | 0.001 | 471.840 |
| | Regulatory services | 851.244 | 2153.084 | 0.648 | 3032.021 | 0.012 | 6037.009 |
| | Support services | 240.972 | 763.024 | 0.243 | 292.519 | 0.004 | 1296.762 |
| | Cultural services | 21.388 | 153.349 | 0.049 | 139.215 | 0.001 | 314.002 |
| | Total | 1126.437 | 3256.700 | 1.004 | 3735.456 | 0.018 | 8119.613 |
| 2005 | Supply services | 12.305 | 188.568 | 0.086 | 286.789 | 0.000 | 487.747 |
| | Regulatory services | 816.209 | 2168.320 | 0.874 | 3200.402 | 0.005 | 6185.811 |
| | Support services | 231.054 | 768.424 | 0.328 | 308.764 | 0.002 | 1308.571 |
| | Cultural services | 20.508 | 154.434 | 0.066 | 146.946 | 0.000 | 321.954 |
| | Total | 1080.076 | 3279.745 | 1.354 | 3942.901 | 0.008 | 8304.084 |
| 2010 | Supply services | 11.859 | 188.719 | 0.116 | 288.370 | 0.000 | 489.065 |
| | Regulatory services | 786.678 | 2170.057 | 1.179 | 3218.051 | 0.004 | 6175.969 |
| | Support services | 222.694 | 769.039 | 0.442 | 310.467 | 0.001 | 1302.644 |
| | Cultural services | 19.766 | 154.558 | 0.089 | 147.756 | 0.000 | 322.169 |
| | Total | 1040.998 | 3282.373 | 1.826 | 3964.644 | 0.006 | 8289.847 |
| 2015 | Supply services | 11.661 | 182.745 | 0.056 | 284.504 | 0.000 | 478.967 |
| | Regulatory services | 773.504 | 2101.370 | 0.573 | 3174.902 | 0.004 | 6050.353 |
| | Support services | 218.965 | 744.698 | 0.215 | 306.304 | 0.001 | 1270.182 |
| | Cultural services | 19.435 | 149.666 | 0.043 | 145.775 | 0.000 | 314.919 |
| | Total | 1023.564 | 3178.479 | 0.887 | 3911.485 | 0.005 | 8114.421 |
| 2020 | Supply services | 11.639 | 181.094 | 0.030 | 259.453 | 0.000 | 452.217 |
| | Regulatory services | 772.035 | 2082.384 | 0.306 | 2895.354 | 0.004 | 5750.083 |
| | Support services | 218.549 | 737.969 | 0.115 | 279.334 | 0.001 | 1235.968 |
| | Cultural services | 19.398 | 148.313 | 0.023 | 132.940 | 0.000 | 300.674 |
| | Total | 1021.621 | 3149.760 | 0.475 | 3567.081 | 0.005 | 7738.942 |

Note: I, II, III, IV and V, respectively, represent farmland, forest land, grassland, water bodies, and unutilized land.

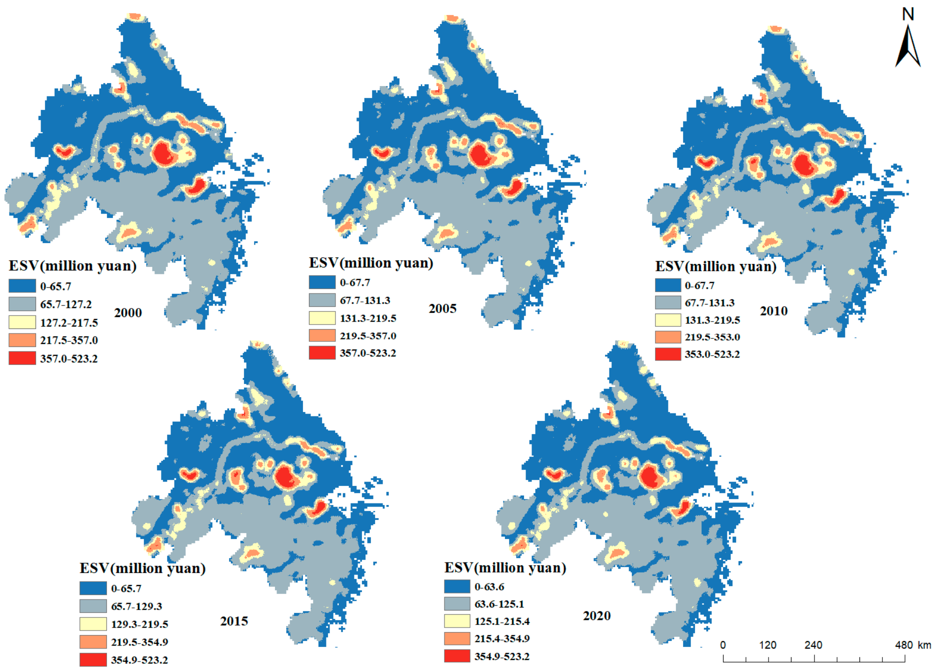


**Figure 3.** Variations and spatial distribution of ESV in YRDUA.

### 3.3. ESV Sensitivity Analysis

Sensitivity analysis is a robust mechanism to ascertain the reliability of ecosystem service valuation outcomes within a study. In this research, the sensitivity index for the ESV coefficients of various land use types in the YRDUA was determined by varying the value coefficients by ±50% for every land use type. As encapsulated in Table 7, the results reveal that the sensitivity coefficients for the ESV across all types are below 1.0, which indicates that the ESV coefficients are inelastic, affirming the credibility of the research findings. The order of sensitivity for each land use type is delineated as follows: water bodies demonstrate the highest sensitivity, followed by forest land and farmlands. In contrast, grasslands and unutilized lands exhibit equal, lower sensitivity levels.

**Table 7.** Sensitivity of ESV in YRDUA.

| Value Coefficient | Sensitivity Index | | | | |
|---|---|---|---|---|---|
| | 2000 | 2005 | 2010 | 2015 | 2020 |
| Farmland | 0.139 | 0.130 | 0.126 | 0.126 | 0.132 |
| Forest land | 0.401 | 0.395 | 0.396 | 0.392 | 0.407 |
| Grassland | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Water body | 0.460 | 0.475 | 0.478 | 0.482 | 0.461 |
| Unutilized Land | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

### 3.4. Coordination Analysis of LUC and ESV Coupling

Swift urbanization, the increased pace of industrialization, and the growth of construction land have collectively driven notable shifts in the land use dynamics within the YRDUA. Thus, maintaining a balanced development of land use and ecosystem services is essential to advancing the area's high-quality, sustainable socio-economic and ecological development. This research quantifies the degree of coupling coordination between land use and ESV to evaluate the orderly development of these elements. The findings in Table 8 and Figure 4 indicate that throughout the period, the overall coupling coordination degree between land use and ecosystem services in the YRDUA experienced an initial increase, succeeded by a subsequent decrease, maintaining a relatively stable range between 0.570 and 0.600. Specifically, the detailed analysis reveals that the coupling coordination degree of the YRDUA slightly improved, moving from 0.572 in 2000 to 0.584 in 2020, which suggests a substantial potential for enhancing the synergistic development between land use and the ecological environment within the urban agglomerations. From the perspective of individual cities, the development of the coupled coordination degree of LUC and ESV was different in each city during the study period. However, most showed an upward trend, indicating that the relationship between land use and ESV among cities is constantly approaching the direction of coordinated development. Moreover, the findings of the spatial distribution reveal notable variations in the degree of coupling coordination across various regions. Shanghai and Jiangsu Province showcase the highest average coupling coordination degrees, 0.655 and 0.641, respectively, achieving primary coordination levels. In contrast, Zhejiang Province displays the lowest, with an average value of 0.471, indicating enormous potential for improvement.

**Table 8.** CCD of LUC and ESV in YRDUA.

| Region | City | 2000 | 2005 | 2010 | 2015 | 2020 | Mean |
|---|---|---|---|---|---|---|---|
| Anhui Province | Anqing | 0.672 | 0.667 | 0.666 | 0.674 | 0.682 | 0.672 |
| | Chuzhou | 0.705 | 0.717 | 0.714 | 0.715 | 0.708 | 0.712 |
| | Chizhou | 0.392 | 0.370 | 0.365 | 0.407 | 0.413 | 0.389 |
| | Hefei | 0.724 | 0.729 | 0.731 | 0.732 | 0.731 | 0.729 |
| | Ma'anshan | 0.507 | 0.513 | 0.532 | 0.539 | 0.526 | 0.523 |
| | Tongling | 0.481 | 0.479 | 0.479 | 0.485 | 0.483 | 0.481 |
| | Wuhu | 0.558 | 0.565 | 0.576 | 0.583 | 0.575 | 0.571 |
| | Xuancheng | 0.512 | 0.501 | 0.504 | 0.532 | 0.530 | 0.516 |
| | Mean | 0.569 | 0.568 | 0.571 | 0.583 | 0.581 | 0.574 |

**Table 8.** *Cont.*

| Region | City | 2000 | 2005 | 2010 | 2015 | 2020 | Mean |
|---|---|---|---|---|---|---|---|
| Jiangsu Province | Nanjing | 0.607 | 0.630 | 0.647 | 0.652 | 0.637 | 0.634 |
| | Wuxi | 0.626 | 0.644 | 0.654 | 0.660 | 0.656 | 0.648 |
| | Changzhou | 0.549 | 0.571 | 0.581 | 0.582 | 0.560 | 0.568 |
| | Suzhou | 0.793 | 0.818 | 0.833 | 0.845 | 0.846 | 0.827 |
| | Nantong | 0.626 | 0.627 | 0.628 | 0.625 | 0.618 | 0.625 |
| | Yancheng | 0.746 | 0.765 | 0.765 | 0.761 | 0.743 | 0.756 |
| | Yangzhou | 0.641 | 0.659 | 0.658 | 0.668 | 0.662 | 0.658 |
| | Zhenjiang | 0.474 | 0.482 | 0.484 | 0.486 | 0.477 | 0.481 |
| | Taizhou | 0.547 | 0.558 | 0.578 | 0.597 | 0.569 | 0.570 |
| | Mean | 0.623 | 0.639 | 0.648 | 0.653 | 0.641 | 0.641 |
| Zhejiang Province | Hangzhou | 0.310 | 0.373 | 0.418 | 0.503 | 0.528 | 0.426 |
| | Ningbo | 0.588 | 0.607 | 0.623 | 0.633 | 0.634 | 0.617 |
| | Wenzhou | 0.156 | 0.300 | 0.333 | 0.425 | 0.454 | 0.334 |
| | Jiaxing | 0.579 | 0.597 | 0.600 | 0.606 | 0.604 | 0.597 |
| | Huzhou | 0.496 | 0.512 | 0.526 | 0.541 | 0.539 | 0.523 |
| | Shaoxing | 0.493 | 0.507 | 0.517 | 0.537 | 0.545 | 0.520 |
| | Jinhua | 0.477 | 0.491 | 0.499 | 0.531 | 0.541 | 0.508 |
| | Zhoushan | 0.258 | 0.263 | 0.244 | 0.216 | 0.000 | 0.196 |
| | Taizhou | 0.453 | 0.477 | 0.493 | 0.512 | 0.523 | 0.492 |
| | Mean | 0.423 | 0.459 | 0.472 | 0.500 | 0.485 | 0.468 |
| Shanghai City | Shanghai | 0.673 | 0.667 | 0.660 | 0.644 | 0.629 | 0.655 |
| | Mean | 0.673 | 0.667 | 0.660 | 0.644 | 0.629 | 0.655 |
| Total mean | | 0.572 | 0.583 | 0.588 | 0.595 | 0.584 | 0.584 |

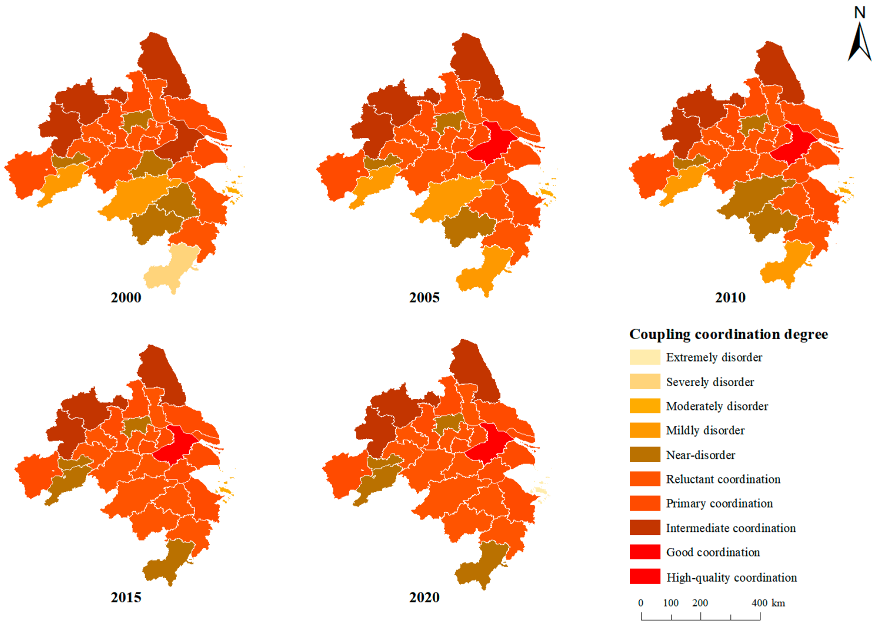


**Figure 4.** Spatial distribution of CCD between LUC and ESV in YRDUA.

## 4. Discussion

### *4.1. Drivers of Land Use Change and ESV*

The dynamic interaction between human endeavors and the ecological backdrop influences the spatial arrangement of land utilization, subsequently altering the ecological system [35]. Factors such as socio-economic developments, urbanization, demographic shifts, climatic variations, and land management policies primarily influence these land use transformations [36,37]. This investigation reveals that between 2000 and 2020, the land usage within the Yangtze River Delta's urban sectors witnessed profound shifts, affecting the ecosystem's structure and functionality [38]. In addition, studies have shown that the growth of GDP and population density will significantly increase the ecological risk in the YRDUA [39]. This period, marked by China's rapid economic growth, accelerated urbanization, and population increase significantly contributed to the swift expansion of constructed spaces. Economically, these urban clusters' GDP leaped from approximately CNY 1.7 trillion in 2000 to over CNY 30 trillion in 2020. Demographically, the population of the Yangtze River Delta's urban areas escalated from 215.714 million a decade ago to 235.386 million in 2020. In terms of urbanization rate, by 2020, the average urbanization rate of the YRDUA was 75.01%, reaching a high level of urbanization, which was 11.12% higher than the national average.

The strong correlation between land use and ESV has been recognized as a fact [36]. In the metropolitan parts of the YRDUA, there has been a general reduction in the ESV associated with different land uses over the past two decades. In particular, the ESV of farmlands decreased by 9.31% over this time, the ESV of water bodies decreased by 4.51%, and forest lands decreased by 3.28%. As a result, the YRDUA's total ESV decreased over time, from 2000's CNY 811.9613 billion to 2020's CNY 773.8942 billion. Furthermore, the swift expansion of areas designated for construction plays a crucial role in diminishing the overall ESV and reshaping its spatial distribution across the YRDUA. In recent years, the YRDUA has experienced rapid economic growth and accelerated urban construction. At the same time, the intensity of land use has also gradually increased, which has led to a gradual increase in the conversion of ecological land to construction land and, thus, a gradual decrease in the ESV. In terms of spatial variation, earlier studies have shown that the expansion of urban construction land into ecological land (including farmland, forest land and waters) may lead to a decrease in ESV [40], which is also confirmed in this paper's study, where ESV in the YRDUA had a rising trend followed by a decline during the period of this paper's study, which has a closely associated with the expansion of urban construction land.

Regarding land use types, farmlands and water bodies emerged as crucial elements impacting the region's ESV, with aquatic environments as the predominant contributors. Areas surrounding significant lakes, including Taihu Lake, West Lake, Gaoyou Lake, and Hongze Lake, and their vicinities, were identified as regions of heightened ESV. Similarly, the vicinity along the Yangtze River exhibited a relatively high ESV, manifesting a zonal pattern paralleling the river's flow [17]. Moreover, an analysis of urban size within the YRDUA revealed a stark contrast in ESV between northern and southern cities, with the latter generally boasting higher ecosystem service values. Furthermore, regions such as western Jiangsu, northern Zhejiang, and eastern Anhui were pinpointed as areas with superior ESV. According to the ESV calculation formula, the ESV coefficient is regarded as an essential indicator for determining changes in ESV, which reflects the sensitivity of ecosystems to land use changes and their responsiveness to changes in the value coefficient. When the area of land types with higher ESV coefficients changes, the value of ecological services they provide will also change more substantially. Therefore, provinces and municipalities in the YRDUA should pay special attention to land types with high ESV coefficients, such as watersheds and farmland, when carrying out land use and ecological protection.

### *4.2. Coupling of LUC and ESV Change*

The degree of coupling coordination between land use intensity and ESV is a critical indicator for evaluating the alignment of LUC with ESV, reflecting the symbiosis between human activities and the environment [8]. Throughout the analysis period, the coupling coordination levels between land use and ecosystem services within the YRDUA varied significantly, indicating that sustainable land management measures were gradually strengthened, which was consistent with Li et al.'s [41] research conclusion. Previous studies suggest that the low coupling coordination degree between LUC and ESV in the early stages may be attributed to the massive migration of rural populations to urban areas in China at the beginning of the 21st century. This migration led to a population surge in the YRDUA, resulting in a decline in ESV [42]. Additionally, urban expansion caused damage to ecological landscapes, further impacting the functions and structures of ecosystems [43].

Spatially, the coupling coordination degree distribution showcased distinct characteristics, predominantly higher in the eastern and northern sectors of the region while lower in its western and southern parts. Notably, Jiangsu Province and Shanghai City exhibited significantly greater coupling coordination levels than the Anhui and Zhejiang provinces. This spatial variation may be attributed to the differing intensities of land use and the varying degrees of ecosystem service provision across these locations. From an economic viewpoint, the study area displayed an uneven distribution of economic strength, primarily evidenced by the GDP disparities among Shanghai, Jiangsu, Anhui, and Zhejiang, wherein the whole area of Jiangsu and the Shanghai Municipality has a higher degree of economic development and more frequent activities of land transformation, thus needing to further strengthen the attention to and protection of the ecological environment, while the two provinces of Zhejiang and Anhui are rich in natural resources and have a strong ecosystem service-provisioning capacity, but the economic development needs to be further enhanced to coordinate the construction and ecological and orderly development. Throughout the whole YRDUA, in terms of time evolution, the coupling coordination between LUC and ESV of each city in 2000–2005 grew significantly faster than that in 2005–2015, while the overall decline in the coupling coordination in 2015–2020 is closely related to the high-intensity development of each province and city in recent years. Therefore, the simultaneous development of effective land use and enhancing the value of ecosystem services is a long-term and gradual process. Specifically, sustainable land use development solutions must be implemented in YRDUA regions with low coordination levels or insufficient coupling coordination, which combine the advantages of ecology and the environment with efficient land use, ensuring a harmonious coexistence between ecological preservation and urban expansion. In addition, while increasing the level of urbanization, the regions should also pay attention to urban planning and ecological civilization construction, as well as continuously improve land use efficiency, such as adopting innovative urbanization approaches and establishing an ecological compensation mechanism that can further elevate the quality of development, enabling a more sustainable and equitable growth model across the Yangtze River Delta [44].

### *4.3. Policy Recommendations*

The swift urbanization, industrialization, and socio-economic growth within the YRDUA have led to significant land-use pattern transformations, exerting considerable pressure on the region's ecosystem services. At the governmental level, in order to address the regional disparities in coupling variations, local governments should focus on increasing the ESV in their areas and protecting ecosystems by increasing and protecting ecosystems with high ESV equivalent factors (e.g., forest land, farmland, and water bodies) [45]. A well-considered land use structure is essential for harmonizing the ecosystem's structure and functions, ensuring a sustainable living environment. Therefore, integrating a quantitative assessment of ecosystem services into sustainable land use policies' planning and decision-making processes is necessary to achieve harmony between ecological functions and urban development [46]. In terms of subject areas, achieving a comprehensive strategy for land resource management and ecological protection requires interdisciplinary research, combining insights from economics, urban planning, and ecology to foster a multidisciplinary and integrated approach.

Furthermore, on a public level, enhancing public awareness about the importance of sustainable development plays a pivotal role in societal engagement. Through community management and public consultation, policymakers can involve residents in the decision-making process of ecological protection and land use, collect their opinions, encourage participation, and ensure the transparency, legitimacy, and social acceptance of the policies formulated. Finally, at the legal and policy level, government agencies should expedite developing and enhancing relevant policy and legal frameworks to facilitate the execution of land management tactics, such as guidelines for assessing the value of ecological services, land use planning, and ecological compensation policies.

In addition, constructing sustainable cities is in line with the UN's Sustainable Development Goals and represents a critical path for urban evolution in the future [47]. Our analysis indicates that the coupled coordination of LUC and ESV among cities in the YRDUA is generally upward but still has room for improvement in achieving high-quality coordination. Moreover, our research highlights that local policies and economic dynamics are pivotal in shaping land use functionality [48]. As a result, to advance the symbiotic progression of land utilization and ecosystem services in the Yangtze River Delta, it is essential to execute varied land use strategies tailored to the specific integration types of land categories and ecosystem services, seeking to address the gaps in regional development [49]. Specifically speaking, in areas where integration between land use and ecosystem services is robust, such as in Jiangsu Province and Shanghai, authorities are encouraged to foster and refine the current land use practices by introducing incentives. In areas with less integrated land use and ecosystem services, like the Anhui and Zhejiang provinces, it is crucial for the government to rethink land use configurations or to intensify efforts in ecological restoration. Finally, governmental departments must enhance the land and spatial planning systems, creating a new land and space utilization and a conservation paradigm characterized by distinct primary functions, mutual benefits, and superior development quality. This involves rigorously applying restrictions to land designated for ecological purposes, such as agricultural fields, forests, and water bodies, and firmly adhering to ecological protection red lines. Furthermore, leveraging scientific and technological developments to increase land use efficiency and ecosystem service quality is essential. For example, implementing a dynamic ecological monitoring system utilizing remote sensing technologies, significantly enhancing the provision and reliability of ecological products, and employing ecological engineering methods to rehabilitate and enrich deteriorating ecosystems can be effective strategies.

### *4.4. Research Deficiency and Prospect*

This paper thoroughly explores the coupling coordination relationship between LUC and ESV in the YRDUA from two dimensions of time and space, which can provide a scientific basis for optimizing land use decisions and enhancing ecosystem service provision in the YRDUA. However, several limitations need to be addressed in future research. Firstly, this study uses the equivalent factor table to estimate the ESV of the YRDUA. While this method is suitable for large-scale ecological value estimation, it has certain inaccuracies. In future work, we will utilize current remote sensing surveys and evaluation systems to construct more precise equivalent factor coefficients applicable to smaller geographic units, thereby improving the accuracy of ESV measurements. Additionally, we will adopt multiple ESV quantification methods to minimize systematic errors caused by using a single estimation method. Moreover, we will use a variety of models to measure and verify the comprehensive land use dynamic degree to improve the accuracy of the calculation further [50,51]. Secondly, although this paper provides a detailed analysis of the coupling coordination relationship between LUC and ESV from both temporal and spatial dimensions, the intrinsic driving factors and mechanisms of their interaction warrant deeper investigation. Finally, we will employ machine learning methods to explore the deeper interaction between urban development and ecosystem services under different land use scenarios.

## 5. Conclusions

This study employed land use analysis alongside an improved equivalent factor methodology to meticulously examine the spatial and temporal dynamics between changes in LUC and ESV within the YRDUA between 2000 and 2020. Furthermore, we utilized a coupling coordination model to dissect the interplay between land use patterns and ecosystem services within the same region. The following is a summary of the key findings:

(1) The principal land categories within YRDUA comprise farmlands, forested areas, water bodies, and construction land, with a minor presence of grasslands and unused

lands. Throughout the analysis, the YRDUA's overall dynamic index of land use was 0.324%, with a total land conversion spanning 27,691.943 km$^2$, representing 12.449% of the entire area. The transformation patterns reveal that farmland experienced the most significant reduction, whereas construction land saw the most substantial expansion.

(2) The YRDUA's ESV fluctuated over the study period, rising from 2000's CNY 811.961 billion to 2005's CNY 830.408 billion before gradually declining to CNY 773.894 billion by 2020. In assessing the ESV across different land use types, water bodies emerged with the highest ESVs, succeeded by forest land and farmlands. Conversely, grasslands and unutilized lands exhibited the lowest contributions to the ESV. Spatially, regions of high ESV within the Yangtze River Delta are predominantly located around significant lakes, including Taihu Lake, West Lake, Gaoyou Lake, and Hongze Lake, with a notable distribution radiating from these lakes. Regarding urban distribution, there is a pronounced disparity in ESV between the northern and southern cities within the agglomeration, with southern cities exhibiting higher ESV.

(3) Throughout the study period, the YRDUA exhibited a positive trend in the coupling coordination degree between LUC and ESV, increasing from 0.572 in 2000 to 0.584 in 2020. Spatial analysis revealed significant variations in coupling coordination across different provinces and cities within the YRDUA. Shanghai and Jiangsu Province had higher overall coupling coordination degrees, while the Zhejiang and Anhui Provinces showed relatively lower averages.

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