

Article

Spatiotemporal Dynamics of Land Use and Ecosystem Service Value in the Dongting Lake Region, China

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Abstract

The Dongting Lake Region is a major river-connected lacustrine ecosystem and ecological security barrier in the middle Yangtze River Basin, where land use change has important implications for ecosystem service provision. However, how land use transition pathways and spatial clustering jointly shape land-cover-based ecosystem service value (ESV) estimates remains insufficiently understood, particularly under a coefficient-based valuation framework. This study used land-use data for 2005, 2010, 2015, 2020, and 2025 (with the 2025 layer being not fully observation-based but derived from remote-sensing interpretation and model-assisted updating rather than direct field observations). The analytical framework integrated land-use transition analysis, land-use dynamic degree analysis, equivalent-factor-based ESV estimation, spatial autocorrelation analysis, one-way parametric sensitivity analysis with a $\pm 50\%$ variation, and stage-specific comparisons aligned with policy implementation timelines. These methods were applied to investigate the spatiotemporal dynamics of estimated ESV in the Dongting Lake Region. Cropland, forestland, and water bodies remained the dominant land use types, while built-up land expanded through the conversion of agricultural and ecological land. Estimated total ESV declined during the study period, although the annual rate of decline was lower during 2015–2025 than during 2005–2015. Under the adopted equivalent-factor framework, water-body-related transitions contributed most to estimated ESV change, reflecting both the ecological importance of water-related systems and the high coefficients assigned to water bodies, especially for hydrological regulation. Estimated ESV showed persistent positive spatial autocorrelation, with High–High clusters concentrated around East Dongting Lake, South Dongting Lake, and West Dongting Lake. These findings provide land-cover-based evidence for territorial spatial optimization and SDG-related ecosystem management. However, the identified clusters should be interpreted as candidate lake-centered high-value ecological spaces for further assessment, rather than as definitive conservation priorities or ecological zoning boundaries.

Keywords: Dongting Lake Region; land use change; ecosystem service value; spatial autocorrelation; sensitivity analysis

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1. Introduction

Land use/land cover change (LUCC) is a major driving factor of structural adjustment and functional evolution in regional ecosystems, as well as a key process linking human activities, resource allocation, and ecological security patterns [1,2]. Under the combined influence of rapid urbanization, industrial expansion, and ecological conservation policies, conversions among different land use types continuously reshape surface landscape patterns, thereby affecting material cycling, energy flow, and the capacity of ecosystems to provide services [3,4]. Ecosystem service value (ESV) comprehensively reflects the contribution of ecosystems to human well-being and regional sustainable development from the perspectives of provisioning, regulating, supporting, and cultural services [5], and has been widely applied to evaluate the ecological effects of land use change within broader international valuation and classification frameworks [6–8]. Previous studies have shown that changes in the area and spatial reconfiguration of cropland, forestland, water bodies, wetlands, and built-up land can significantly alter ecosystem service functions, such as hydrological regulation, climate regulation, food production, biodiversity maintenance, and soil conservation, further influencing regional ecological management and land-use decision-making [1,9]. Therefore, systematically revealing the spatiotemporal evolution of land use and the response of ecosystem service value is of great significance for optimizing land resource allocation, identifying priority areas for ecological conservation, and enhancing regional ecosystem stability [9]. The study of land use change and ecosystem service value is closely related to the ecological dimensions of the 2030 Agenda for Sustainable Development [4,10]. In the Dongting Lake Region, changes in water bodies, wetlands, cropland, forestland, and built-up land are directly linked to SDG 6.6, which emphasizes the protection and restoration of water-related ecosystems; SDG 15.1, which focuses on terrestrial and inland freshwater ecosystems; SDG 2.4, which concerns sustainable agricultural systems; SDG 11.4, which stresses the protection of natural heritage; and SDG 13, which highlights climate adaptation and ecological resilience. Therefore, incorporating an SDG perspective can enhance the policy relevance of LUCC and ESV assessment in lacustrine wetland regions.

In recent years, the coupling relationship between land use change and ecosystem service value has become an important topic in geography, ecology, and land system science [11]. Existing studies have commonly employed methods such as land use transition matrices and land use dynamic degree [12], landscape pattern indices [13], spatial autocorrelation [14], coupling coordination models [15], and scenario simulation models [16] to identify quantitative changes in land use, spatial transition directions, and differences in ecological effects. In terms of ESV estimation, the equivalent value factor method remains widely used for assessing ecosystem service value under the background of land use change because of its relatively low data requirements and strong regional applicability [17]. Meanwhile, some studies have further introduced spatial heterogeneity correction, socioeconomic adjustment, resource scarcity correction, and correction for the negative effects of built-up land to improve the regional adaptability and spatial representation of ESV assessment. For example, Wang et al. [18] revealed pronounced spatial heterogeneity in ecosystem services and their trade-offs in the Hengdian Mountain region, indicating that ecosystem service patterns and relationships may vary considerably across spatial units. He et al. [19] and Jing et al. [20] further revealed the spatiotemporal coupling relationship between land use intensity and ESV by taking Hubei Province and Jiangsu Province as case studies, respectively. These studies provide an important methodological foundation for regional land use optimization and ecosystem service management.

Lacustrine wetlands are among the areas where terrestrial ecosystems and aquatic ecosystems interact most intensely. They provide multiple ecological functions, including flood regulation and storage, water conservation, climate regulation, pollution purification, habitat maintenance, and landscape recreation [21,22]. Compared with general terrestrial ecosystems, lacustrine wetland ecosystems are more sensitive to changes in hydrological processes and land development intensity. Their capacity to provide ecosystem services often exhibits pronounced spatial heterogeneity, scale effects, and stage-specific variation [21–23]. Based on a multi-lake urban study, Xu et al. [22] indicated that ecosystem services of lacustrine wetlands show evident spatiotemporal heterogeneity and scale effects, and that wetland size, urban expansion gradients, and conservation measures jointly influence their service-provisioning capacity. For the lacustrine wetland region in the middle reaches of the Yangtze River, changes in land use structure not only affect the supply of local ecosystem services but are also closely related to flood regulation, aquatic ecological security, and regional sustainable development at the watershed scale [23–25].

The Dongting Lake Region is an important lacustrine wetland ecosystem in China and an ecological security barrier in the middle reaches of the Yangtze River. It plays an irreplaceable role in maintaining hydrological regulation, wetland biodiversity conservation, and regional ecological stability in the Yangtze River Basin [26]. Connected with the Yangtze River system, Dongting Lake is an important river-connected lake and flood-regulating lacustrine wetland in the middle reaches of the Yangtze River [27].

Although previous studies have improved the understanding of land use change and its ecological effects in the Dongting Lake Region, the mechanisms through which specific land use transition pathways affect ecosystem service value remain insufficiently clarified. Compared with prior Dongting Lake LUCC–ESV studies that often quantified aggregate land-use change and overall ESV without explicitly resolving transition-pathway-specific ecological effects, the structural linkage between land conversion processes and ecosystem service functions remains insufficiently addressed [28–30]. In particular, three inter-related gaps persist: (i) insufficient differentiation of ecological effects across land-use transition pathways, as most studies treat LUCC as aggregated change; (ii) limited resolution of ecosystem service function-specific responses; and (iii) inadequate characterization of the temporal persistence and spatial clustering of ESV hotspots and coldspots. Based on these unresolved issues and the ecological characteristics of the Dongting Lake Region, this study proposes three expectations: first, ecological conservation and restoration policies may alter the trajectory of ESV change after 2015; second, because water bodies provide dominant hydrological regulation services, water-body-related land use transitions are expected to be the primary drivers of ESV change; and third, significant positive spatial clustering of ESV is expected to persist because high-value ecosystem services are concentrated in major wetland and waterbody areas. To test these expectations, this study integrates land use transition analysis, land use dynamic degree, ecosystem service value assessment, spatial autocorrelation analysis, and sensitivity analysis within a unified framework. By linking land use transition pathways, individual ecosystem service functions, and the spatial evolution of ESV hotspots and coldspots, this study aims to reveal the mechanisms connecting land use change and ecosystem service dynamics in a typical river-connected lacustrine wetland region.

2. Materials and Methods

2.1. Study Area

The Dongting Lake Region is located in northern Hunan Province, south of the Jingjiang reach of the middle Yangtze River. It is an important lacustrine wetland ecological region and flood regulation area in the Yangtze River Basin, playing a crucial role in maintaining regional flood control security, food security, and ecological security. Following previous studies, the study area was delineated as comprising 24 districts and counties in the Dongting Lake area (Figure 1) [30]. With Dongting Lake as its core, the study area is characterized by a typical river–lake connectivity pattern, where the Xiangjiang, Zishui, Yuanjiang, and Lishui rivers flow into Dongting Lake and subsequently connect with the Yangtze River. The regional landscape is dominated by lakes, river networks, floodplain wetlands, alluvial plains, farmland, and surrounding hilly uplands. The northern Dongting Lake Plain is low-lying and flat, with dense water networks and interlaced land use types. The study area has a subtropical humid monsoon climate, characterized by abundant light and heat resources, plentiful precipitation, and simultaneous rainfall and heat, providing favorable natural conditions for agricultural production and the development of wetland ecosystems. Under the combined influence of urban expansion, agricultural development, and ecological conservation and restoration, the land use structure and ecosystem service functions of the Dongting Lake Region exhibit significant spatiotemporal variations. Therefore, this region is suitable as a representative area for studying land use evolution and ecosystem service value.

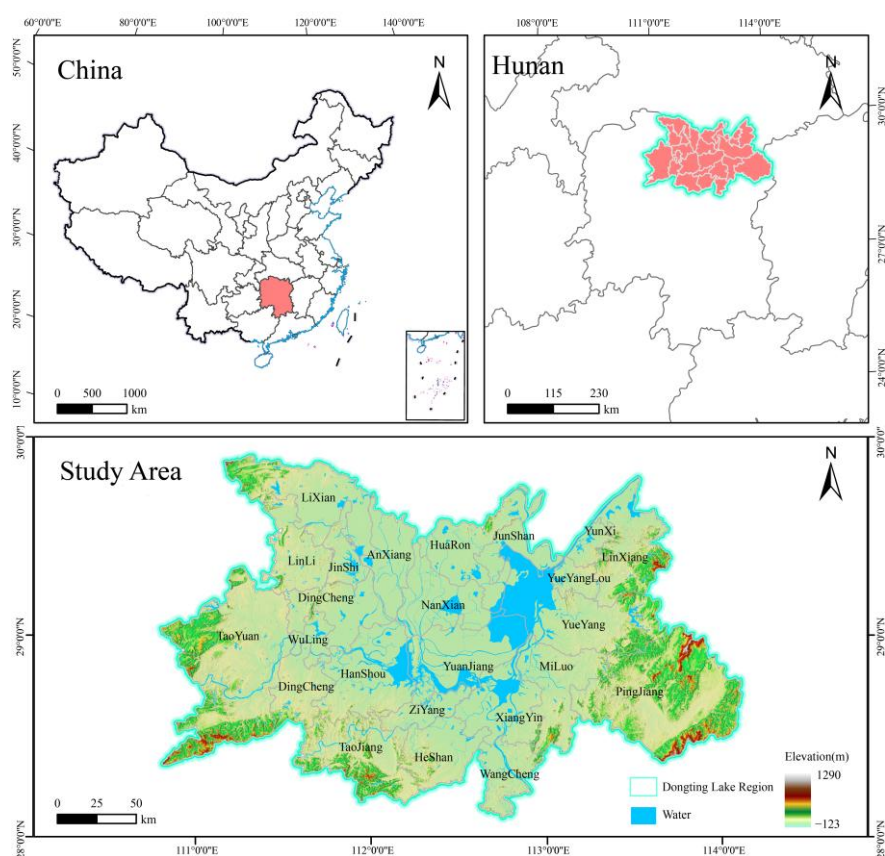


Figure 1. Location of the Dongting Lake Region. (This map depicts the Dongting Lake region, located in Hunan Province, China, in the middle reaches of the Yangtze River. The coordinate reference system uses the Albers Equal-Area Conic Projection (China Albers), and distances are measured in kilometers (km). The map includes latitude and longitude coordinates and a scale bar for spatial reference.)

2.2. Data Sources

The data used in this study mainly include administrative boundary data, grain yield data, and land use data. The 30 m-resolution land-use data for 2005–2025 were obtained from the Resource and Environmental Science Data Platform (<https://www.resdc.cn/data.aspx?DATAID=360>, accessed on 10 May 2026) [31]. It should be noted that the 2025 land use data are not fully observation-based historical data; rather, they were produced based on the 2020 and 2023 land use data, combined with comparative analysis of remote sensing images from 2020, 2023, and 2025, manual visual interpretation, and simulation-based compilation. Therefore, the 2025 land use data were used in this study to characterize recent land use change trends and support scenario-oriented ecological impact assessment, rather than being treated as a fully observation-based historical record. The CNLUCC dataset adopts a two-level classification system. The first-level categories include six land use types: cropland, forestland, grassland, water bodies, built-up land, and unused land. The second-level categories further subdivide these first-level classes into 25 subclasses. It should be further noted that no independent accuracy assessment or validation report was available for the 2025 land-use layer. For compatibility with the ESV equivalent-factor approach and long-term transition analysis, all land use datasets were uniformly reclassified into the six first-level CNLUCC categories, while this aggregation inevitably reduces the ecological resolution of wetland-specific land-cover information. This treatment ensures methodological consistency across land-use classification, transition matrix construction, and ESV coefficient assignment. Data pre-processing, including projection unification, clipping, reclassification, raster alignment, and area calculation, was conducted in ArcGIS to ensure spatial consistency in extent, resolution, and classification scheme. Grain yield data were obtained from statistical yearbooks, statistical bulletins, and official statistical reports of the cities and counties in the study area from 2005 to 2025. These data were used to correct regional ecosystem service value equivalent factors and to calculate ecosystem service value per unit area.

2.3. Methods

2.3.1. Land Use Transition Matrix

The land use transition matrix can quantitatively reveal the conversion-in and conversion-out relationships among different land use types across different periods. It is an important method for analyzing changes in land use structure and spatial transformation processes. In this study, with the support of ArcGIS 10.8, land use raster data for 2005, 2010, 2015, 2020, and 2025 were first subjected to projection unification, spatial clipping, reclassification, and raster alignment to ensure consistency in spatial extent, resolution, and classification criteria across all periods. On this basis, raster overlay analysis was used to construct land use transition matrices for four study intervals, namely 2005–2010, 2010–2015, 2015–2020, and 2020–2025, in order to identify the transition directions and transition magnitudes among different land use types.

2.3.2. Land Use Dynamic Degree

The comprehensive land use dynamic degree describes the overall rate of land use change within an entire region. It plays an important role in examining regional differences in dynamic land use changes and serves as a key indicator for identifying hotspots of land use transformation. It has also been widely applied in comparisons of land use change at global, local, and interregional scales. The calculation formula is shown in Equation (1):

$$LC = \frac{\sum_{i=1}^n \Delta LU_{i-j}}{2 \sum_{i=1}^n LU_i} \times \frac{1}{T} \times 100\% \quad (1)$$

where LC denotes the comprehensive land use dynamic degree during the study period; LU_i represents the area of land use type i at the beginning of the study period; ΔLU_{i-j} represents the area converted from land use type i to land use type j during the study period, where $j = 1, 2, \dots, n$, and n is the number of land use types; and T is the length of the study period. When the unit of T is set as year, the result calculated using Equation (1) represents the annual comprehensive rate of regional land use change.

The single land use dynamic degree is an indicator that reflects the rate of area change for a specific land use type within a given time period. It focuses on analyzing the change characteristics of each land use type. The calculation formula is as follows:

$$k_i = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (2)$$

where k_i denotes the dynamic degree of land use type i during the study period; U_a and U_b represent the areas of land use type i at the beginning and end of the study period, respectively; and T is the length of the study period. When the unit of T is set as year, the result calculated using Equation (2) represents the annual rate of change for land use type i .

2.3.3. Ecosystem Service Value Estimation

Because this study aimed to evaluate regional-scale ESV changes associated with long-term land use transitions, and because detailed and consistent biophysical parameters for all ecosystem service processes were not available for the entire study period, the equivalent-factor approach was adopted. This approach provides a comparable framework for linking land use categories with ecosystem service values and is suitable for assessing the overall ecological effects of land use change in the Dongting Lake Region across multiple periods. Based on the value equivalent factors per unit area improved by Xie et al. in 2015 for China's terrestrial ecosystems [32], and with reference to the study of Li et al. [29], this study constructed value equivalent factors per unit area for six first-level land use categories in the Dongting Lake Region. To ensure consistency with the land use transition analysis, ESV coefficients were assigned to the same six first-level CNLUCC categories: cropland, forestland, grassland, water bodies, built-up land, and unused land.

According to previous studies, the economic value of one standard equivalent factor is approximately equal to one-seventh of the market value of the average grain yield per unit area [32]. In this study, the economic value of grain production per unit area of farmland was corrected based on the average grain crop yield in the Dongting Lake Region from 2005 to 2025, which was 4962.11 kg/hm², and the grain crop price, which was set as the average constant price of rice and maize in 2020 at 2.71 CNY/kg. The calculated monetary value of one standard equivalent factor was 1921.05 CNY·hm⁻²·yr⁻¹. The ESV coefficients for the Dongting Lake Region are shown in Table 1. This regional correction procedure has been widely applied in ESV studies using the equivalent-factor method [33,34], and it improves the applicability of the national equivalent-factor system to the Dongting Lake Region. For built-up land, no consensus has been reached regarding its ecological effects, and its evaluation and monetization remain controversial. Following the equivalent-factor framework widely used in ecosystem service valuation studies [30–32], built-up land is assigned an ecosystem service value coefficient of zero because its ecosystem services are not explicitly quantified within this accounting system and its ecological effects are highly heterogeneous and difficult to parameterize at regional scale [33]. However, this does not imply that built-up land has no ecological effects; rather, it reflects the methodological limitation that both positive and negative urban ecological processes are not separately monetized within the equivalent-factor approach.

Table 1. ESV coefficients for the Dongting Lake Region.

Ecosystem Services	Land Use Types					
	Cropland	Forestland	Grassland	Water Bodies	Built-Up Land	Unused Land
food production	2122.76	461.05	448.25	2516.58	0.00	19.21
raw material production	470.66	1046.97	659.56	1402.37	0.00	57.63
water supply	−2506.97	537.89	365.00	20,901.02	0.00	38.42
gas regulation	1709.74	3438.68	2318.07	5129.20	0.00	211.32
climate regulation	893.29	10,306.43	6128.15	11,314.98	0.00	192.10
environmental purification	259.34	3083.29	2023.51	17,577.61	0.00	595.53
hydrological regulation	2871.97	7770.65	4488.85	242,955.20	0.00	403.42
soil conservation	998.95	4197.49	2823.94	6224.20	0.00	249.74
nutrient cycling maintenance	297.76	316.97	217.72	480.26	0.00	19.21
biodiversity maintenance	326.58	3822.89	2567.80	20,017.34	0.00	230.53
aesthetic landscape	144.08	1680.92	1133.42	12,717.35	0.00	96.05
total	7588.15	36,663.24	23,174.27	341,236.10	0.00	2113.16

Note: The negative coefficient for the water-supply service of cropland reflects the net consumption of water resources associated with agricultural irrigation, particularly in paddy fields, rather than a direct monetary irrigation cost. All coefficients are expressed in CNY·hm^{−2}·yr^{−1}. The relatively high value coefficient for hydrological regulation services of water bodies reflects the ecological functional characteristics of the Dongting Lake area as an important flood-regulation and flood-storage lake and a river–lake-connected wetland system in the Yangtze River Basin. This coefficient was not independently defined in this study; rather, it was determined based on the value equivalent factor system proposed by Xie Gaodi et al. and by referring to existing regional correction studies for the Dongting Lake area.

Based on this table, the ecosystem service value of land in the Dongting Lake Region can be calculated. The calculation methods are shown in Equations (3) and (4).

$$ESV = \sum (A_i \times VC_j) \quad (3)$$

$$ESV_f = \sum (A_i \times VC_{fj}) \quad (4)$$

where ESV denotes the ecosystem service value of land; A_i represents the area of the corresponding land use type i ; VC_j is the ecosystem service value coefficient of the corresponding land use type, expressed in CNY·hm^{−2}·yr^{−1}; ESV_f represents the value of ecosystem service function f ; and VC_{fj} denotes the coefficient of ecosystem service function f for land use type j . To avoid confusion with coefficient-based sensitivity analysis, this study refers to this metric as the relative ESV contribution index. It was used to measure the relative contribution of changes in a specific land use type or ecosystem service function to the overall ESV change during the same period.

Given the limitations of the CNLUCC classification system, this study classified the lake wetland subcategories (shoreline wetlands and marshes) under the first-level land use categories “water bodies” and “unutilized land,” respectively. To assess the potential influence of this classification treatment on the calculation of total ESV, a sensitivity analysis was conducted by independently estimating the ESV of floodplains and marshes using the standard wetland ecosystem value coefficient proposed in Xie Gaodi’s equivalent-factor system. The formula for quantifying the deviation is defined as follows:

$$ltaESV_{bias} = \sum_t [A_{marsh}(t) \times (VC_{wetland} - VC_{barren}) + A_{beach}(t) \times (VC_{wetland} - VC_{water})]$$

In this context, ESV_{bias} represents the amount by which the value is underestimated due to the failure to separately account for wetlands; A_{marsh} and A_{beach} denote the annual areas of tidal flats and marshes, respectively; and $VC_{wetland}$ uses the standard “wetland” service coefficient of 868,575 CNY·hm⁻² from the Xie Gaodi Ecosystem Service Value Improvement System.

2.3.4. Spatial Autocorrelation Analysis

Spatial autocorrelation analysis is a method used to measure whether, and to what extent, the spatial distribution of a given attribute is correlated with that of neighboring areas. It can directly reveal the associations and differences among specific spatial phenomena.

(1) Global Spatial Autocorrelation Analysis

Global spatial autocorrelation analysis was used to characterize the overall spatial correlation of ESV across the Dongting Lake Region by calculating Moran’s I index. The value of Moran’s I ranges from −1 to 1. A Moran’s I value greater than 0 indicates positive spatial autocorrelation; the larger the value, the stronger the positive correlation and the more pronounced the spatial clustering. A Moran’s I value equal to 0 indicates no spatial correlation, suggesting a random spatial distribution among spatial units. A Moran’s I value less than 0 indicates negative spatial autocorrelation; the smaller the value, the stronger the negative correlation and the greater the spatial heterogeneity. To analyze the spatial distribution of ESV, the study area was divided into 5 km × 5 km grids, with the average ESV of each grid used as the spatial analysis unit. This scale was selected to balance spatial heterogeneity and avoid excessive fragmentation, given the large area and mixed distribution of lakes, wetlands, cropland, and built-up land in the Dongting Lake Region. Spatial autocorrelation analysis was conducted in GeoDa using a first-order Queen contiguity spatial weights matrix. The significance of Moran’s I was tested using 999 random permutations, and grid cells with pseudo-*p* values below 0.05 were considered statistically significant. Significant local spatial associations were classified as High–High (HH), Low–Low (LL), High–Low (HL), and Low–High (LH), with HH and LL indicating positive local spatial autocorrelation and HL and LH indicating negative local spatial autocorrelation. The calculation formula is as follows:

$$Moran's\ I = \frac{n \sum_{i=1}^n \sum_{j \neq 1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{(\sum_{i=1}^n \sum_{j=1}^n w_{ij}) \sum_{i=1}^n (x_i - \bar{x})^2} \quad (5)$$

where *n* denotes the number of spatial units; x_i and x_j represent the ecosystem service value (ESV) of spatial units *i* and *j*, respectively; $\bar{x}$ denotes the mean ESV; and w_{ij} is the corresponding spatial weight matrix.

(2) Local Spatial Autocorrelation Analysis

Local spatial autocorrelation was analyzed by calculating the local Moran’s I index, also known as the local indicators of spatial association (LISA), to reveal the local spatial correlation patterns of ESV in the Dongting Lake Region. Different spatial association patterns can be identified according to the value of local Moran’s I. A local Moran’s I value less than 0 indicates that the ESV of a spatial unit belongs to a High–Low or Low–High clustering type. A local Moran’s I value greater than 0 indicates that the ESV of a spatial unit exhibits a High–High or Low–Low clustering type.

$$Moran's I_i = \frac{(x_i - \bar{x})}{m_o} \sum_j w_{ij} (x_j - \bar{x}) \quad (6)$$

$$m_o = \sum_i (x_i - \bar{x})^2 / n \quad (7)$$

where x_i , x_j , $\bar{x}$, and w_{ij} have the same meanings as those defined in Equation (5).

2.3.5. SDG-Related Indicator Interpretation

To respond to the SDG framework, this study linked the selected LUCC and ESV indicators with relevant SDG targets where possible. Changes in water bodies, lakes, reservoirs, floodplains, and marshland were used as regional ecological proxies for SDG 6.6. Forestland change and ESV high-value clusters were used to interpret implications for SDG 15.1. Cropland change and food production service value were related to SDG 2.4. Wetland conservation and control of built-up land expansion were discussed in relation to SDG 11.4, while hydrological regulation, climate regulation, and ecological security functions were linked to SDG 13. Because some official SDG indicators require additional socioeconomic, protected-area, financial, or disaster-risk data, the SDG interpretation in this study is regarded as a regional ecological proxy assessment rather than a direct replacement for official SDG monitoring.

2.3.6. Value-Coefficient Sensitivity Analysis

A one-at-a-time parameter sensitivity analysis was conducted to assess the dependence of the equivalent-factor-based ESV estimates on the adopted value coefficients. Following Kreuter et al. [34], the ESV coefficient of each land use type was independently increased and decreased by 50%, while the coefficients of all other land use types and the corresponding land use areas were held constant. The adjusted coefficient and total ESV were calculated as follows:

$$VC_k^{\pm} = VC_k(1 \pm 0.50) \quad (8)$$

$$ESV_k^{\pm} = \sum_{i \neq k} A_i VC_i + A_k VC_k(1 \pm 0.50) \quad (9)$$

The coefficient of sensitivity was calculated as follows:

$$CS_k = \left| \frac{(ESV_k^{\pm} - ESV_0)/ESV_0}{(VC_k^{\pm} - VC_k)/VC_k} \right| \quad (10)$$

where CS_k is the coefficient of sensitivity for land use type k ; ESV_0 is the total ESV calculated using the baseline coefficients; $ESV_k^{\pm}$ is the recalculated total ESV after increasing or decreasing the coefficient of land use type k by 50%; and VC_k and $VC_k^{\pm}$ are the baseline and adjusted value coefficients, respectively. A value of $CS_k > 1$ indicates an elastic response of total ESV to the adjusted coefficient, whereas $CS_k < 1$ indicates an inelastic response. Built-up land was excluded because its baseline coefficient was zero and its proportional change was therefore undefined. This procedure is a deterministic parameter-perturbation analysis. Statistical confidence intervals were not estimated because empirically supported probability distributions or repeated observations were unavailable for the land-cover classification errors and ESV coefficients.

3. Results

3.1. Characteristics of Land Use Change

As shown in Table 2 and Figure 2, the land use structure of the Dongting Lake Region from 2005 to 2025 was generally dominated by cropland, forestland, and water bodies; however, the direction of change differed markedly among land use types. During the study period, the area of cropland decreased from 15,926.38 km² to 15,458.18 km², with a cumulative reduction of 468.20 km². Among cropland types, paddy fields decreased by 395.73 km², representing the main source of cropland loss. Forestland decreased from 14,426.91 km² to 14,195.66 km², with a cumulative reduction of 231.25 km², mainly characterized by decreases in forested land and sparse woodland. The area of water bodies showed an overall declining trend. In particular, the lake area decreased from 2213.34 km² to 1610.30 km², with a cumulative reduction of 603.04 km². However, the areas of reservoirs, ponds, and floodplains increased, indicating a marked adjustment in the internal structure of water bodies.

In contrast, the expansion of built-up land was the most prominent. Its area increased from 939.18 km² to 1644.39 km², with a cumulative increase of 705.21 km². Among built-up land types, other built-up land, urban land, and rural settlements all showed increasing trends, reflecting the continuous influence of urbanization and construction activities on the regional land use pattern. The area of unused land increased from 693.36 km² to 958.01 km², mainly due to the expansion of marshland. Overall, land use change in the Dongting Lake Region from 2005 to 2025 was characterized by decreases in cropland, forestland, and lake area, continuous expansion of built-up land, and obvious structural adjustment within waterbody–wetland types. The land use pattern exhibited strong characteristics of human disturbance.

Table 2. Area statistics of different land use types in the Dongting Lake Region in different years (Unit: km²).

Primary Land-Use Category	Secondary Land-Use Category	2005	2010	2015	2020	2025
cropland	Paddy field	13,804.41	13,659.65	13,601.06	13,495.36	13,408.68
	Dryland cropland	2121.97	2095.03	2074.54	2062.75	2049.5
Forest land	Forestland	9368.56	9260.10	9136.53	9071.82	9030.51
	Shrubland	683.55	684.97	681.89	680.17	677.07
	Sparse woodland	4281.56	4263.42	4233.07	4193.95	4174.85
	Other forestland	93.24	178.41	277.61	315.07	313.64
grassland	High-coverage grassland	244.72	206.44	205.66	203.39	201.82
	Moderate-coverage grassland	184.33	185.98	183.96	182.93	181.52
	Low-coverage grassland	3.38	4.30	4.29	4.30	4.27
water bodies	Rivers and canals	861.71	896.01	890.48	892.10	892.19
	Lakes	2213.34	1907.78	1628.66	1610.22	1610.38
	Reservoirs and ponds	1077.27	1277.05	1287.31	1277.06	1277.18
	Shoal land/Beach land	824.54	662.88	941.81	966.62	966.71
built-up land	Urban land	307.45	393.44	400.17	417.34	467.89
	Rural settlements	539.59	527.42	529.88	547.14	613.41
	Other construction land	92.14	212.70	339.06	502.45	563.31
	Marshland	693.11	972.63	972.22	961.87	951.68
unused land	Bare land	0.25	3.66	3.53	3.26	3.23
	Bare rock and gravel land	0.00	3.32	3.24	3.13	3.1

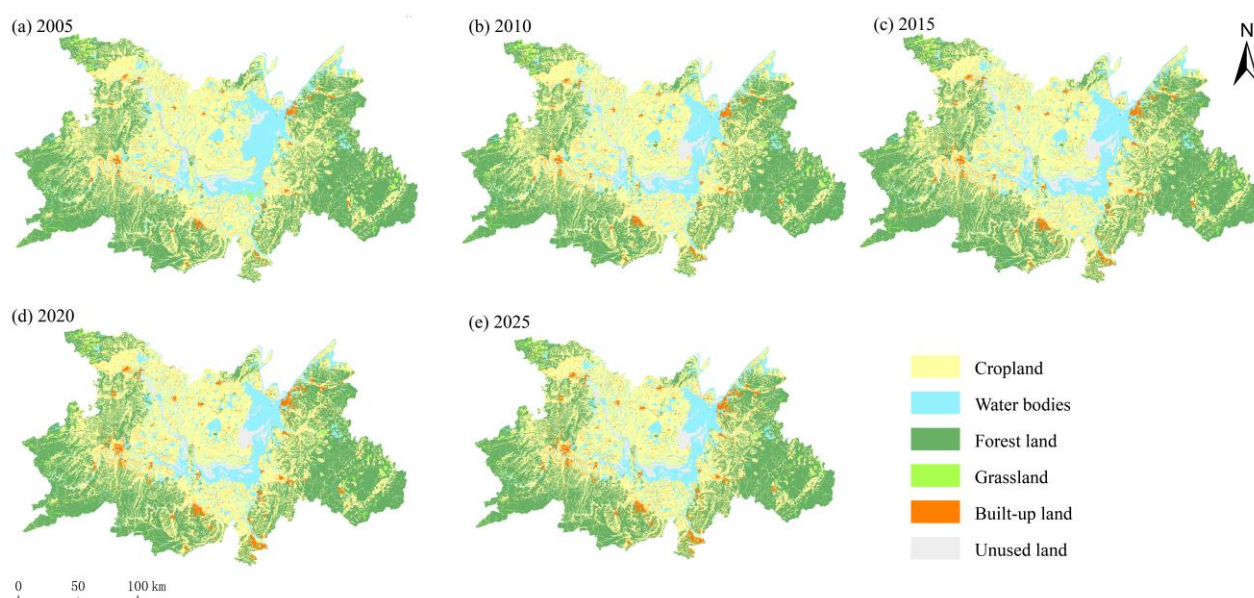


Figure 2. Spatial distribution of land use in the Dongting Lake region from 2005 to 2025. (Land use classes include cropland, forestland, grassland, water bodies, built-up land, and unused land. The coordinate reference system is Albers Equal-Area Conic Projection (China Albers), and distances are expressed in kilometres (km). A north arrow and scale bar are included for spatial reference. It should be noted that the 2025 land-use layer is not fully observation-based and was derived from remote sensing interpretation and model-assisted updating.).

Table 3 shows the area transition matrix of land use types in the Dongting Lake Region from 2005 to 2025. Overall, land use transitions during the study period mainly occurred among cropland, forestland, water bodies, and built-up land, with the expansion of built-up land being the most prominent. Cropland had the largest transferred-out area, with a cumulative transferred-out area of 1307.31 km². It was mainly converted into built-up land, forestland, and water bodies, with areas of 461.23 km², 429.65 km², and 390.32 km², respectively. This indicates that the decrease in cropland was closely related to built-up land expansion and conversions between cropland, forestland, and water bodies. Forestland had a cumulative transferred-out area of 736.31 km², mainly converting into cropland and built-up land, with areas of 372.31 km² and 295.28 km², respectively. Meanwhile, 429.65 km² of cropland was converted into forestland, resulting in relatively moderate overall changes in forestland. Water bodies showed active transitions, with a cumulative transferred-out area of 839.75 km². They were mainly converted into cropland and unused land, with areas of 385.44 km² and 370.07 km², respectively. The transferred-in area of water bodies was 611.55 km², mainly from cropland and unused land. Built-up land had a transferred-in area of 803.94 km², mainly from cropland and forestland, making it the land use type with the most significant area increase from 2005 to 2025. Grassland and unused land showed relatively small transition magnitudes, although clear mutual conversions occurred between unused land and water bodies. In summary, land use change in the Dongting Lake Region from 2005 to 2025 was characterized by marked conversions from cropland, forestland, and water bodies to built-up land, as well as active transitions between water bodies and unused land. These changes suggest that urban expansion and changes in the wetland hydrological environment have strongly affected the regional land use pattern.

To more clearly characterize the stage-specific features of land use transitions, chord diagrams of land use transitions were constructed for two 10-year intervals, namely 2005–2015 and 2015–2025. As shown in Figure 3, land use transitions were relatively active during 2005–2015. Cropland showed marked transfers to forestland, water bodies, and built-up land, with particularly prominent transitions from cropland to built-up land and forestland. Water bodies also showed a certain degree of conversion to unused land. Considering the changes in secondary land use types, this process may be related to the decrease in lake area and the increase in wetland types such as marshland and floodplains. Built-up land expanded markedly during this period, with its newly increased area mainly originating from cropland and forestland, reflecting the influence of urbanization and construction activities on the land use pattern. During 2015–2025, land use transitions generally became more moderate. The transferred-out area of cropland decreased, and the area of water bodies remained relatively stable; however, built-up land continued to expand, mainly from cropland and forestland. Overall, land use transitions in the Dongting Lake Region from 2005 to 2025 were characterized by marked conversions from cropland, forestland, and water bodies to built-up land, as well as certain transitions between water bodies and unused land. These findings indicate that urban expansion and internal structural adjustment of wetlands were important features of land use change in the study area.

Table 3. Land use transition matrix in the study area from 2005 to 2025. Unit: km².

Land Use Type in 2005	Area Transferred to Each Land Use Type in 2025					
	Cropland	Forestland	Grassland	Water Bodies	Built-Up Land	Unused Land
Cropland	14,615.97	429.65	7.72	390.32	461.23	18.39
Forestland	372.31	13,686.74	20.62	44.69	295.28	3.41
Grassland	5.48	24.43	355.44	37.05	6.55	3.07
Water bodies	385.44	41.51	2.28	4134.54	40.45	370.07
Built-up land	65.96	9.68	0.76	20.59	840.56	1.55
Unused land	11.90	0.08	0.54	118.90	0.43	561.41

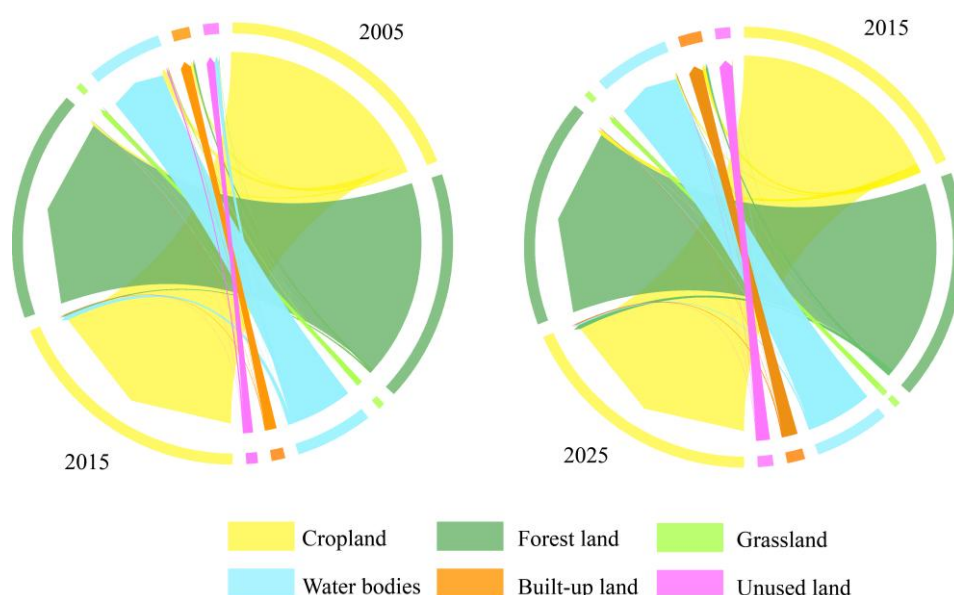


Figure 3. Chord diagram of area transitions among major land use types in the Dongting Lake Region.

The calculated comprehensive land use dynamic degree and single land use dynamic degree are shown in Figure 4. From 2005 to 2025, the comprehensive land use dynamic degree of the study area was 0.130%, indicating that the overall magnitude of land use change in the Dongting Lake Region was relatively small. At the stage scale, the comprehensive land use dynamic degree was highest during 2005–2010, at 0.064%, decreased to 0.019% during 2010–2015, slightly increased to 0.027% during 2015–2020, and reached 0.024% during 2020–2025. Overall, land use change was relatively active in the early stage and became more moderate in the later stage, with slight fluctuations. The single land use dynamic degree showed that cropland, forestland, grassland, and water bodies had values of -0.146% , -0.080% , -0.517% , and -0.229% , respectively, from 2005 to 2025, indicating decreasing trends, with grassland showing the largest relative decrease. In contrast, built-up land and unused land had values of 3.756% and 1.909% , respectively, indicating marked expansion. By stage, built-up land maintained positive growth in all periods, with dynamic degree values of 1.035% , 0.598% , 0.779% , and 0.606% , respectively, making it the land use type with the most significant expansion during the study period. Unused land increased rapidly during 2005–2010, with a dynamic degree of 2.064% , but shifted to a slight decrease after 2010. Water bodies decreased markedly during 2005–2010, with a dynamic degree of -0.234% , but their subsequent changes were close to zero, indicating that their area gradually stabilized. Overall, land use change in the Dongting Lake Region from 2005 to 2025 was mainly characterized by the continuous expansion of built-up land and varying decreases in cropland, forestland, grassland, and water bodies. The intensity of land use change showed a stage-specific pattern, shifting from relatively strong change in the early stage to more moderate change in the later stage.

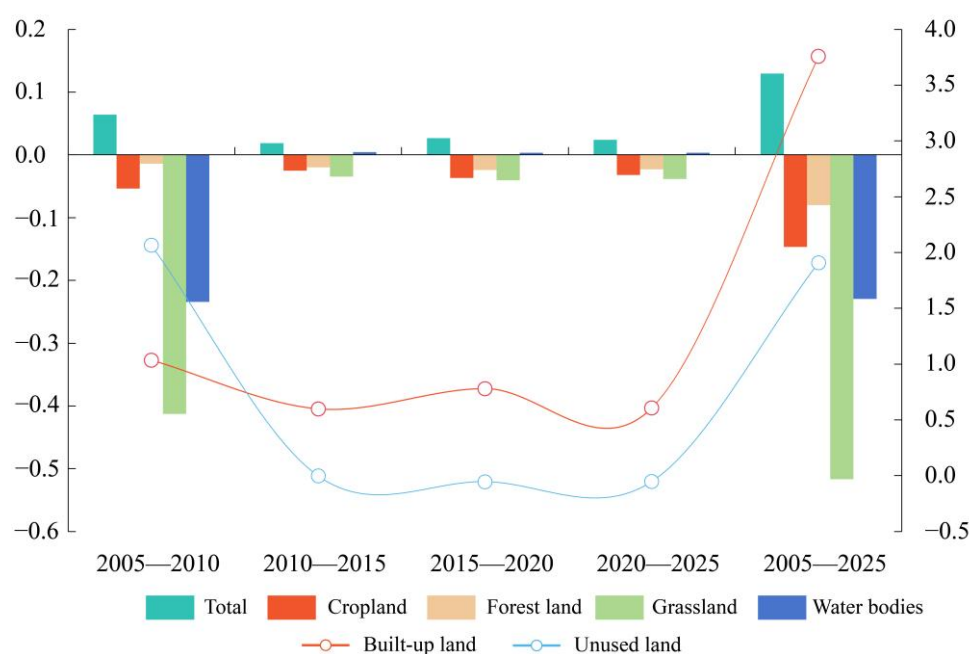


Figure 4. Changes in land use dynamic degree.

3.2. Temporal Changes in Ecosystem Service Value

From 2005 to 2025, the total ecosystem service value (ESV) in the Dongting Lake Region showed a decreasing trend. As shown in Table 4, ESV decreased from CNY 230.17 billion in 2005 to CNY 226.13 billion in 2025, with a cumulative decrease of CNY 4.05 billion and a decline rate of 1.76%. The decline was most pronounced during 2005–2010, narrowed during 2010–2020, and increased again during 2020–2025. Among different land use types, water bodies were consistently the main contributor to ESV in the Dongting

Lake Region, with a value much higher than those of other land use types. Water bodies accounted for the largest share of the decline, followed by forestland and cropland, whereas grassland and unused land had limited effects because of their relatively small base values. These results indicate that temporal ESV variation was primarily driven by changes in water bodies.

Table 4. Changes in ecosystem service value by land use type in the Dongting Lake Region from 2005 to 2025.

Land Use Type		Cropland	Forestland	Grassland	Water Bodies	Unused Land	Total
ESV (CNY billion)	2005	12.11	52.90	0.96	164.03	0.18	230.17
	2010	11.96	52.75	0.91	161.87	0.21	227.69
	2015	11.87	52.49	0.90	161.92	0.21	227.39
	2020	11.81	52.29	0.90	161.95	0.21	227.14
	2025	11.70	52.09	0.87	161.24	0.22	226.13
ESV Change (CNY billion) (%)	2005–2010	−0.15	−0.16	−0.05	−2.16	0.03	−2.48
	2005–2010	−1.24	−0.29	−5.31	−1.32	18.56	−1.08
	2010–2015	−0.08	−0.25	−0.01	0.04	0.00	−0.30
	2010–2015	−0.69	−0.48	−0.85	0.03	−0.53	−0.13
	2015–2020	−0.07	−0.21	−0.01	0.04	0.00	−0.25
	2015–2020	−0.56	−0.40	−0.70	0.02	−0.44	−0.11
	2020–2025	−0.10	−0.20	−0.03	−0.71	0.02	−1.02
	2020–2025	−0.88	−0.37	−2.91	−0.44	7.80	−0.45
	2005–2025	−0.40	−0.81	−0.09	−2.79	0.05	−4.05
	2005–2025	−3.34	−1.54	−9.48	−1.70	26.29	−1.76

At the ecosystem-service level, hydrological regulation remained the dominant contributor to ESV in the Dongting Lake Region. Its value decreased by CNY 2.38 billion, making it the primary source of the overall ESV loss (Table 5 and Figure 5). Climate regulation, biodiversity maintenance, environmental purification, and gas regulation also decreased, whereas water supply showed slight fluctuations. The structure of individual ecosystem services remained generally stable from 2005 to 2025. Hydrological regulation was consistently the dominant ecosystem service function in the Dongting Lake Region, accounting for 57.61–57.70% of total ESV, reflecting the core role of lake wetland ecosystems in hydrological regulation and storage. Together, hydrological regulation, climate regulation, biodiversity maintenance, environmental purification, and soil conservation accounted for 84.63–84.65% of total ESV, confirming the dominant role of regulating and supporting services in the regional wetland ecosystem.

Table 5. Changes in individual ecosystem service values in the Dongting Lake Region from 2005 to 2025.

Ecosystem Services	ESV (Year/CNY Billion)				
	2005	2010	2015	2020	2025
food production	5.28	5.22	5.20	5.17	5.15
raw material production	2.97	2.95	2.93	2.92	2.91
water supply	6.84	6.76	6.78	6.80	6.77
gas regulation	10.28	10.19	10.14	10.11	10.08
climate regulation	22.04	21.86	21.78	21.71	21.68
environmental purification	13.45	13.32	13.30	13.28	13.23
hydrological regulation	132.73	131.17	131.12	131.07	130.35

soil conservation	10.79	10.70	10.66	10.63	10.60
nutrient cycling maintenance	1.17	1.16	1.16	1.15	1.15
biodiversity maintenance	15.79	15.63	15.61	15.58	15.53
aesthetic landscape	8.82	8.73	8.72	8.71	8.67
total	230.17	227.69	227.39	227.14	226.13

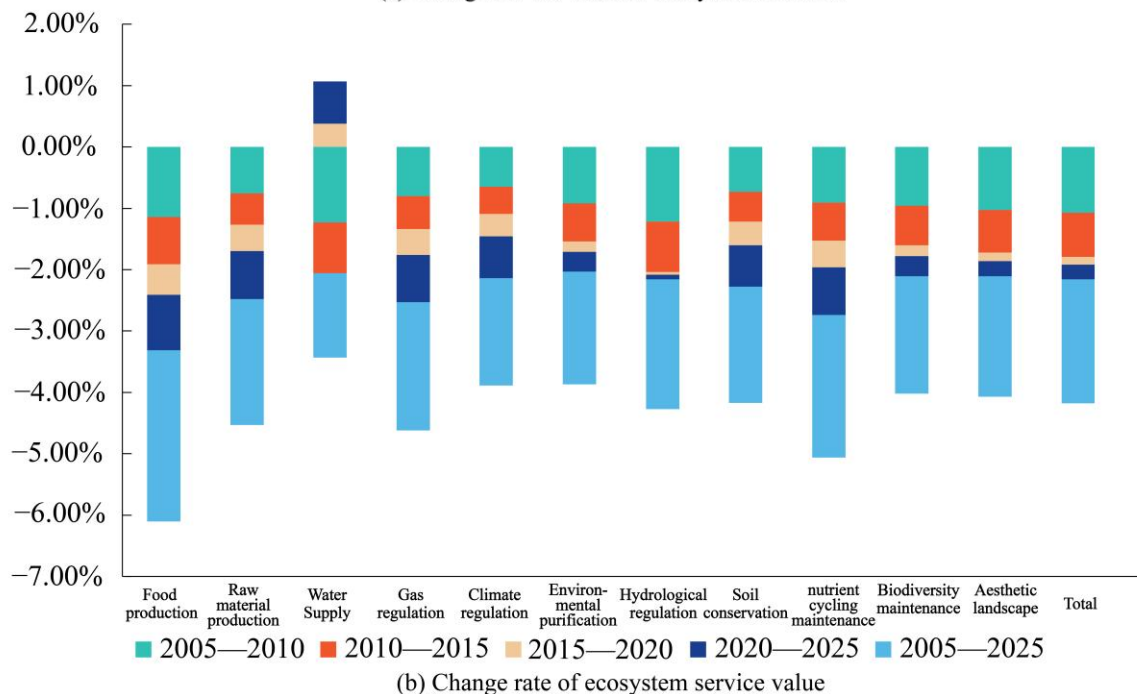
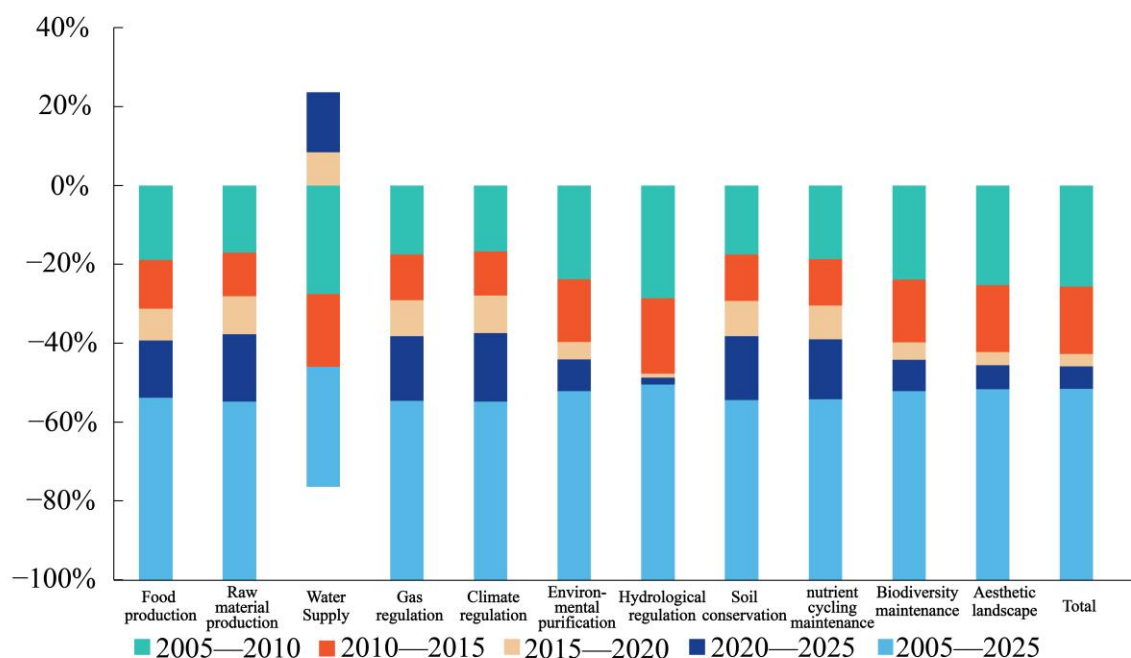


Figure 5. Change rates of ecosystem service value in the Dongting Lake Region from 2005 to 2025.

3.3. Spatial Analysis of Ecosystem Service Value

In this study, 5 km × 5 km grid cells were generated in ArcGIS 10.8 as the basic analysis units to measure the spatial correlation of ecosystem service value (ESV) in the Dongting Lake Region in 2005, 2010, 2015, 2020, and 2025. The global Moran's I index was calculated using GeoDa. The results showed that Moran's I values were positive in all years and were consistently above 0.660, indicating significant positive spatial autocorrelation of ESV in the Dongting Lake Region, with both high-value and low-value areas showing clustered distributions. Specifically, Moran's I decreased from 0.684 in 2005 to 0.666 in 2010 and further to 0.660 in 2015, before increasing to 0.668 in 2020 and 0.669 in 2025. This indicates that the spatial clustering of ESV weakened during 2005–2015 but strengthened after 2015. This stage-specific change is primarily attributed to land use transitions: urban expansion and wetland degradation during 2005–2015 fragmented high-value areas, while ecological restoration after 2015 restored wetland continuity.

To further reveal the local spatial differentiation of ESV, the local Moran's I index was calculated based on the 5 km × 5 km grid cells, and Moran scatter plots and LISA cluster maps were generated. As shown in Figure 6, the scatter points in all years were mainly distributed in the first and third quadrants, indicating that local ESV in the Dongting Lake Region was dominated by High–High and Low–Low clusters and showed clear positive spatial autocorrelation. According to the LISA cluster maps (Figure 7), only grid cells with statistically significant local Moran's I values (pseudo- $p < 0.05$) were classified into High–High (HH), Low–Low (LL), High–Low (HL), and Low–High (LH) clusters. HH clusters were mainly distributed in East Dongting Lake, South Dongting Lake, and West Dongting Lake, whereas LL clusters were mainly located in surrounding low-ESV areas and some built-up land clusters. HH clusters became generally more stable after 2015, while HL and LH outliers were few and scattered. This pattern is driven by natural endowment and human activities: lake wetlands, with high water conservation and biodiversity, form HH cores; built-up expansion degrades ecological functions, forming LL areas. We propose two management zones: core protection zones (HH clusters in East, South, and West Dongting Lake) with strictly restricted development and ecological restoration, and regulation-optimization zones (surrounding LL built-up areas) with enhanced land-use control and ecological compensation.

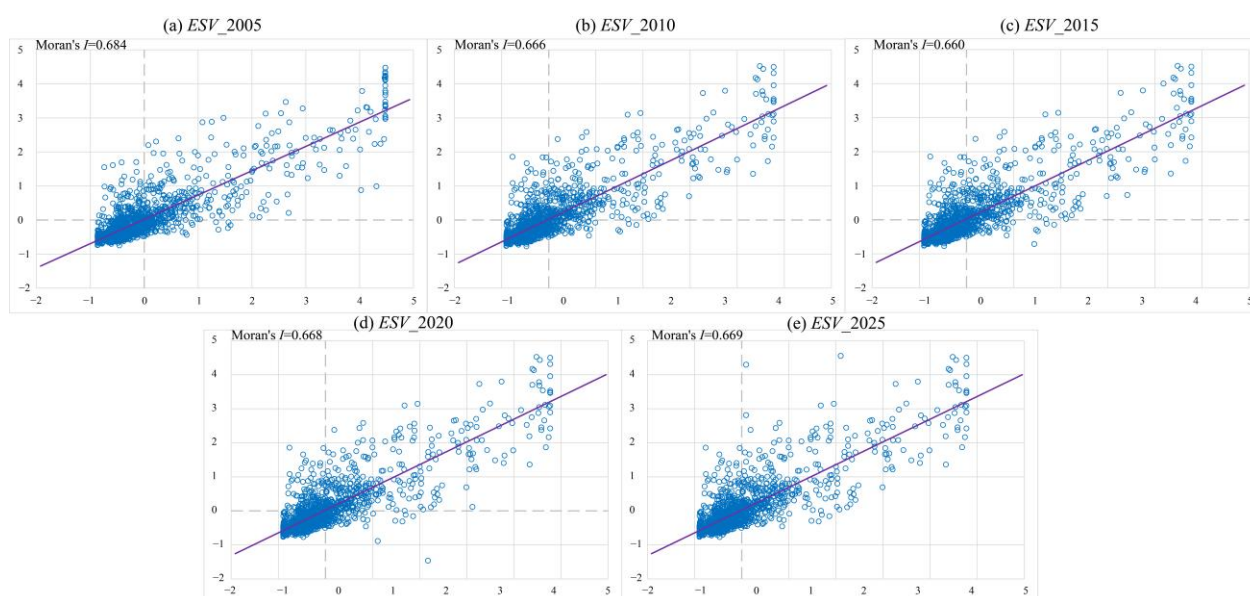


Figure 6. Moran scatter plots of ecosystem service value in the Dongting Lake Region from 2005 to 2025 (ESV refers to land-cover-based ecosystem service value estimated using the equivalent-factor approach. Moran's I measures global spatial autocorrelation based on a 5 km × 5 km grid system).

The analysis uses first-order Queen contiguity spatial weights and permutation testing with a pseudo p -value threshold of 0.05. The coordinate reference system is Albers Equal-Area Conic Projection (China Albers.).

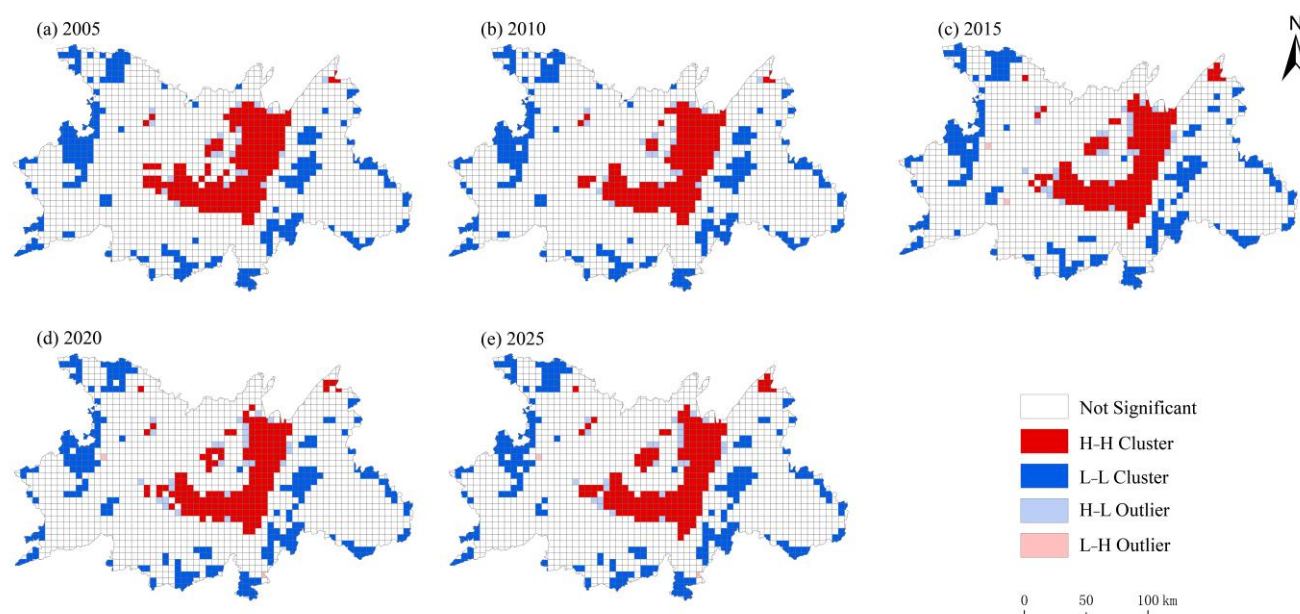


Figure 7. LISA cluster maps of ecosystem service value in the Dongting Lake Region from 2005 to 2025 (ESV is estimated using the equivalent-factor approach. Cluster types include High–High (HH), Low–Low (LL), High–Low (HL), Low–High (LH), and non-significant areas. The analysis is based on a $5\text{ km} \times 5\text{ km}$ grid using first-order Queen contiguity weights and permutation tests. Statistical significance is defined at pseudo $p < 0.05$. The coordinate reference system is Albers Equal-Area Conic Projection (China Albers), and distances are expressed in kilometres (km).).

3.4. Ecological Contribution Rates of Transitions Among Land Use Types

From 2005 to 2025, different land use transition types in the Dongting Lake Region showed marked differences in their contributions to ESV change (Table 6). Overall, land use transitions that increased ESV were dominated by conversions from other land use types to water bodies, which accounted for 93.59% of the total ESV increase. Cropland-to-waterbody and unused-land-to-waterbody transitions were the two main contributors, accounting for 60.05% and 18.59% of the increase, respectively. By contrast, land use transitions that decreased ESV were dominated by conversions from water bodies to other land use types, which accounted for 91.56% of the total ESV decrease. Waterbody-to-cropland and waterbody-to-unused-land transitions were the two primary sources of ESV loss, accounting for 41.86% and 40.85% of the decrease, respectively. Overall, ESV change in the Dongting Lake Region from 2005 to 2025 was highly sensitive to changes in water bodies. Therefore, waterbody conservation and restoration should remain a priority, while cropland expansion, unused land conversion, built-up land development, and ecological conservation should be better coordinated.

Table 6. ESV contribution rates of land use transitions in the Dongting Lake Region from 2005 to 2025.

Land Use Transition Types Contributing to ESV Increase			Land Use Transition Types Contributing to ESV Decrease		
Land Use Transition Type	Contribution Rate (%)	Proportion (%)	Land Use Transition Type	Contribution Rate (%)	Proportion (%)
Cropland → Water bodies	24.848	60.05	Water bodies → Cropland	−24.538	41.86
Unused land → Water bodies	7.694	18.59	Water bodies → Unused land	−23.946	40.85
Forestland → Water bodies	2.597	6.28	Water bodies → Built-up land	−2.634	4.49
Cropland → Forestland	2.384	5.76	Water bodies → Forestland	−2.412	4.12
Grassland → Water bodies	2.248	5.43	Forestland → Built-up land	−2.066	3.52
Built-up land → Water bodies	1.341	3.24	Forestland → Cropland	−2.065	3.52
Built-up land → Cropland	0.096	0.23	Cropland → Built-up land	−0.668	1.14
Built-up land → Forestland	0.068	0.16	Water bodies → Grassland	−0.138	0.24
Grassland → Forestland	0.063	0.15	Forestland → Grassland	−0.053	0.09
Cropland → Grassland	0.023	0.06	Grassland → Built-up land	−0.029	0.05
Unused land → Cropland	0.012	0.03	Forestland → Unused land	−0.022	0.04
Built-up land → Grassland	0.003	0.01	Cropland → Unused land	−0.019	0.03
Unused land → Grassland	0.002	0.01	Grassland → Cropland	−0.016	0.03
Built-up land → Unused land	0.001	0	Grassland → Unused land	−0.012	0.02
Unused land → Forestland	0.001	0	Unused land → Built-up land	0	0

3.5. Contribution of Land Use Types and Ecosystem Service Functions to ESV Changes

From 2005 to 2025, the ESV contribution index in the Dongting Lake Region showed a pattern of rapid decline, low-level stability, and end-stage rebound. By land use type (Table 7), the total change rates in the four periods were 1.08%, 0.13%, 0.11%, and 0.45%, respectively. Unused land and grassland showed relatively high contribution indices. The contribution index of unused land reached 18.56% and 7.80% during 2005–2010 and 2020–2025, respectively, while that of grassland reached 5.31% and 2.91%, indicating that area changes in these two land use types caused strong disturbances to ESV. The contribution index of water bodies decreased markedly during 2010–2020, reaching only 0.03% and 0.02%, indicating that changes in water bodies had a weak effect on ESV during this period. By ecosystem service function (Table 8 and Figure 8), the contribution indices of individual services were generally high during 2005–2010, then decreased, and showed divergent changes during 2020–2025. The contribution indices of food production, water supply, hydrological regulation, biodiversity maintenance, and aesthetic landscape rebounded,

whereas those of raw material production, gas regulation, climate regulation, and soil conservation continued to decline. Overall, these results indicate that the response of ESV to land use change in the Dongting Lake Region showed clear stage-specific and type-specific differences. Unused land, grassland, and ecosystem service functions with marked end-stage rebounds should be prioritized in regional land use optimization and ecological conservation management.

Table 7. ESV contribution indices of different land use types in the Dongting Lake Region from 2005 to 2025 (%).

Land Use Type	2005–2010	2010–2015	2015–2020	2020–2025
Cropland	1.24	0.69	0.56	0.88
Forestland	0.29	0.48	0.4	0.37
Grassland	5.31	0.85	0.7	2.91
Water bodies	1.32	0.03	0.02	0.44
Unused land	18.56	0.53	0.44	7.8
Total change rate	1.08	0.13	0.11	0.45

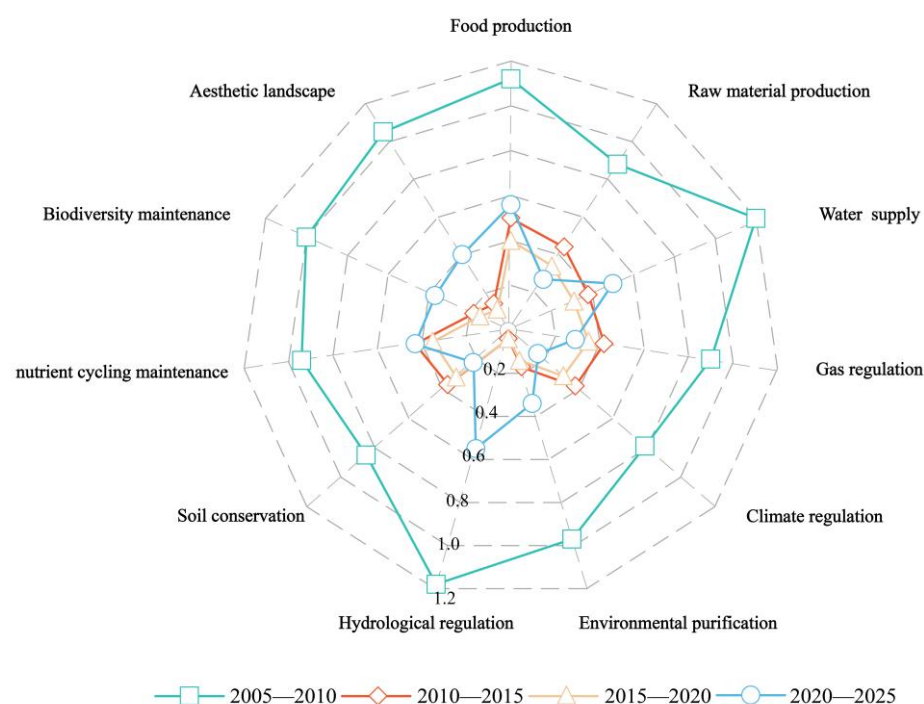


Figure 8. ESV contribution indices of individual ecosystem service functions in the Dongting Lake Region from 2005 to 2025.

Table 8. ESV contribution indices of different ecosystem service functions in the Dongting Lake Region from 2005 to 2025 (%).

Type	Individual Ecosystem Service Function	2005–2010	2010–2015	2015–2020	2020–2025
Provisioning services	food production	1.12	0.5	0.4	0.56
	raw material production	0.88	0.44	0.34	0.27
	water supply	1.2	0.38	0.31	0.5
	gas regulation	0.9	0.42	0.35	0.29
Regulating services	climate regulation	0.79	0.38	0.31	0.16
	environmental purification	0.97	0.17	0.14	0.34
	hydrological regulation	1.18	0.04	0.04	0.55

Supporting services	soil conservation	0.85	0.37	0.32	0.22
	nutrient cycling maintenance	0.94	0.43	0.35	0.43
	biodiversity maintenance	1	0.18	0.15	0.37
Cultural services	aesthetic landscape	1.05	0.14	0.11	0.4

3.6. Results of the Value-Coefficient Sensitivity Analysis

The one-at-a-time $\pm 50\%$ coefficient perturbations produced sensitivity coefficients below 1 for every land use type with a non-zero baseline coefficient in all study years (Table 9). Water bodies had the highest sensitivity coefficients, ranging from 0.7109 to 0.7131, followed by forestland (0.2298–0.2317) and cropland (0.0518–0.0526). The sensitivity coefficients of grassland and unused land remained below 0.005.

Because the ESV model is linear when land use areas are held constant, increasing and decreasing the coefficient of a given land use type by 50% produced the same sensitivity coefficient. Under every tested individual-coefficient scenario, total ESV in 2025 remained below that in 2005. Thus, the direction of the estimated ESV decline was not reversed by the $\pm 50\%$ perturbations. Nevertheless, adjusting the water-body coefficient by $\pm 50\%$ changed the 2025 total ESV by approximately $\pm 35.65\%$ relative to the baseline estimate. The temporal direction was therefore stable under the tested scenarios, whereas the absolute monetary estimates remained strongly dependent on the water-body coefficient.

Table 9. Sensitivity coefficients under one-at-a-time $\pm 50\%$ value-coefficient adjustments.

Land Use Type	2005	2010	2015	2020	2025
Cropland	0.0526	0.0525	0.0522	0.0520	0.0518
Forestland	0.2298	0.2317	0.2309	0.2302	0.2304
Grassland	0.0042	0.0040	0.0040	0.0039	0.0038
Water bodies	0.7126	0.7109	0.7121	0.7130	0.7131
Unused land	0.0008	0.0009	0.0009	0.0009	0.0010

Note: Increasing and decreasing the coefficient of a given land use type by 50% produced the same sensitivity coefficient. Built-up land was excluded because its baseline coefficient was zero. For the most influential water-body coefficient, the recalculated total ESV ranged from 148.158 to 312.189 CNY billion in 2005 and from 145.503 to 306.747 CNY billion in 2025. Baseline total ESV was 230.173 CNY billion in 2005 and 226.125 CNY billion in 2025.

3.7. Results of the Policy Chronology and Stage-Specific Accounting Analysis

The three policy documents indicate a concentrated sequence of Dongting Lake ecological and water-environment interventions beginning in late 2017 and extending through 2025 (Table 10). Because 2015 was the closest land use observation preceding this sequence, stage-specific changes were compared between 2005–2015 and 2015–2025 (Table 11). Total ESV decreased by 2.784 CNY billion during 2005–2015, corresponding to a mean annual decline of 0.2784 CNY billion·yr^{−1}. During 2015–2025, total ESV decreased by 1.264 CNY billion, corresponding to a mean annual decline of 0.1264 CNY billion·yr^{−1}. The rate of estimated ESV decline was therefore lower in the later stage. Total water-body area decreased by 228.60 km² during 2005–2015 but by only 1.80 km² during 2015–2025. In contrast, built-up land increased by 329.93 km² and 375.50 km² during the two stages, respectively. Global Moran's I decreased by 0.024 before 2015 and increased by 0.009 after 2015. The accounting composition of gross ESV losses also changed. The water-body share declined from 75.12% during 2005–2015 to 52.50% during 2015–2025, whereas the forestland share increased from 14.52% to 31.61%. These results indicate that the later stage combined slower ESV decline and greater stability of the first-level water-body category with continuing built-up land expansion and an increased accounting contribution from forestland loss.

Table 10. Chronology of principal ecological- and water-environment policies considered in the stage comparison.

Policy Document	Issue/Implementation Timing	Analytical Relevance
Three-Year Action Plan for Special Rectification of the Ecological Environment of Dongting Lake (2018–2020)	Issued on 29 December 2017; implemented during 2018–2020	Ecological rectification, water-pollution control, ecological restoration, and resource management
Implementation Plan for the Comprehensive Water Environment Management Plan of Dongting Lake in Hunan Province (2018–2025)	Planning period 2018–2025; provincial implementation plan published in 2019	Comprehensive water-environment management and ecosystem restoration
Action Plan for Total Phosphorus Pollution Control and Reduction in Dongting Lake (2022–2025)	Issued in 2022; implemented during 2022–2025	Total-phosphorus reduction and coordinated land–water pollution control

Table 11. Comparison of ESV and land use changes between 2005–2015 and 2015–2025.

Indicator	2005–2015	2015–2025
Total ESV change (CNY billion)	−2.784	−1.264
Mean annual ESV change (CNY billion·yr ^{−1})	−0.2784	−0.1264
Change in water-body area (km ²)	−228.60	−1.80
Change in built-up land area (km ²)	329.93	375.50
Change in global Moran's I	−0.024	0.009
Water-body share of gross ESV losses (%)	75.12	52.50
Forestland share of gross ESV losses (%)	14.52	31.61

Note: Gross ESV-loss shares were calculated using the sum of the absolute ESV decreases in all land use types showing negative changes during the corresponding stage as the denominator. Positive changes in unused-land ESV were excluded from the denominator.

4. Discussion

4.1. Post-2015 ESV Trajectory and Its Temporal Alignment with Policy Implementation

The policy chronology and stage-specific accounting comparison indicate that the post-2015 trajectory differed from that of the preceding stage. Compared with 2005–2015, the 2015–2025 period showed a lower mean annual ESV decline, broad stability of total water-body area, and a shift in global Moran's I from decline to recovery. These changes temporally overlapped with the implementation of the 2018–2020 ecological-environment rectification plan, the 2018–2025 comprehensive water-environment management plan, and the 2022–2025 total-phosphorus control plan [35–37]. The accounting decomposition provides additional information on possible explanatory factors. Water bodies remained the largest source of gross ESV loss, but their share decreased from 75.12% to 52.50%, whereas the forestland share increased from 14.52% to 31.61%. At the same time, built-up land continued to expand. The later stage therefore cannot be characterized as uniform ecological improvement; rather, it combined greater stability of the first-level water-body category with persistent development pressure and an increased contribution from forestland loss. These temporal correspondences do not establish causal policy effects. Changes in water bodies, wetlands, and ESV may also reflect hydrological variability, sediment processes, climatic conditions, agricultural adjustment, urban expansion, restoration projects, and differences in land-cover updating. In addition, the 2025 layer was model-assisted rather than fully observation-based. The post-2015 results should there-

fore be interpreted as stage-specific signals temporally aligned with policy implementation, not as statistically identified evidence of policy effectiveness.

4.2. Water-Body-Related Transitions Under the Adopted ESV Framework

Freshwater lakes provide substantial ecosystem service values globally [38], and water-body-related transitions dominate ESV changes in the Dongting Lake Region under the adopted equivalent-factor framework. This section addresses the second expectation proposed in the Introduction, which hypothesizes that water-body-related transitions are the dominant contributors to ESV change due to their high hydrological regulation value. The results are consistent with this expectation under the adopted equivalent-factor framework: transitions into water bodies contributed most to estimated ESV increases, whereas transitions from water bodies to other land use types contributed most to estimated ESV decreases. This pattern is ecologically plausible in the Dongting Lake Region, where water bodies and wetland-associated spaces are closely linked to flood regulation, water storage, habitat maintenance, and landscape connectivity [39].

Nevertheless, this dominance should be interpreted as a framework-dependent valuation outcome [40]. Given the relatively high hydrological regulation coefficients assigned to water bodies in the equivalent-factor system, the prominence of water-body-related transitions largely reflects the coefficient structure rather than an independent ecological mechanism. In this framework, water bodies receive substantially higher coefficients than most other land use types, particularly for hydrological regulation; therefore, even small areal changes can lead to large variations in estimated ESV [41]. The wetland compensation test further shows that the six-class scheme underestimated the absolute value of wetland-related spaces, although the main spatial pattern remained broadly consistent after correction (Table 12). This indicates that the classification scheme is suitable for capturing broad regional ESV patterns and dominant transition pathways, but limited in representing wetland subtype heterogeneity. The $\pm 50\%$ value-coefficient sensitivity analysis showed that the direction of the estimated ESV decline remained unchanged under all tested one-at-a-time scenarios. However, the water-body sensitivity coefficient remained approximately 0.71, substantially higher than those of the other land use types. Thus, the temporal direction was stable under the tested perturbations, whereas the absolute monetary estimates remained strongly dependent on the water-body coefficient, particularly the hydrological-regulation component. The dominance of water-body-related transitions should therefore be interpreted as an ecologically plausible but coefficient-structured valuation result rather than as evidence independent of parameter selection. This interpretation is consistent with previous methodological literature on equivalent-factor-based ecosystem service valuation approaches [32,41].

Table 12. Quantitative Assessment and Uncertainty Analysis of Wetlands and Tidal Flats.

Time (year)	Marshland Area (km ²)	Floodplain Area (km ²)	ESV Before Substitution (Billion CNY)	ESV After Substitution (Billion CNY)	Absolute Underestimation (Billion CNY)	Systematic Underestimation Ratio (%)
2005	693.11	824.54	230.173	312.94	82.767	35.96%
2010	972.63	662.88	227.691	305.185	77.494	34.03%
2015	972.22	941.81	227.389	307.349	79.96	35.16%
2020	961.87	966.62	227.141	307.218	80.077	35.25%
2025	951.68	966.71	226.125	298.606	72.481	32.05%

4.3. Interpretation of Persistent Spatial Clustering

This section addresses the third expectation proposed in the Introduction, which hypothesizes persistent positive spatial clustering of ESV due to the concentration of high-value ecosystem services in lake and wetland regions. The results are consistent with this expectation, but the clustering should not be interpreted simply as a direct consequence of high-coefficient land-cover classes around the lake. High–High clusters around East Dongting Lake, South Dongting Lake, and West Dongting Lake partly reflect the distribution of water bodies and wetland-associated ecological spaces (Figure 7), but the temporal variation in Moran’s I provides additional information.

Specifically, the temporal dynamics of Moran’s I (declining during 2005–2015 and increasing after 2015) indicate that the spatial organization of estimated ESV was not static under the same coefficient system (Figure 6), but evolved in response to land use transitions. This suggests that high-value ecological spaces experienced changes in fragmentation or spatial consolidation, rather than remaining a fixed reflection of waterbody distribution. Therefore, spatial autocorrelation analysis complements total ESV assessment by revealing changes in the spatial continuity of lake-centered ecological spaces. In addition, the differential responses of individual ecosystem service functions (e.g., water supply, hydrological regulation, biodiversity maintenance, and aesthetic landscape) indicate functional heterogeneity that is not captured by total ESV alone [42].

4.4. Management Implications for Territorial Spatial Optimization in the Dongting Lake Region

The management implications of this study should be interpreted within the analytical limits of the adopted ESV and spatial autocorrelation framework. The ESV and LISA results can help identify candidate lake-centered high-value ecological spaces for further assessment, but they cannot independently define conservation priorities, ecological red-lines, ecological zoning boundaries, or wetland restoration zones. Therefore, the High–High clusters around East Dongting Lake, South Dongting Lake, and West Dongting Lake should be regarded as preliminary reference areas for territorial spatial optimization and candidate areas for further integrated assessment.

Any formal conservation delineation or management decision requires comprehensive supporting evidence, including biodiversity data, hydrological validation, ecological threat assessment, feasibility evaluation, cost information, and ecosystem service demand analysis [43]. Future territorial spatial planning may prioritize areas experiencing overlapping pressures from built-up land expansion and ecological land conversion, including cropland, forestland, water bodies, and wetland-associated ecosystems. However, specific interventions should be determined through integrated ecological, socioeconomic, and governance assessments rather than based solely on ESV or spatial clustering results [44].

4.5. Policy Implications for SDG Achievement in the Dongting Lake Region

The results of this study provide SDG-related implications for land use governance and ecological protection in the Dongting Lake Region. The high sensitivity of calculated ESV to water-body-related transitions indicates that the protection of water-related ecosystems should remain an important consideration in territorial spatial governance, which is closely related to SDG 6.6. Meanwhile, the decrease in forestland and the concentration of ESV High–High clusters in East Dongting Lake, South Dongting Lake, and West Dongting Lake suggest that these areas may be considered as candidate ecological spaces for further assessment in relation to SDG 15.1 through wetland protection, biodiversity conservation, and ecosystem service maintenance. In addition, the reduction in cropland and its conversion to built-up land suggest potential pressure on SDG 2.4. Future territorial spatial planning should therefore coordinate cropland protection, construction land control, water-related ecosystem restoration, and ecological security pattern optimization.

These results can provide supporting information for SDG 11.4 and SDG 13 by highlighting areas where natural heritage protection, flood regulation, climate adaptation, and regional ecological resilience may require further policy attention.

4.6. Limitations and Future Perspectives

This study has several limitations. First, wetlands were not extracted as an independent land use type because of data and classification constraints. Although the wetland compensation test was used to examine the potential bias of the six-class scheme, it cannot replace a full wetland-subtype-based assessment. In addition, a separate confusion matrix and class-specific accuracy assessment were unavailable for the 2025 land use map, which may introduce uncertainty into the estimated land use transitions and associated ESV changes. Second, the ESV estimation was based on land use types and the equivalent-factor method. Therefore, the results should be interpreted as framework-dependent estimates of potential ecosystem service value rather than direct measurements of ecological processes or independently verified causal mechanisms. The dominance of water-body-related transitions may partly reflect the high coefficients assigned to water bodies, while the negative externalities of built-up land, such as heat island effects, pollution, runoff increase, and habitat fragmentation, were not monetarily quantified. A one-at-a-time $\pm 50\%$ value-coefficient sensitivity analysis was conducted, but it represents a deterministic parameter-perturbation test rather than a probabilistic uncertainty assessment. Because empirical probability distributions and repeated observations were unavailable for land-cover classification errors and ESV coefficients, statistical confidence intervals and Monte Carlo uncertainty ranges were not estimated. The sensitivity results demonstrate stability in the direction of ESV change under the tested scenarios, but also reveal substantial dependence of the absolute estimates on the water-body coefficient. Third, the spatial autocorrelation analysis was conducted using a single $5\text{ km} \times 5\text{ km}$ grid. This resolution was selected to balance spatial heterogeneity against excessive spatial fragmentation; however, the absence of multi-scale sensitivity analysis may affect the robustness of the identified spatial patterns. Finally, this study added a policy chronology and a stage-specific accounting comparison, including changes in ESV, water-body area, built-up land, Moran's I , and land-use-type shares of gross ESV losses. However, this descriptive analysis cannot identify causal policy effects or quantify the independent contributions of policy, hydrological, climatic, socioeconomic, and restoration-related factors. GeoDetector, regression, causal-inference, or other multivariate attribution methods were not applied. Future studies should combine annual land-use and hydrological observations, policy-implementation intensity, socioeconomic controls, and suitable counterfactual regions to distinguish policy effects from alternative explanatory processes. Their integration with hydrological data and land use scenario models would further clarify the mechanisms and planning implications of ESV change [45].

5. Conclusions

This study integrated land use transition analysis, equivalent-factor-based ESV estimation, spatial autocorrelation, wetland-classification substitution, $\pm 50\%$ value-coefficient sensitivity analysis, and policy-stage comparison to assess land-cover-based ESV dynamics in the Dongting Lake Region from 2005 to 2025 (with the 2025 layer being not fully observation-based but derived from remote-sensing interpretation and model-assisted updating rather than direct field observations). The study highlights how land use transitions and spatial clustering jointly shape ESV patterns, while clarifying parameter dependence and stage-specific policy alignment.

The most robust finding is that estimated ESV change was strongly associated with water-body-related transitions, while High–High clusters remained concentrated around East Dongting Lake, South Dongting Lake, and West Dongting Lake. This result is ecologically plausible in a lake-centered wetland region, but it is also conditional on the adopted equivalent-factor framework, in which water bodies receive high coefficients, especially for hydrological regulation. All non-zero sensitivity coefficients were below 1, and the declining ESV trend remained unchanged under all $\pm 50\%$ coefficient scenarios. However, the water-body sensitivity coefficient was approximately 0.71, indicating that absolute ESV estimates remained strongly dependent on the adopted water-body coefficient. Therefore, the dominance of water-body-related transitions should be interpreted as a framework-dependent result. Compared with the 2005–2015 period, the rate of decline in ESV slowed during 2015–2025, while water body stability increased and spatial clustering became more pronounced; this trend coincided temporally with major ecological policies.

The main limitation is that wetlands were not extracted as an independent land use class. Wetland subtypes such as beach land, floodplains, and marshland were represented within broader land use categories, meaning that the results are land-cover-based and framework-dependent ESV estimates rather than wetland-specific assessments or direct measurements of ecosystem processes.

For regional planning, ESV and LISA outputs can help identify candidate lake-centered high-value ecological spaces for further assessment, but they cannot by themselves define conservation priorities, ecological zoning, ecological redlines, or wetland restoration boundaries. Future planning should integrate these ESV-based patterns with finer wetland classification, biodiversity data, hydrological connectivity, restoration feasibility, land ownership, governance constraints, and cost analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

ESV	Ecosystem Service Value
LUCC	Land use/land cover change
CNY	Chinese Yuan

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