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Original Research

Spatial-Temporal Evolution and Influencing Mechanism of Land Use on Ecosystem Service Values in the Taihu Lake Basin in China

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Abstract

The Taihu Lake basin is a critical ecological protection area in China. Understanding the evolutionary process of land use and the Ecosystem Service Values (ESVs) of the Taihu Lake basin is an important prerequisite for promoting its sustainable development. The land use change patterns in the Taihu Lake basin based on data from 2005, 2010, 2015, and 2022, using land use transition matrices and land dynamic index. Use of the land use classification precision of *Kappa* coefficient test improves the equivalent factor method for calculating ecosystem services value. The result demonstrated that: (1) the *Kappa* coefficient of 0.932; From 2005 to 2022, land use in the Taihu Lake basin underwent significant changes, with the most prominent conversion from plowland to construction land. The increase in water and forestland areas led to an 8.31% increase in total ESVs. (2) ESVs increased by $1.181 billion over the past 17 years. Land use types such as water bodies, grasslands, and forestlands accounted for 92.16% of the total ESVs. Key ecosystem services in the region, including hydrological regulation, water resource supply, climate regulation, and environment cleaning, together contributed 83.61% of the total ESVs; (3) the ESVs are relatively insensitive to changes in coefficient values. Currently, the primary challenge of ESVs is from plowland degradation. In the lower reaches, regulatory services should be strengthened, provided that vegetation protection is maintained. Research on land use evolution analysis in the Taihu Lake basin can provide valuable references for environmental protection and urban and rural development.

Keywords: ecosystem service value, spatial planning, ecological protection, land use change, Taihu Lake basin

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Introduction

Ecosystem services (ES) are the benefits provided by ecosystems to humans [1, 2]. The assessment of Ecosystem Service Values (ESVs) is a process aimed at evaluating the contributions of ecosystem services while considering factors such as sustainability, equitable distribution, and efficiency in allocation. Increasing demands for clean water, food, and energy pose a serious threat of irreversible damage to global ecosystems [3]. The expansion of urban areas has led to the occupation of vast areas of cultivated and forestlands, causing significant changes in land use and a substantial reduction in the value of ecosystem services [4]. Land use changes are driven by both natural and human factors, with anthropogenic activities being a key driver of ecosystem service loss [5-7]. Investigating the impact of land use change on ecosystem service values is crucial for regional ecological planning and sustainable development [8].

As demonstrated by the MEA initiative, ecosystem services provide a conceptual framework for understanding the relationship between human activities and the complexities of environmental degradation [2]. Building upon this framework, numerous cities in China have begun to analyze ecosystem services to better understand the role and functioning of their natural resources, thereby enhancing urban decision-making processes. For instance, an analysis based on land use data, socioeconomic data, and landscape index studied the spatial and temporal characteristics of ecosystem services and ecological risks in the Yangtze River Delta from 2000 to 2019 [9]. Based on the Google Earth Engine platform, analyze the factors influencing the spatial heterogeneity of the eco-environment and the relationship between the eco-environment and land use changes based on RSEI [10]. This analysis enabled stakeholders in the YRD to move beyond abstract discussions of resource quantity and location, fostering more direct conversations about how and where ecosystems provide tangible benefits to local communities.

In China, the field and practice of urban and regional planning play a significant role in shaping and implementing policies that govern urbanized and rapidly urbanizing areas [11]. While ecosystem service studies often reference planning efforts and the impact of urban decisions on ecological functions, it is uncommon for these insights to be incorporated into planning practices as a tool for development and land use decision-making, except in a few cases, such as those mentioned above [12]. Although there is a long-standing recognition within planning that ecosystems provide important benefits, examples of plans in China that explicitly apply an ES framework are still limited [13]. Most land use and comprehensive plans rely on inventories of land types, uses, and resources, typically based on basic quantitative assessments, such as the area of open space, trail miles, or wetland acreage [14]. While these indicators are valuable, they often overlook the quality and health of ecosystems, failing to distinguish between different types of ecosystem services (as categorized by the Millennium Ecosystem Assessment into provisioning, regulating, supporting, and cultural services). For instance, rather than merely considering forestland or wetland areas in a planning process, an ES-based approach could explore aspects like stormwater retention, nutrient cycling, or air quality improvement, all of which are influenced by vegetation types and coverage. High-resolution, disaggregated environmental data can support assessments of ecological quality, facilitate trade-off analyses, and enable the exploration of complex spatial relationships during the decision-making process [15]. In this context, ES-based approaches may help guide the development of plans that not only preserve ecosystem services but also meet other objectives related to economic growth, transportation, agriculture, and other societal needs. Although an ES approach might require more extensive data, such information is potentially more accessible to the public and more effective in communicating the trade-offs associated with different planning choices (e.g., discussing “floodwater reduction” may be easier for a nonexpert than explaining “hectares of wetlands”).

Both the work of Albert Christian and more recent studies advocate for the explicit integration of ES into planning processes. Recent research suggests modifying existing frameworks, such as multicriteria decision analysis (MCDA), and developing new models to better incorporate ES into land use planning and decision-making [15]. However, studies examining the integration of ecological data into comprehensive plans indicate that the inclusion of ecological information remains insufficiently addressed [16]. Furthermore, few studies focus on the ecosystem services of lakes that provide actionable recommendations for policymakers on how to effectively incorporate an ES framework into decision-making processes [17, 18]. These findings highlight the need for clearer guidance on integrating ES into planning in order to achieve a balance between urbanization and environmental sustainability.

Nowadays, basin management is a critical issue that needs to be addressed in China. More attention must be paid to achieving a balance between sustainable ecological protection and economic development, which represents a significant challenge. Quantitative assessment of Ecosystem Service Values forms the foundation for evaluating ecosystem health. ESVs not only help to link ecosystems with social and economic systems, but also play a key role in identifying ecosystem service zoning and optimizing the spatial distribution of these services [19]. In recent years, rapid urbanization has led to significant changes in land use and the water ecological environment in the Taihu basin. Agricultural nonpoint source pollution has surpassed urban domestic and industrial pollution in terms of its impact on environmental security, contributing significantly to regional water eutrophication [20].

A water supply crisis occurred around Taihu Lake, particularly in Wuxi and Yixing in Jiangsu Province of China [21]. The Taihu Lake basin is also facing severe environmental issues, including the destruction of biological resources and damage to the hydrological landscape [22]. Previous studies on ESVs have mainly focused on improving the estimation methods and revising value equivalence, with less emphasis on describing the spatiotemporal characteristics of these values. However, these methods often require numerous input parameters and involve complex calculations. More critically, unifying evaluation methods and parameter standards for different service values remains challenging [23]. The equivalent factor method, by contrast, is intuitive, simple to apply, and requires fewer data, making it particularly well-suited for assessing ecosystem service values at regional and global scales [24]. The impact of multitemporal land use changes on the ESVs in the circum-Taihu basin is still not well understood. ESVs' assessments play a significant role in shaping regional sustainable development policies, ecological security [25], the delineation of ecological red lines [26], forestland conservation, protection, and ecological compensation mechanisms [27].

To further analyze the relationships between land use change, ecosystem service values, basin management, and spatial planning in China, this study takes the Taihu Lake basin as a case study. The objectives are to explore: (1) how the spatio-temporal characteristics of land use in the target area have changed; (2) how land use changes affect ecosystem service values; and (3) how to establish connections between ecological protection, basin management, and regional development. Ecosystem services offer significant social and economic benefits, and the ecological protection of basins is of paramount importance. In the present study, we first analyze the spatiotemporal characteristics of land use in 2005, 2010, 2015, and 2022 with remote sensing data, followed by the variation assessment of ESVs in the Taihu Lake basin based on revised coefficient application. Finally, we developed a spatial planning framework that integrates ecological protection, basin management, and regional sustainable development. The findings of this study can inform future spatial planning and strategies for sustainable basin ecological conservation in China and other similar regions.

Materials and Methods

Study Area and Data Sources

Study Area

The Taihu Lake basin (119°11'-121°53'E, 30°28'-32°15'N) is the core area within China, and is one of the most ecologically sensitive regions in the world, necessitating precise spatial delineation to support future ecological protection and enhance the functional performance of Ecosystem Services Values (ESVs) [28, 29]. Spanning approximately 36,900 hectares, the basin features a complex river network and numerous lakes, with a river density of about 3.4 km per hectare. The administrative boundaries of the basin include Suzhou, Wuxi, Changzhou, and Danyang cities in Jiangsu Province, parts of Jiaxing, Huzhou, and Hangzhou in Zhejiang Province, most of Shanghai, and a small area of Anhui Province [30]. The Taihu Lake basin is characterized by a mixture of deciduous and evergreen broadleaf vegetation typical of the northern subtropical zone, with dominant soil types including yellow-brown soil, red soil, and agricultural soil. It is the third-largest freshwater lake in China [31]. This study focuses on several areas surrounding Taihu Lake, covering approximately 10,856.97 hectares. The study area encompasses 14 cities and counties (districts) across Jiangsu and Zhejiang provinces (Fig. 1).

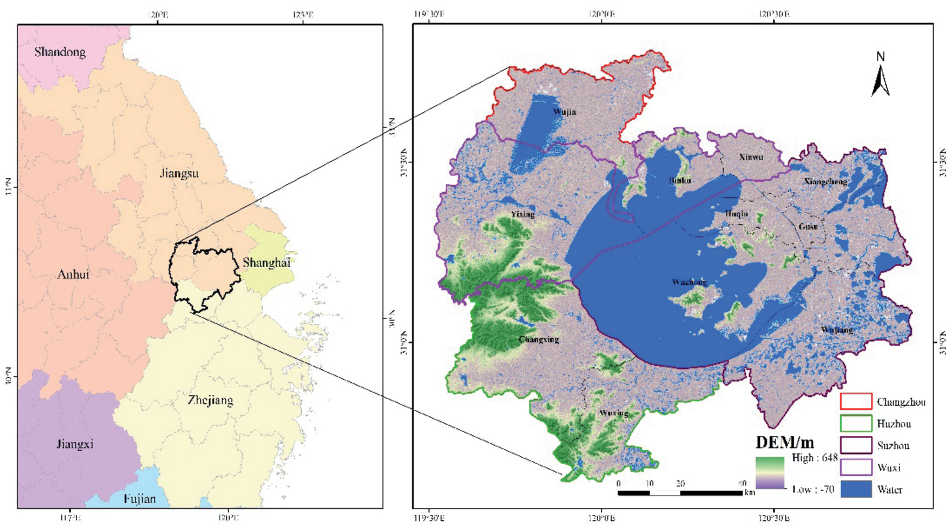

Fig. 1. Summary map of the study area.

Data Source and Processing

A series of datasets were utilized in this study: (1) Land-use data at a resolution of 30 m were obtained from the Resources and Environment Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/, accessed on 15 September 2022) to track changes in Land Use and Cover Change (LUCC) in the Taihu Lake basin. (2) Elevation and slope data were derived from the 30m resolution available from the Geospatial Data Cloud (http://www.gscloud.cn, accessed on 15 September 2022). (3) Meteorological data, including Net Primary Productivity (NPP), precipitation, and soil conservation measures, were sourced from the China Meteorological Science Data Sharing Service Network (http://dara.cma.cn, accessed on 15 September 2022). (4) The boundary of the target area was determined based on prior studies identifying regions most influenced by agricultural nonpoint source pollution. The watershed boundary was delineated using hydrological spatial analysis. All spatial data were reclassified into 30 m × 30 m grids using the Nearest Neighbor resampling method in ArcGIS 10.8, with the minimum remote sensing interpretation accuracy set at 89%.

Research Methods

Analysis of Remote Sensing Data

The technical process of land use information extraction in this study main steps are (1) Landsat TM and Landsat 8 data were used for 2005-2010 and 2015-2022, respectively, band extraction, false color composite, geometric precision correction, county-level image mosaicking and stitching, and other related processes; (2) The classification accuracy of multi-temporal land use remote sensing data was evaluated using the *Kappa* coefficient analysis [32]. As shown in Table 1, the land use classification accuracy in the Taihu Lake basin exceeded 90% across all study years (2005, 2010, 2015, and 2022), with mean *Kappa* coefficients surpassing 0.90. These results indicate high-quality remote sensing imagery and demonstrate strong reliability of the 30-meter resolution land use dataset. (3) Using spatio-temporal dynamic factors such as NPP (Net Primary Productivity), precipitation, and soil conservation regulation improves the equivalent factor method for calculating ecosystem services value.

Table 1. Accuracy analysis of land use data from 2005 to 2022.

Year	Accuracy (%)	*Kappa*
2005	91.19	0.893
2010	90.37	0.901
2015	92.15	0.929
2022	93.97	0.907
Average value	91.82	0.908

Dynamic Analysis of Land Use Changes

The dynamic analysis of land use in the ecosystem surrounding the Taihu Lake basin primarily relies on land dynamic change rates and land use transfer matrices [32]. These methods enable a quantitative assessment of the degree of change (%) in a specific land use type over a defined time period. The land use transfer matrix, in particular, illustrates the direction and extent of conversion among various land use types. The formula for the land use transition matrix is as follows:

$$S_{ij} = \begin{vmatrix} S_{11} & \cdots & S_{1n} \\ S_{21} & \cdots & S_{2n} \\ S_{n1} & \cdots & S_{nn} \end{vmatrix}$$

Where, S_{ij} represents the area, and *ij* (*ij* = 1, 2, ..., n) denotes the land use types before and after the transition.

The formula for the land use dynamic degree is as follows:

$$S = \frac{Ub - Ua}{Ua} \times \frac{1}{T} \times 100\%$$

Where, *Ua* represents the total area of a certain landscape at the initial stage, *Ub* represents the total area of the same landscape at the end of the study, and *T* represents the duration of the study.

Calculation of Ecosystem Service Values

Xie proposed the concept of ecosystem service values for terrestrial ecosystems, which represent the economic value of the natural grain yield per year for cropland with an average yield of 1 hectare, and analyzed the changes in ESV in the Taihu Lake basin by examining grain yield and the average purchase price of agricultural products in the region. They further discussed the relationship between land use changes and ESV changes [33, 34].

Based on the revised data, we updated the coefficient for the ecosystem service values (Table 2). Using spatio-temporal dynamic factors such as NPP (Net Primary Productivity), precipitation, and soil conservation regulation, we constructed a spatio-temporal dynamic scale of ecological service value changes, integrated with the base scale of ecosystem service values, which improves the equivalent factor method for calculating ecosystem service values. Subsequently, using data on major crops （rice, wheat）, crop yield per unit area (rice:5.30 $t\cdot ha^{-1}$, wheat:4.36 $t\cdot ha^{-1}$), and sown area (rice: 339376 ha, wheat: 313228 ha） from the 2015 Statistical Yearbook of the study area, we calculated the economic value of grain production per unit area in the Taihu Lake region for 2015, which amounted to 271.51 $\$\cdot ha^{-1}\cdot a^{-1}$.

This figure represents the economic value of one standard unit of the ecosystem service value equivalent factor, equal to 271.51 $·ha^{-1}·a^{-1}. Given the relatively small area of construction land in the study area, ESVs for construction land were excluded from the calculation. Using the revised coefficient, we computed the changes in the ESVs for six types of land (excluding construction land) in various periods within the Taihu Lake region.

Sensitivity of Ecosystem Service Values

Currently, methods for estimating ecosystem service values based on coefficients per unit area for different land use categories are widely employed. However, the accuracy of these methods heavily depends on the determination of the coefficients. The sensitivity model employed in this study calculates the response of ecosystem service value (ESV) to variations in value coefficients (VC) by adjusting the ESV coefficients for each land use type by ±50% [35], thereby determining both the temporal trends of ESV and its sensitivity to VC changes.

Results and Discussion

Taihu Lake Basin Heterogeneity of Land Use Changes

Spatial-Temporal Characteristics of Land Use Changes

The study area is characterized by a large population and a thriving economy. The main land use types include plowland, forestland, construction land, and water, which together shape the landscape. Grasslands and unutilized lands occupy a much smaller proportion. The spatial distribution of these land use types exhibits distinct patterns (Fig. 3). The region has a relatively flat topography and favorable climatic conditions, making it highly suitable for agricultural cultivation. Plowland is the most extensively distributed land use type, while forestland primarily covers the southwest mountainous region of the basin. Construction land is mainly concentrated around urban centers. Forestlands and grasslands have been increasingly replaced by construction land, particularly in cities such as Suzhou, Wuxi, Changzhou, and Hangzhou. The distribution of water remains largely unchanged, although in some regions, plowland has been replaced by either construction land or unutilized land.

The areas of each land-use type in 2005, 2010, 2015, and 2022 are presented in Fig. 4. The area of plowland has shown a declining trend, decreasing from 4,907.85 hectares in 2005 to 4,364.21 hectares in 2022. The area of unutilized land remained minimal and almost unchanged. The forestland has remained relatively stable with only slight variations, indicating effective management of forestland resources. The area of construction land has increased significantly, rising from 1,212.97 hectares in 2005 to 2,171 hectares in 2022, reflecting the acceleration of urbanization. The area of grassland has experienced a dramatic decline, dropping to just 0.3 hectares in 2022, which may reflect ecological shifts or land use conversion. The waters have remained mostly stable, but have shown a slight decline, from 3,472.03 hectares in 2005 to 3,129.76 hectares in 2022. Land use changes are closely linked to urbanization, ecological management, and natural resource conservation. While plowland and grassland have decreased, construction land has expanded, and forestland and waters have remained relatively stable. The proportion of unutilized land has remained extremely low. These trends underscore the ongoing development, conservation, and optimal allocation of land resources in the study area.

Land Use Dynamic Degree

Table 3 shows that from 2005 to 2010, the dynamic degree of reservoir pits was 14.22%, while that of construction land was 9.87%, indicating that the scale of reservoir pits was larger than that of construction land. The dynamic degree of forestland was -3.96%, that of shrubland was -0.21%, and that of lakes was -0.13%, all showing a continuous decline. From 2010 to 2015, the rate of decline for these three land use types slowed down, with plowland experiencing a faster decrease compared to forestland and lakes. The dynamic degrees of open woodland, other woodland, grassland, river channels, reservoir pits, and unutilized land changed from positive to negative, showing a gradual decline. The dynamic degree of construction land remained positive, reflecting the continued expansion of construction land during this period. From 2015 to 2022, the area of grassland began to show a rapid upward trend, with its dynamic degree turning from negative to positive, reaching 13.30%. Conversely, the area changes of other green space types exhibited an opposite trend, primarily due to the gradual transformation of original forestland and shrubland into other green space types, such as dredge land or other forestland. Among these, the most noticeable changes occurred in other forestlands and reservoir pits. The dynamic degree was -0.21%.

With the rapid economic development and accelerated urbanization, large areas of plowland and forestland were destroyed and converted for use. While the area of forestland decreased, the area of other forestland and shrubland increased. From 2010 to 2015, the dynamic degree of grassland in the Taihu Lake area was -1.13%. The areas of plowland, forestland, dredge land, and other forestland decreased rapidly, indicating that a large amount of plowland, forestland, and grassland was converted into construction land during this period. From 2015 to 2022, the area changes of plowland, forestland, shrubland, dredge land, other forestland, river and canal, and lakes showed a stable and fluctuating trend. Overall, from 2005 to 2022,

Table 2. ESV of unit area of different land use categories in the Taihu Lake basin ($\$\cdot ha^{-1}\cdot a^{-1}$).

Type	Function	Plowland	Forestland	Shrubbery	Open forestland	Other woodlands	Grassland	River and canal	Lakes	Reservoir pit	Bare land	Unutilized
Supply service	FP	597.80	115.82	78.46	82.20	141.98	188.82	215.79	404.61	161.85	0	0
	RMP	224.18	302.65	194.29	168.13	112.09	194.22	62.04	148.36	40.46	0	5.40
	WRS	-709.42	972.70	112.09	100.88	78.42	124.22	3236.91	4046.14	2400.71	0	8.09
Regulating service	GR	410.99	769.78	582.86	635.17	560.44	507.12	512.51	782.25	539.49	5.40	53.95
	CR	194.29	2428.57	1580.44	1489.29	1681.32	1235.42	593.43	617.71	431.59	0	26.97
	CTE	56.04	784.62	459.56	556.70	535.37	469.35	944.10	1497.07	1213.84	26.97	97.11
	HR	1102.20	1770.98	1110.25	1247.91	971.43	1006.14	18946.73	27578.50	21644.16	8.09	80.92
Support service	SC	467.03	1270.33	642.64	769.67	149.45	987.26	64.74	253.56	172.64	5.40	161.85
	NC	377.36	112.09	97.14	59.78	67.25	83.62	18.88	72.83	45.86	0	0
	B	298.91	900.44	586.59	702.42	440.88	938.70	526.00	687.84	660.87	5.40	40.46
Cultural service	AL	29.89	560.44	269.01	306.37	160.66	418.10	161.85	509.81	275.14	5.40	13.49
	Total	4140.62	9988.43	5713.33	6523.52	3937.65	6152.97	25282.99	36598.70	27586.59	56.63	488.23

Notes: FP – Food production; RMP – Raw material production; WRS – Water sources supply; GR – Gas regulation; CR – Climate regulation; CTE – Clean the environment; HR – Hydrologic regulation; SC – Soil conservation; NC – Nutrient cycle; B – Biodiversity; AL – Aesthetic landscape.

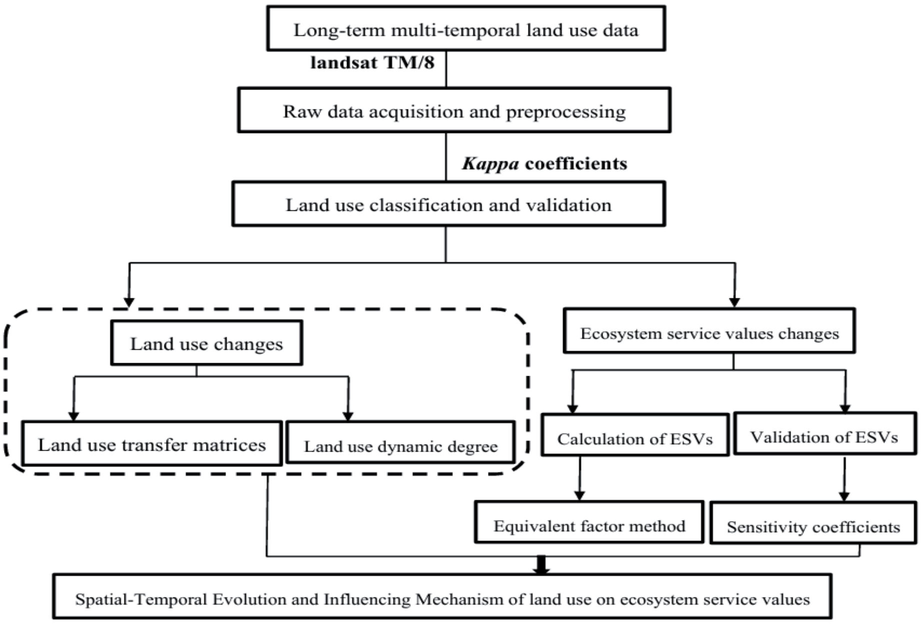

Fig. 2. Technical flow diagram.

the land use dynamics reflect various trends, such as a decrease in agricultural and natural land uses (e.g., plowland, forestland) and significant increases in urban and developed areas (e.g., construction land, reservoir pit). The data suggest a shift from traditional land uses to more urbanized and constructed land in the Taihu Lake basin over the 17-year period, with environmental consequences on natural ecosystems, particularly forestland and grassland areas.

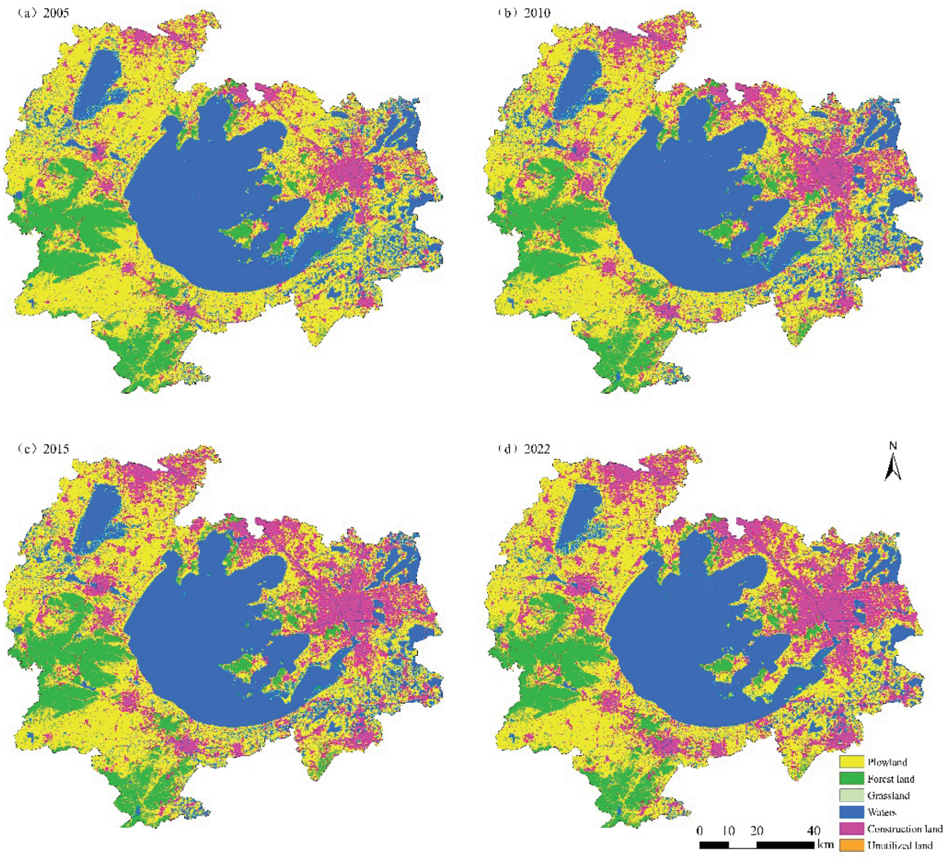

Fig. 3. Land-use maps of the Taihu Lake basin from 2005, 2010, 2015, and 2022.

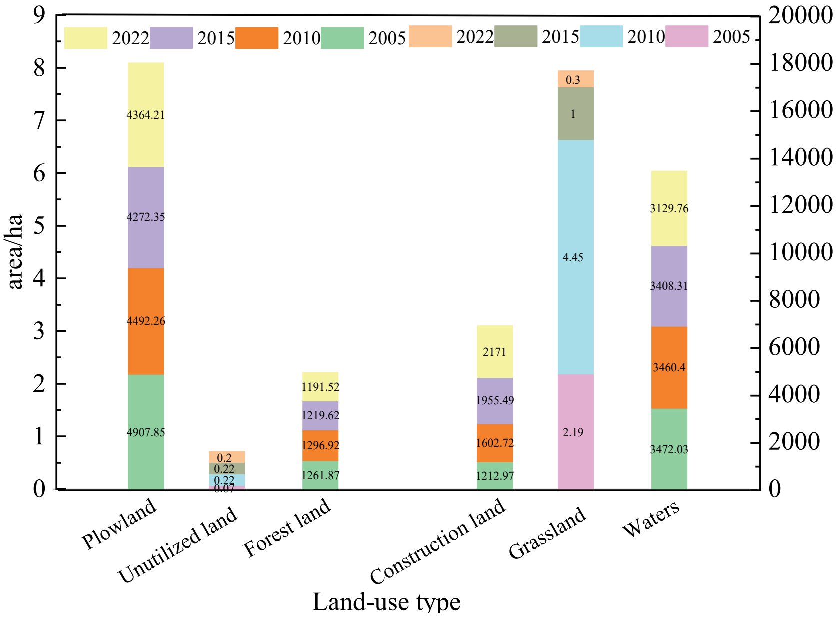

Fig. 4. Dynamics of land use area in the Taihu Lake basin from 2005, 2010, 2015, and 2022.

Table 3. Dynamics of different land-use types in the Taihu Lake basin from 2005 to 2022.

Land use type/year	2005-2010 (%)	2010-2015 (%)	2015-2022 (%)	2005-2022 (%)
Plowland	-3.96	-0.56	-0.52	-1.26
Forestland	-0.21	-0.02	-0.15	-0.11
Shrubbery	0.18	0.01	-0.03	0.03
Open forestland	0.07	-0.29	-0.15	-0.11
Other woodlands	0.35	-0.38	-0.33	-0.11
Grassland	3.1	-1.13	13.30	4.56
River and canal	0.03	-0.01	-0.07	-0.01
Lakes	-0.13	0.01	0.13	0.24
Reservoir pit	14.22	-0.46	-2.14	-0.02
Constructed land	9.87	1.24	6.92	4.18
Bare land	3.15	-1.58	-0.93	0.8
Unutilized land	-4.06	-0.04	0	-1.23

Land Use Transition Matrix

In order to gain a deeper understanding of the interactions among different land use types during the rapid urbanization process, a land use transition matrix was developed and visualized (Fig. 5).

Longitudinal analysis conducted over the 17-year study period revealed extensive interconversion among nearly all land use categories. Notably, the most significant transition observed was the conversion of plowland to construction land, representing a major alteration in land use patterns. Specifically, 647.71 ha (Fig. 5a)), 124.06 ha (Fig. 5b)), and 138.06 ha (Fig. 5c)) of plowland were converted into construction land during the three periods. Over the entire study period (Fig. 5d)), a total of 885.58 ha of plowland was transformed into construction land, while only 29.50 ha of construction land was converted back into plowland. This highlights that urban spatial expansion during rapid urbanization predominantly encroached upon plowland. In addition, a small portion of plowland was converted into water or forestland, with very little transformation into other land use types. The primary reason for the plowland-to-waters conversion was the local farmers' spontaneous excavation of plowland to create ponds for aquaculture, aiming to generate higher incomes. The conversion of other land use types was relatively limited, though waters were notably transformed into construction land,

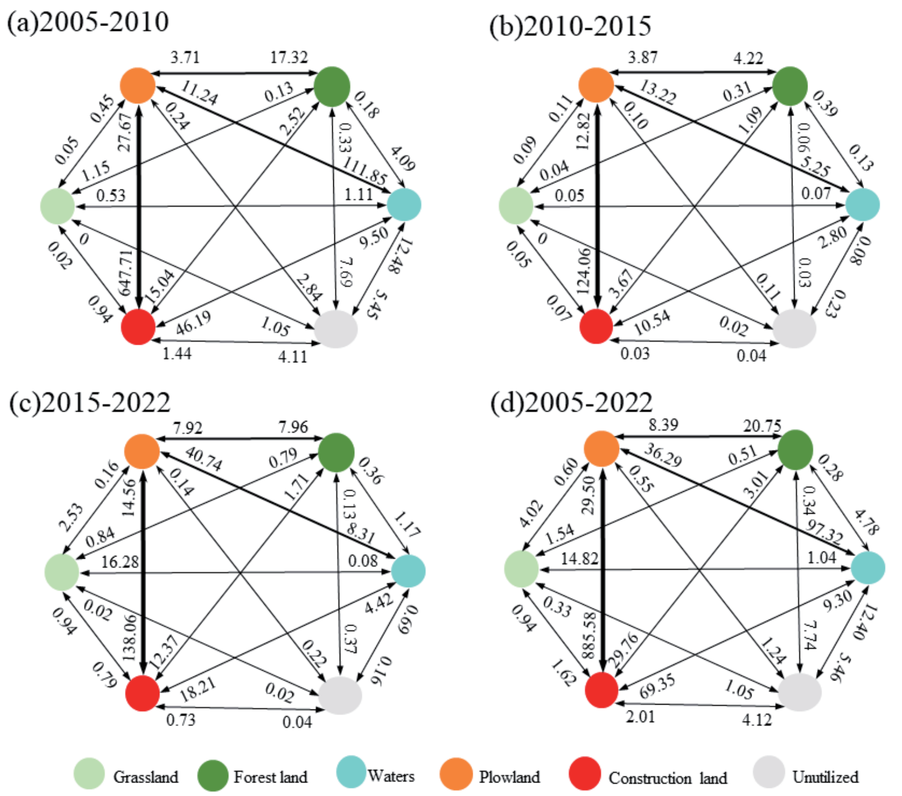

Fig. 5. Transition matrix of land-use type between different years (ha). a) 2005-2010, b) 2010-2015, c) 2015-2022, and d) 2005-2022 values close to the land-use type, representing the conversion area from the other land-use types.

with a total of 69.35 ha being converted between 2005 and 2022. This suggests that the shrinkage of waters has become more pronounced with the rapid pace of urbanization and industrialization. Some aquatic regions have been progressively encroached upon by urban development and industrial expansion, capitalizing on the accessibility of water resources and favorable ecological conditions.

This analysis illustrates significant shifts from natural landscapes (such as grasslands and forestlands) to urbanized or agricultural lands (including construction land and plowland). These trends reflect increasing urbanization and agricultural expansion, often at the expense of natural habitats. Such land use changes are critical for understanding environmental impacts, including habitat loss, biodiversity changes, and potential land degradation. Moreover, this information can guide policies focused on sustainable land management and urban planning.

Effects of Different Land Use Types Changes on the Ecosystem Service Values

Temporal Dynamic Characteristics of Ecosystem Service Values

Different land types exhibited varying trends in their ecosystem service values, which can be broadly categorized into four distinct patterns of change (Table 4). Among the components, plowland showed a downward trend in ESVs, with annual rates of -1.26%. Specifically, the ESVs of plowland decreased from $ 1,357.57 million per year in 2005 to $ 1,073.17 million per year in 2022. For forestland and waters, the ESVs followed an inverted "V" shaped trend, with dynamic changes of 0.19% and 0.21%, respectively. Grassland exhibited a "V" shaped trend, with a decline followed by an increase from 2005 to 2022, showing annual rates of 4.56%. Unutilized land demonstrated an "N" shaped trend, with annual rates of 0.43%, reflecting an overall increase in ESVs from $ 0.57 million per year in 2005 to $ 1.32 million per year in 2022.

The most notable changes in ESVs from 2005 to 2010 were observed in plowland and forestland, where ESVs decreased by $ 224.56 million and $ 70.24 million, respectively. In contrast, the ESV of waters increased by $1 92.02 million. Between 2010 and 2015, forestland saw a significant increase in ESVs by $ 426.13 million, while plowland and waters experienced declines of $ 31.58 million and $ 42.63 million, respectively. From 2015 to 2022, all three land types (plowland, forestland, and waters) showed a downward trend, with ESVs decreasing by $ 28.26 million, $ 381.98 million, and $ 153.04 million, respectively. Over the entire period from 2005 to 2022, the ESVs of plowland and forestland experienced the most significant declines, while grassland and unutilized land saw gradual increases after 2015.

Table 4. Ecosystem service values of Taihu Lake basin in 2005, 2010, 2015, and 2022 (10^6\$·ha^{-1}·a^{-1}).

	Plowland	Forestland	Grassland	Waters	Unutilized land	Total
2005	1357.57	1376.33	9.10	12169.16	0.57	14912.73
2010	1133.01	1906.09	8.59	12361.18	1.16	15410.03
2015	1101.43	1732.22	8.59	12318.55	1.04	15161.83
2022	1073.17	1350.24	13.57	12165.51	1.32	14603.81

Overall, from 2005 to 2022, the total ecosystem service values (ESVs) experienced a decline due to land use changes, with the exception of grassland and unutilized land, which demonstrated an upward trend. The primary factors contributing to the overall decrease in ESVs were reductions in plowland and forestland ESVs. The steady decline in ESVs for these land types suggests that land use practices in these areas may not have been conducive to optimal ecosystem services during this period. Conversely, the increase in grassland and unutilized land ESVs suggests that ecological improvements, likely driven by conservation efforts or changes in land management practices, have positively contributed to the overall ecosystem service values of the region. The overall decrease in the total ESV for the Taihu Lake region (annual rates approximately 2.12% from 2005 to 2022) indicates that while certain areas have seen improvements, the overall sustainability of ecosystem services in the region may be at risk unless concerted efforts are made to restore and maintain the ESVs of other land types, such as plowland and forestland.

The Proportion of Different Ecosystem Service Values

From the perspective of individual ecosystem service values, the total ecosystem service values in the study area for 2005, 2010, 2015, and 2022 were \$ 14,913 million, \$ 14,810 million, \$ 15,162 million, and \$ 14,604 million, respectively (Table 5). Among these, the value of hydrological regulation services was the highest, amounting to \$ 399.02×10^8, which stands out significantly in magnitude. This reflects the critical role of hydrological regulation services in maintaining environmental balance. Following this, water resource supply, climate regulation, and environment cleaning services had values of \$ 45.51×10^8, \$ 25.95×10^8, and \$ 25.88×10^8, respectively. Water services have gradually become the main contributor to the basin's ecosystem service value. The study area, located in the Yangtze River Delta, is characterized by a large population, a developed economy, and limited plowland. Consequently, raw material production and nutrient cycling services have relatively lower values, at \$ 6.92×10^8 and \$ 7.38×10^8, respectively. The temporal changes in the values of different ecosystem services exhibit distinct trends. Food production, raw material production, gas regulation, climate regulation, environment cleaning, soil conservation, nutrient cycling, biodiversity, and aesthetic landscape services show an inverted "N" trend, while water resource supply and hydrological regulation services exhibit an inverted "V" trend. These findings underscore the varying importance of different ecosystem services,

Table 5. The proportion of ecosystem service values of the Taihu Lake basin in 2005, 2010, 2015, and 2022 (10^8\$·ha^{-1}·a^{-1}).

Type	Function	2005	%	2010	%	2015	%	2022	%
Supply service	FP	4.08	2.75	3.64	2.45	3.68	2.48	3.52	2.368
	RMP	1.86	1.24	1.67	1.12	1.75	1.17	1.64	1.10
	WRS	11.17	7.45	11.77	7.89	11.87	7.96	11.75	7.88
Regulating service	GR	5.50	3.70	5.17	3.48	5.60	3.76	5.10	3.42
	CR	6.35	4.26	6.04	4.05	7.45	4.99	6.11	4.10
	CTE	6.39	4.28	6.38	4.27	6.80	4.56	6.32	4.24
	HR	99.65	66.82	100.23	67.21	100.62	67.47	98.55	66.08
Support Service	SC	4.62	3.11	4.21	2.83	4.33	2.92	4.16	2.79
	NC	2.07	1.39	1.79	1.20	1.81	1.21	1.72	1.15
	B	4.99	3.35	4.74	3.37	5.09	3.43	4.69	3.15
Cultural service	AL	2.51	1.69	2.47	1.67	2.61	1.7	2.47	1.66
Total		149.13		148.10		151.62		146.04	

Note: FP – Food production; RMP – Raw material production; WRS – Water sources supply; GR – Gas regulation; CR – Climate regulation; CTE – Clean the environment; HR – Hydrologic regulation; SC – Soil conservation; NC – Nutrient cycle; B – Biodiversity; AL – Aesthetic landscape.

with a notable emphasis on regulating and cultural services over supply services, highlighting the need to protect hydrological systems and cultural landscapes.

Watershed Distribution of Ecosystem Service Values

The distribution of ecosystem service values (ESVs) exhibits significant spatial heterogeneity, with certain regularities in spatial variation (Fig. 6). Areas with reduced ESVs are mainly found in the lower reaches, particularly around Wujiang and Xiangcheng. Although ESVs in these areas are relatively high, this is largely due to the conversion of plowland into forestland. However, plowland degradation has led to a decrease in ESVs per unit area, resulting in an overall reduction in ESVs. In contrast, areas with significantly increased ESVs are primarily located in the upper and middle reaches, with a few such areas also found in the lower reaches of Wuxing and Changxing. The distribution of high ESV areas is concentrated mainly in the central and northeastern parts of the study area, particularly in Jiangsu Province. In contrast, ESVs in Zhejiang Province, situated in the southern part of the study area, are generally lower. This spatial discrepancy is closely related to the scale of water bodies. Zhejiang Province has extensive plains, large areas of forestland and plowland, and a relatively small area of water.

Urban expansion between 2005 and 2010 resulted in a continuous reduction of high ESV regions. In 2005, high-value areas were concentrated in the eastern part of the study area. By 2010, the extent of low ESV regions had expanded, while high ESV regions continued to shrink. However, in 2015, the scope of high ESV regions slightly increased again. Human encroachment caused a continuous reduction in the area of forestland and grassland adjacent to waters, which led to a significant increase in low ESV regions during this period. By 2022, the low ESV regions had further expanded compared to 2005, 2010, and 2015, while high ESV regions had diminished. Overall, the high ESV regions of the Taihu Lake basin demonstrate high stability, indicating that the core functions of its ecosystem remain robust. The slight expansion of low ESV regions may be attributed to the intensification of human activities in surrounding areas. Thus, there is a need to strengthen ecological protection and management in the lake region to prevent further ecological degradation.

Sensitivity Analysis of Ecosystem Service Values

According to the formula, the values of plowland, forestland, grassland, waters, construction land, and unutilized land are each adjusted by 50%. The sensitivity index of ecosystem services in the study area for the years 2005, 2010, 2015, and 2022 was then calculated (Table 6). The results show that the sensitivity index of Ecosystem Service Values (ESVs) is consistently less than 1, indicating that the ESVs in the study area are inelastic with respect to changes in VC, and the results are thus reliable. Among these, since the area

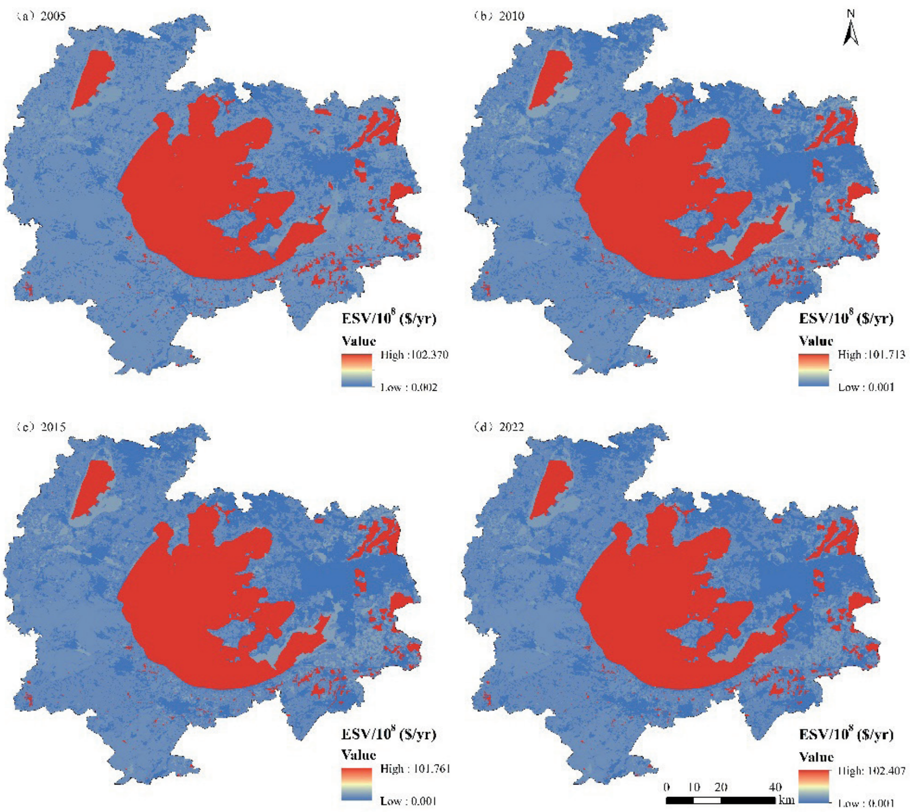

Fig. 6. Spatial distribution of ecosystem service values in the Taihu Lake basin.

Table 6. The total ecosystem service values and the sensitivity coefficient (CS) under different ecosystem value coefficient scenarios (VC).

Value coefficient change	2005		2010		2015		2022	
	%	CS	%	CS	%	CS	%	CS
Plowland VC±50%	9.101	0.192	7.650	0.189	7.264	0.186	7.349	0.184
Forestland VC±50%	9.237	0.192	8.819	0.191	11.425	0.211	9.246	0.192
Grassland VC±50%	0.029	0.091	0.057	0.093	0.565	0.013	0.093	0.094
Waters VC±50%	27.205	0.574	83.465	0.893	81.247	0.891	83.304	0.892
Construction land VC±50%	0	0	0	0	0	0	0	0
Unutilized VC±50%	0.002	0.001	0.008	0.001	0.007	0.913	0.009	0.094

of waters and the ecological service value per unit area are relatively high, the sensitivity index of forestland is the highest, at 0.892, which suggests that a 1% increase in the VC of forestland results in a 0.892% increase in its ESV. The CS values for all other land use types are significantly less than 1.

Response of Ecosystem Service Values to Land Use Changes

Based on the analysis of the spatio-temporal evolution of land use, this paper addresses the limitation of using the basin's mean value to represent the land use distribution across the entire Taihu Lake basin. Research shows that the core feature of land use change in the Taihu Lake basin from 2005 to 2022 was the reduction in plowland area (from 4907.85 hectares to 4364.21 hectares) and the significant expansion of construction land (from 1212.97 hectares to 2171 hectares). This trend is closely related to the rapid urbanization in the Yangtze River Delta region, especially the industrialization and population concentration in urban agglomerations such as Suzhou and Wuxi. The conversion of plowland to construction land (a total of 885.58 hectares) directly led to a decline in ecosystem service value (ESV) (a decrease of 1.26% per year in plowland ESV), which is consistent with the negative impact of construction land expansion on carbon sequestration capacity found in other studies in the Taihu Lake basin [34]. Notably, although the overall water area remained stable, local reductions occurred in some areas due to aquaculture and industrial encroachment (such as 69.35 hectares converted to construction land), which may exacerbate the degradation of hydrological regulation functions.

The increasing intensity of land use has led to a reduction in the integration of the forestland and plowland modules, as well as the loss of strong synergies within the ecosystem. There is a positive correlation between forestland and water, as well as with ecosystem service values. The expansion of both waters and forestland has contributed to an 8.31% increase in ESVs. The ecological service functions of Taihu Lake basin in 2005, 2010, 2015, and 2022 are primarily reflected in hydrologic regulation services, which are different to the ESV evaluations in previous studies, where Yang evaluated ecosystem service values through emergy analysis, demonstrating that the Dongjiang River basin's key ecological functions predominantly manifested as ecological regulation, ecological support, and freshwater provision [36]. The fundamental causation resides in the aquatic ecosystem of the Taihu Lake basin, serving as a critical sustainer for the structural framework, functional processes, and regional eco-environmental services of the entire natural system. Its hydrological regulation and water sources supply capacities demonstrate multifaceted ecological significance and substantial economic valuation [37]. The hydrological regulation function plays a critical role in regulating surface runoff and mitigating heavy rainfall and flood disasters, significantly influencing the production and development of the Taihu Lake basin area. Additionally, water supply, as one of the core functions of Taihu Lake, further underscores the importance of the lake as a crucial water source in the Yangtze River Delta region. In comparison to previous evaluations of Taihu Lake's ESVs, many earlier studies employed economic valuation methods, which tend to overestimate the value due to the double counting of certain functions, such as flood control, storage, and water conservation functions [28].

Sustainable Spatial Planning of Land Use Based on the Dynamic Evolution of Ecosystem Service Values

The total ecosystem service value (ESV) in the study area decreased from $ 14.913 billion in 2005 to $ 14.604 billion in 2022, reflecting an annual decline rate of 2.12%, primarily driven by the reduction in ESV from plowland and forestland ecosystems. This trend aligns with findings from Taihu Lake wetland studies, where regulatory functions dominated ecosystem services (48.98% of total ESV). The decline in ESV in the downstream low value regions (such as Wujiang and Xiangcheng) is directly related to the expansion of construction land and the degradation of plowland, confirming the squeezing effect of urbanization in the eastern part of the Taihu Lake basin on ecological services; the recovery of ESV in the upstream high value regions (such as Changxing, Huzhou) may be related to cross-regional ecological compensation mechanisms (such as the water source protection policies implemented in Suzhou) and wetland restoration projects [37, 38].

Demographic density and urbanization are the primary driving forces behind land use changes and are also the key factors influencing regional human-environment interactions [39]. Population growth often leads to an expansion of plowland and may trigger agricultural restructuring. Additionally, urbanization and land expansion are strongly negatively correlated with the provision of certain ecosystem services [40]. Prior to 2010, the value of ecological services continued to rise, which aligns with the expansion of lakes driven by the "Returning Farmland to Lakes" policy during this period [41]. Forestlands, waters, and other areas expanded, and ecosystem services such as water resources supply, hydrologic regulation, climate regulation, gas regulation, environment cleaning, biodiversity, and aesthetic landscape also significantly improved, which indicates the notable positive impact of environmental protection policies on the enhancement of ESVs. In the long term, the high growth rate of these services positively affects the ecosystem. Therefore, the protection of high ESV regions, such as forestlands, waters, and grasslands, is crucial for maintaining the balance between future economic development and sustainable ecosystem management. To emphasize the importance and sustainability of these efforts, it is essential to give equal priority to their role in spatial planning.

Considerations and Future Prospects

Spatial planning approaches are often constrained by baseline data, and our study is no exception [42]. For example, we did not define a detailed vegetation distinction between different forestland. We utilized an ecosystem services matrix, which considers the capacity of various land cover types to support ecosystem services. Mapping the potential supply of ecosystem services based on land cover information using the matrix approach is a common and valuable practice for informing policy decisions [43]. However, some limitations of the matrix approach should be acknowledged, including its inability to capture other important dimensions of ecosystem services, caution is also warranted when interpreting certain scores in our study, as land cover types with lower potential for ecosystem service provision (e.g., burned and invaded areas) were also less frequently reported in the reviewed cases. In the field of ecosystem services mapping and assessment, more advanced analytical tools are available that incorporate both the supply and demand dimensions of ecosystems [44]. Since the benefits derived from ecosystems are intrinsically dependent on human appropriation and management, further research is needed to address the increasing complexity in the ecosystem services domain [45]. This includes a more detailed analysis of service flows, interactions, demand, preferences, and values (in addition to potential supply), which can influence the prioritization and efficiency of planning and management efforts [46]. We advocate for future progress in integrating socioeconomic factors, such as the costs of ecosystem restoration, as well as the opportunity costs associated with alternative management practices, to provide a more quantifiable cost-benefit analysis for decision-makers [47]. One potential approach is to incorporate cost functions into the land use transition matrix, thereby directly accounting for the social and economic values assigned to individual planning units [40]. This could include, for example, revenue from ecosystem services based on relevant indicators (such as market prices for agricultural products or tourism visitation numbers), where available [48]. Despite the simplifications and limitations inherent in our approach, this study represents an initial step toward engaging decision-makers in the protection and sustainable use of natural assets through a legally binding framework at the municipal level in China, with practical implications for landscape planning and management. Understanding the underlying causes of declines in specific ecosystem services, particularly in food production, biodiversity, and aesthetic landscapes, could inform targeted conservation efforts. Research aimed at improving soil conservation and nutrient cycling may enhance ecosystem service values.

Conclusions

This study utilized Landsat TM/8 data; the images from 2005, 2010, 2015, and 2022 were classified into land use types, and analyses of land use change and the dynamic evolution of ecosystem service values were conducted. The main conclusions are as follows:

(1) The total ESVs in the Taihu Lake basin have decreased by $ 3.09×10^8, primarily due to the reduction in plowland, waters, and forestlands. Correspondingly, the values of several ecosystem services, including food production, raw material production, gas regulation, climate regulation, cleaning the environment, soil conservation, nutrient cycling, biodiversity, and aesthetic landscape, have also declined. Notably, the increase in ESVs is most pronounced in the upper and middle reaches of the basin, particularly in the Wuzhong and Huqiu regions. The highest ESVs are present in the middle reaches of the Lake, with different services being spatially concentrated, exhibiting clear spatial clustering patterns. Attention should be paid to the reduction of water and forestland, and efforts should be made to increase the proportion of food production and raw material production. Additionally, the middle reaches should focus on improving supporting services, while

regulation services should be enhanced in the lower reaches, with a focus on vegetation protection.

(2) Although the ESVs in the basin have increased, ecological issues such as plowland degradation and forestland have become more prominent. To protect natural resources and promote coordinated development around the Taihu Lake basin, a new framework for ecological management and sustainable spatial development is essential. Furthermore, it is of great significance to formulate protection and management policies for key ecological functional areas, as well as to account for the value of natural resource assets, for the environmental protection of the Taihu Lake basin.

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Conflict of Interest

The authors declare no conflict of interest.

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