Long-Term Evolution of Urban Wetland Ecosystem Service Values and Ecological Compensation Mechanisms under Carbon Neutrality Targets: A Case Study of East Lake, Wuhan

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ABSTRACT

Scientific assessment of the evolution characteristics of ecosystem service value (ESV) in urban wetlands is the foundation for constructing an ecological compensation mechanism. This study takes East Lake in Wuhan as the object and reconstructs a long-term continuous dataset of ESV from 2010 to 2024 by integrating multi-source data. Spearman correlation analysis is used to identify the time-dimensional trade-offs and synergistic relationships of service functions. Combined with the horizontal comparison of wetlands in the city, a cross-regional multi-dimensional ecological compensation framework is calculated and constructed. The results show that: (1) During the study period, the total ESV of East Lake showed a non-linear growth, and the value structure underwent a substantial replacement. Cultural services such as leisure and entertainment expanded rapidly and occupied an absolute dominant position, while basic natural functions such as climate regulation stagnated or declined. (2) There are clear trade-offs and synergistic effects among various services. Leisure and entertainment showed a significant negative correlation with air purification and scientific research and education; water purification, carbon sequestration and oxygen release showed a high positive correlation with habitat conservation. The wetlands in Wuhan present a spatial functional division pattern of “the core area dominates cultural services and the peripheral area undertakes ecological regulation”. (3) To address the mismatch between internal service trade-offs and external space, a market-based compensation path of “carbon trading + tourism feedback” was constructed. Calculations show that the potential annual carbon trading volume of East Lake is approximately RMB 4.28 million, and the dynamically extracted tourism feedback fund is approximately RMB 75.9 million per year. Based on this, a fund transfer payment framework of “core area feedback to peripheral regulating wetlands” under municipal-level coordination was established, providing a quantitative basis for regional wetland collaborative governance.

Keywords: Carbon Neutrality; Ecosystem Service Value; Long-Term Evolution; Trade-offs and Synergy; Ecological Compensation; East Lake, Wuhan.

1. INTRODUCTION

1.1 Background

Wetlands, as vital surface ecosystems, play a fundamental role in maintaining biodiversity, regulating climate, and sustaining material cycles [1]. With the advancement of carbon neutrality goals, the multiple functions of urban lakes and wetlands in carbon sequestration and environmental protection have received increasing attention. Ecosystem services, as a direct bridge connecting natural capital and human well-being, require quantitative value assessment as a fundamental prerequisite for measuring regional ecological benefits and formulating environmental management policies. Urban lakes possess both natural regulatory and socio-cultural service attributes, and the intense urbanization and tourism development activities cause their internal ecological functions to be in constant dynamic change [2].

International systematic research on ecosystem service value (ESV) began with Costanza et al.’s economic assessment of global natural capital. Subsequently, the Millennium Ecosystem Assessment (MEA) established a four-category classification framework including supply, regulation, support, and culture services. Domestic scholars, such as Xie Gaodi et al., proposed the value equivalent factor correction method, providing a standard approach for the localized quantification of ESV at the regional scale in China [3]. In recent years, academic research on ESV has gradually shifted from static accounting to dynamic measurement, with a focus on analyzing the trade-offs and synergies between different ecosystem services, and attempting to use the value accounting results as a quantitative basis for determining ecological protection compensation standards [4].

Existing research on the ecological energy storage capacity (ESV) of lakes in rapidly urbanizing areas still has certain limitations [5]. Most valuations rely primarily on remote sensing data from a few discrete years, lacking long-term, continuous, and dynamic sequence measurements, making it difficult to accurately capture the true impact trajectory of major socio-economic events on specific indicators such as cultural services. Analysis of the trade-offs and synergies of service functions often focuses on spatial-scale differentiation characteristics [6], with relatively weak verification of long-term evolutionary patterns over time. Regarding ecological compensation practices, existing mechanisms mostly rely on single public financial payments, lacking a market-oriented, diversified compensation framework design that combines carbon sequestration potential with cultural and tourism revenue for urban center lakes with “high cultural services and high economic returns.”

This study focuses on East Lake in Wuhan, reconstructing a 15-year ESV time-series dataset from 2010 to 2024 based on multi-source environmental monitoring and socio-economic statistics. The study quantitatively analyzes the long-term evolution of its multifunctional service value. Correlation analysis is used to identify the trade-offs and synergies among various service functions over a long timescale, and spatial functional division is defined through horizontal comparison with typical wetland parks within the city. Based on value assessment and trade-off characteristics, and coupling regional carbon trading market average prices with tourism economic data, a diversified ecological compensation mechanism of “carbon trading + tourism feedback” is calculated and designed, providing a scientific basis for urban wetland protection and regional collaborative governance under dual-carbon objectives.

1.2 Overview of the study area

Wuhan East Lake Scenic Area (114°21’—114°28’E, 30°31’—30°36’N) is located in the core urban area of Wuhan, a megacity in the middle reaches of the Yangtze River. It borders Hongshan District to the east, Jiangxia District to the south, Wuchang District to the west, and Qingshan District to the north. It is a core component of Wuhan’s “Two Rivers and Four Banks” ecological pattern and is only 3 kilometers from the main channel of the Yangtze River. 5km, indirectly connected to the Yangtze River through the “Great East Lake Ecological Water Network Project”, the geographical location combines the convenience of the city center and the connectivity of the ecological corridor. As one of the largest urban lakes in China, the scenic area has a total area of about 88km², of which the water area is 33km², accounting for 37.5%; the total shoreline of the lake is about 115km long, the shape is an irregular fan shape, the average water depth is 2.5m (the deepest point is about 6m), and it is a typical shallow lake in the subtropical monsoon climate zone. Its unique location and morphological characteristics make it a key “green lung” for maintaining the ecological balance of Wuhan city.

2. RESEARCH METHODS

2.1 Data Source

This study constructed a continuous dataset of ecosystem service value from 2010 to 2024. The required basic data mainly covered ecological environment, meteorological and hydrological data, and socio-economic data. Meteorological and hydrological data, such as annual lake evaporation, peak reservoir capacity difference, and annual water supply, were obtained from the annual “Wuhan Water Resources Bulletin” and publicly available data from local meteorological stations. Parameters such as carbon sequestration and oxygen release by aquatic plants and lakeside green spaces, nitrogen and phosphorus pollutant absorption in water bodies, and atmospheric pollutant adsorption were obtained from routine monitoring data of the Wuhan Municipal Bureau of Ecology and Environment and relevant long-term ecological observation literature. For some basic ecological parameters missing in non-baseline years, linear interpolation was used for sequential extrapolation. Data on the annual fishery output and agricultural water unit price of East Lake, which are relevant to socio-economic accounting, were obtained from the “Wuhan Statistical Yearbook” and water industry reports; data on the annual total municipal tourism revenue used to calculate the recreational value were obtained from the “Wuhan National Economic and Social Development Statistical Bulletin” from 2010 to 2024. In addition, the academic research data required to assess the value of scientific research and education were obtained by independently searching and statistically analyzing the CNKI database annually using “Wuhan East Lake” and “ecology/wetland/environment” as keywords.

2.2 Accounting Indicators and Value Evaluation Methods

To comprehensively reflect the ESV of Wuhan East Lake, this study established an evaluation system of 10 specific indicators (Table 1) under the four major service categories of “supply-regulation-support-culture” and constructed a comprehensive value assessment framework.

Table 1. Service Value Evaluation Index System for Wuhan East Lake Scenic Area.

Service Value Classification	Evaluation indicators	Calculation indicators	Evaluation methods
Supply services	Freshwater products	Annual fishery output	Market value method
	Water resource supply	annual water supply of the lake	Market value method
Adjustment service	Flood regulation	The difference between peak and normal water levels in a lake	Shadow Engineering
	Water purification	Total N and P content in lake water	Results-based referencing
	Climate Regulation	annual evaporation of lakes	Alternative cost method
	Carbon fixation and oxygen release	Annual carbon sequestration and annual oxygen release by aquatic plants	Carbon Tax Law
	Air purification	Total amount of PM2.5 and PM10 adsorbed by lakeside green spaces and water surfaces	Alternative cost method
	Habitat conservation	Effective habitat area for key species	Alternative cost method
Cultural services	Leisure and entertainment	Total number of tourists and total tourism revenue throughout the year	Travel Expenses Law
	Scientific Research and Education	Number of related papers published	Shadow pricing method

2.3 ESV Calculation Method

Multiple methods were employed to value different service types [7, 8]. To accurately reflect the dynamic evolution of long-term ecosystem service physical quantities, this study comprehensively collected and integrated 15 consecutive years of ecological environment monitoring data and annual socio-economic statistics from 2010 to 2024, constructing a continuous annual dataset of basic ecological parameters. Simultaneously, to scientifically quantify the actual changes in ecosystem service supply capacity, constant base year prices and fixed value parameters were uniformly adopted in the value accounting process to eliminate the interference of inflation and foreign exchange market fluctuations on the final accounting results [9].

2.3.1 Supply of service value

The value of freshwater products is determined using the market value approach, which combines annual fishery production with market prices. The formula is as follows:

$$V_1=Q_1\times P_1 \tag{1}$$

V_1 1. The annual value of freshwater products (yuan); Q_1 2. The annual output of freshwater products in East Lake (t); P_1 3. The average market price of freshwater products in that year, taken as 14,000 yuan/t.

The value of water resource supply is estimated based on the annual water supply and the price of agricultural water, and the calculation formula is as follows:

$$V_2=Q_2\times P_2 \tag{2}$$

V_2 Let be the annual value of water resources (yuan); Q_2 be the annual water supply of East Lake (m^3); P_2 and be the unit price of water resources (yuan/m^3). Using agricultural water consumption as the evaluation standard, and noting that East Lake water was no longer used for domestic water in 1999, the value of freshwater resources is estimated according to the agricultural surface water price (0.002 yuan/m^3) set by the China Urban Water Supply and Drainage Association.

2.3.2 Adjusting service value

Regulation services include five components: flood control, water purification, climate regulation, carbon sequestration and oxygen release, and air purification.

The value of flood control is estimated using the shadow project method, which estimates the effective flood control capacity and the unit reservoir construction cost. The calculation formula is as follows:

$$V_3=Q_3\times C_3 \tag{3}$$

V_3The annual value of flood control is RMB; $Q_3$the effective storage capacity of East Lake is m³, which usually refers to the difference in storage capacity between the highest water level during the flood season and the normal storage level; $C_3$and the construction cost per unit storage capacity of the reservoir is RMB 6.11/m³.

The value of water purification is calculated by multiplying the reduction in total nitrogen and total phosphorus by the equivalent pollution treatment cost. The calculation formula is as follows:

$$V_4=\sum_{i=1}^{n}\left(Q_{4i}\times C_{4i}\right) \tag{4}$$

$V_4$1. Annual value of water purification (yuan); 2. Q_{4i}Total amount of Class I pollutants C_{4i}purified annually in the lake (kg); i3. Cost of removing a unit mass of Class I pollutants using artificial treatment methods (yuan/kg) i, with a unit price of 1.5 yuan/kg for total nitrogen purification and 2.5 yuan/kg for total phosphorus purification.

The climate regulation value is based on the heat absorption caused by lake evaporation, converted into the equivalent electrical energy value, and the calculation formula is as follows:

$$V_5=125\times Q_5\times C_5 \tag{5}$$

V_5=Climate regulation annual value (yuan); Q_5Total heat absorbed by East Lake annual evaporation (m³), which can be converted into corresponding electrical energy (kW·h). The power consumption to convert 1 m³ of water into steam is approximately 125 kW/h [20, 21]; C_5Unit electricity price, which adopts the first tier of Wuhan electricity price of 0.573 yuan/(kW·h).

The value of carbon sequestration and oxygen release is calculated by multiplying the annual carbon sequestration and oxygen release of aquatic vegetation by the carbon tax and oxygen production costs. The calculation formula is as follows:

$$V_6=V_{6a}+V_{6b}=Q_{6a}\times C_{6a}+Q_{6b}\times C_{6b} \tag{6}$$

$V_6$1. Total value of carbon sequestration and oxygen release (RMB); 1 $V_{6a}$and V_{6b}2 are the values of carbon sequestration and oxygen release, respectively; 3 Q_{6a} and Q_{6b} 4 are the annual carbon sequestration and annual oxygen release, respectively (t); C_{6a}5 is the carbon tax or market price per unit of carbon value (RMB/t), and the cost of CO2 afforestation is RMB 1320/t carbon; 6 $C_{6b}$is the unit cost of industrial oxygen production (RMB/t), and the price of O2 is RMB 1000/t based on the price on the website of the Ministry of Health of the People's Republic of China.

The air purification value is calculated using the pollutant treatment cost method, determining the equivalent treatment value of water bodies and lakeside vegetation adsorbing PM2.5, PM10, SO_2, and NOx. The calculation formula is as follows:

$$V_7=\sum_{i=1}^{n}\left(Q_{7i}\times C_{7i}\right) \tag{7}$$

V_7=The annual value of air purification (yuan); $Q_{7i}$the total amount of Class I air pollutants iadsorbed by the East Lake ecosystem each year (tons/year), which, according to the data calculated in this study, ispecifically includes four types of pollutants: PM2.5, PM10, SO_2 and NOx; and the industrial treatment cost (yuan/ton) $C_{7i}$for removing a unit mass (ton) iof Class I pollutants. Among them, the treatment cost of PM2.5 and PM10 is taken as 150 yuan/t based on the industrial dust removal cost, while the treatment cost of SO_2 and NOx is taken as the operating cost of industrial flue gas desulfurization and denitrification, respectively [10]. The desulfurization cost is taken as 1423 yuan/t, and the denitrification cost is taken as 8600 yuan/t.

2.3.3 Support service value

The habitat conservation value was estimated using the globally established unit area value method, by multiplying the area of East Lake by the unit ecological value. Considering the rich habitat types in East Lake wetlands, this study converted the unit value using exchange rates and made appropriate adjustments to better reflect the regional ecological carrying capacity. The calculation formula is as follows:

$$V_8=A\times C_8 \tag{8}$$

V_8The total value of biodiversity and habitat conservation is given in RMB; A the total area of the East Lake ecosystem is given in hm²; $C_8$and the species conservation value per unit area of habitat is given in RMB/hm². The species conservation value of habitat is USD 304/hm², calculated in RMB for that year.

2.3.4 Cultural Service Value

Leisure and Entertainment Value. Given the limited availability of long-term continuous statistical data for single scenic spots and the limitations of conventional linear interpolation in reflecting the true impact of sudden public events (such as the COVID-19 pandemic) on the cultural and tourism industry, this study introduces a macro-trend downscaling extrapolation method [11]. Using the annual total tourism revenue of Wuhan City published in the annual National Economic and Social Development Statistical Bulletin as a macro-environmental variable, the dynamic weight share of East Lake Scenic Area's tourism revenue in the city's total revenue in 2010, 2015, 2020, and 2024 is calculated and interpolated. Subsequently, an inverse fitting is performed to derive the historical leisure and entertainment value of East Lake that incorporates real socio-economic fluctuations [12]. The calculation formula is:

$$V_9=C_t\times w_t \tag{9}$$

$V_9$1. The leisure and entertainment value of East Lake $C_t$in the ____ year (RMB); t2. The actual statistical value of Wuhan's total tourism revenue $w_t$in the ____ year (RMB); t3. The proportion and weight of East Lake Scenic Area's tourism revenue in Wuhan in the ____ year.t

Scientific research and educational value. Based on the number of related papers published by East Lake, and estimated by multiplying by the average research investment cost, the calculation formula is as follows:

$$V_{10}=\sum(N_i\times P_i) \tag{10}$$

V_{10}The annual value of scientific research and education is RMB; the number of academic papers $N_i$related to the theme of East Lake ecosystem is iRMB; the value of $P_i$related iliterature is RMB/paper, with an average value of RMB119,200.

3. RESULTS AND ANALYSIS

3.1 Time Series Evolution of ESV

Between 2010 and 2024, the total ecosystem service value (ESV) of Wuhan East Lake exhibited a significant non-linear growth trend. The total ESV increased from RMB 2.579 billion in 2010 to RMB 10.14 billion in 2024, a cumulative increase of nearly three times. The total value maintained a steady upward trend between 2010 and 2019. Due to macroeconomic and socioeconomic events restricting human activities in the region, the total ESV value dropped significantly to RMB 5.013 billion in 2020, followed by another temporary decline to RMB 5.952 billion in 2022. After 2023, the total value rebounded rapidly and reached a new historical high. This fluctuation characteristic indicates that, under the background of high-intensity development, changes in the total ESV of East Lake are highly sensitive to the external socioeconomic environment.

The composition of ecosystem services has undergone structural changes. In 2010, regulatory services held an absolute advantage in total value, accounting for approximately 95%, while cultural services accounted for less than 3%. Over time, the proportion of cultural services continued to expand, significantly squeezing the relative share of regulatory services. By 2024, cultural services accounted for approximately 75% of the total ESV, becoming the absolute core of value composition, while the proportion of regulatory services correspondingly shrank to below 25%. Throughout the study period, the proportions of supply services and support services remained extremely low, totaling less than 1%. The restructuring of the structural system reflects that the ecosystem function in this region has evolved from a unidirectional succession dominated by natural regulation to one dominated by cultural and recreational supply [13].

Among the various specific service indicators, the exponential growth of leisure and recreation value is the single dominant variable driving the increase in total ESV, with its absolute value surging from 0.63 billion yuan in 2010 to 7.59 billion yuan in 2024. Meanwhile, some traditional ecological services directly dependent on the natural environment are showing a continuous decline. The value of freshwater products in supply services has unilaterally decreased from 23.54 million yuan to 8.91 million yuan; the value of air purification in regulation services has dropped from 370,000 yuan to 260,000 yuan; and the value of scientific research and education in cultural services has also shown a decreasing trend year by year. Climate regulation services, as a core natural function, have long fluctuated and stagnated in value between 23.6 billion yuan and 28.3 billion yuan, failing to grow in sync with the total value. However, some indicators directly related to local ecological restoration projects have achieved some growth. Over 15 years, the water purification value of Donghu Wetland has increased from 32,300 yuan to 151,700 yuan, the carbon sequestration and oxygen release value from 9.39 million yuan to 18.22 million yuan, and the habitat conservation value from 480,000 yuan to 1.03 million yuan. However, the absolute base of these three indicators is relatively small [14], and the incremental value brought about by their growth is overshadowed by the massive expansion of leisure and entertainment functions, failing to reverse the overall pressure on basic ecological regulation functions on a macro scale.

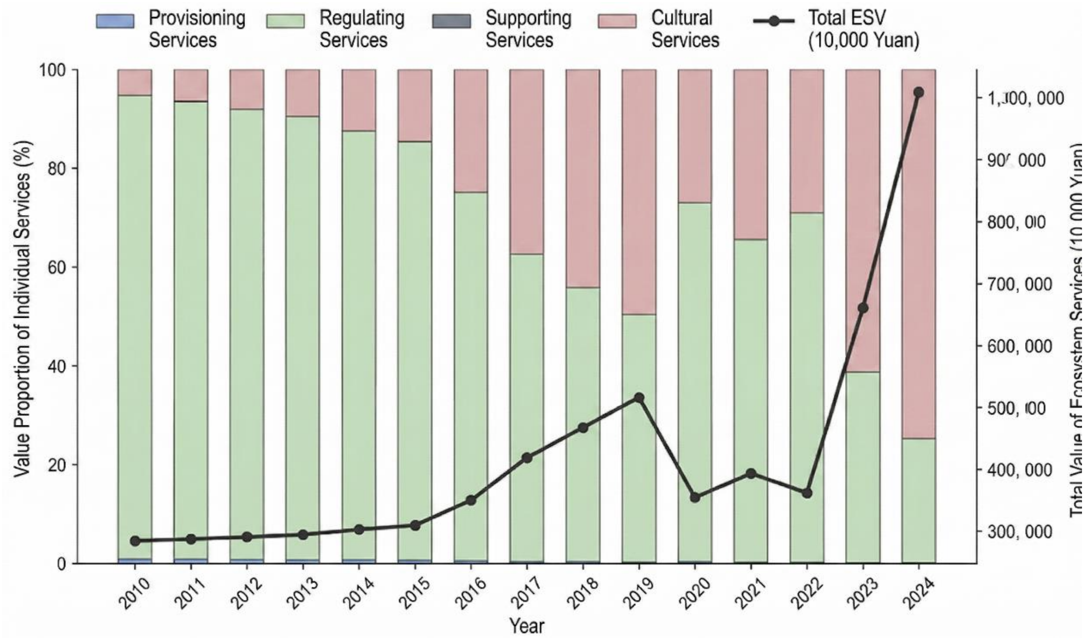

Figure 1. Evolution of total ecosystem service value and structure of East Lake, Wuhan, from 2010 to 2024.

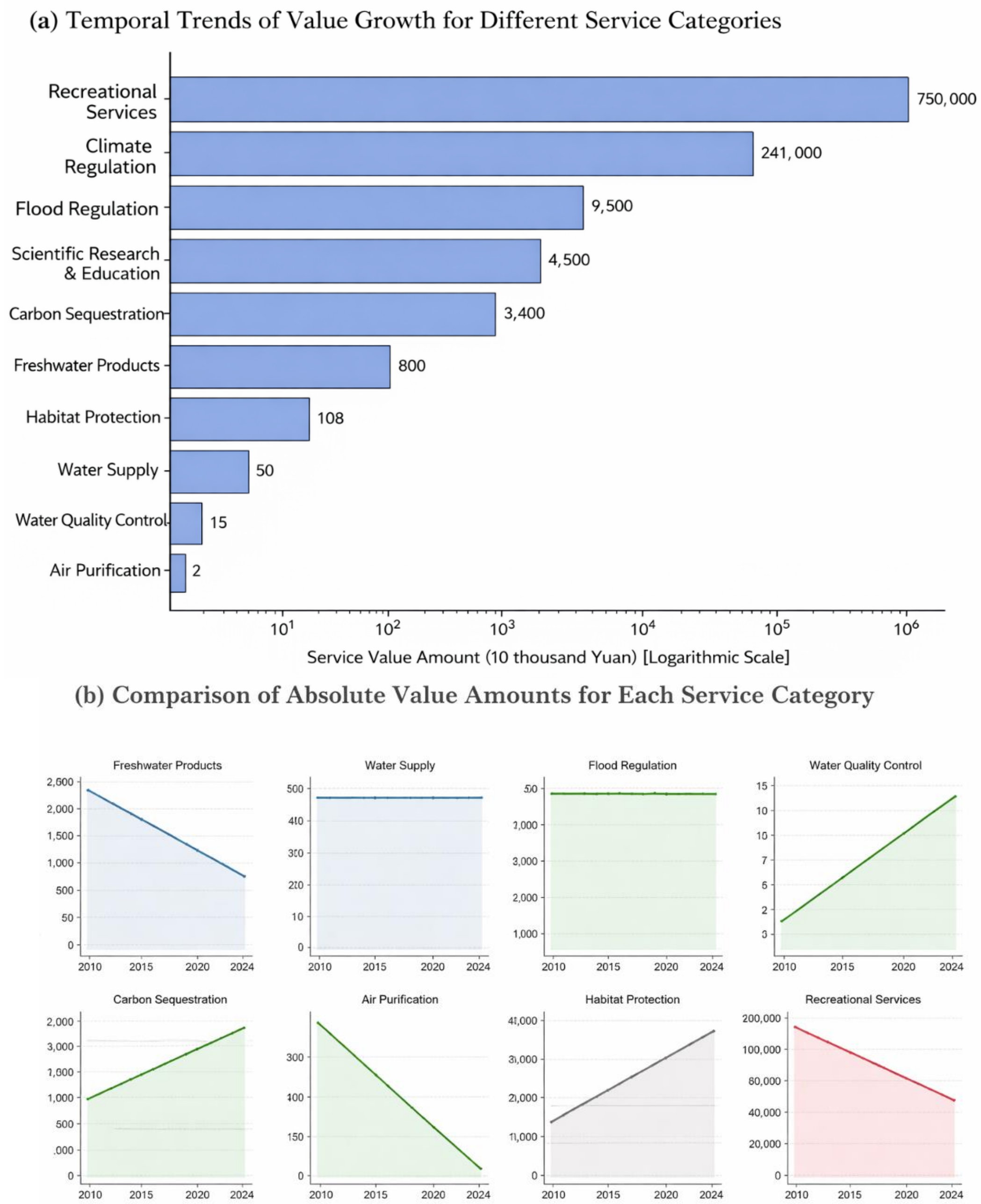

Figure 2. Dynamic characteristics of the ecosystem service value of individual lakes in Wuhan East Lake from 2010 to 2024.

3.2 Long-term trade-offs and synergistic relationships of various ecosystem service values in East Lake

Based on time-series data from 2010 to 2024, Spearman correlation analysis was used to analyze the relationships among various ecosystem services of East Lake. The analysis revealed significant synergies and trade-offs among these services. Regarding synergies, water resource supply, water purification, carbon sequestration and oxygen release, and habitat conservation showed highly significant positive correlations ($R \geq 0.99$, $p<0.001$), as did recreation and leisure activities ($R \geq 0.98$, $p<0.001$). Furthermore, flood control and climate regulation showed highly significant positive correlations ($R=0.89$, $p<0.001$). This reflects a synchronous upward trend in the regulatory and support services of East Lake and some cultural services (recreational activities) during the study period. Regarding trade-offs, freshwater product supply showed highly significant negative correlations with water resource supply, water purification, carbon sequestration and oxygen release, habitat conservation, and recreation and leisure activities (R≤−0.97, p<0.001). This phenomenon corresponds to the actual process of reduced material output and increased ecological and cultural functions during regional ecological restoration. Meanwhile, air purification and leisure activities showed a highly significant negative correlation (R=−0.96, p<0.001), and scientific research and education showed a significant negative correlation (R=−0.74, p<0.01), indicating that the growth of leisure activities had a reverse squeeze on local air purification and scientific research and education services.

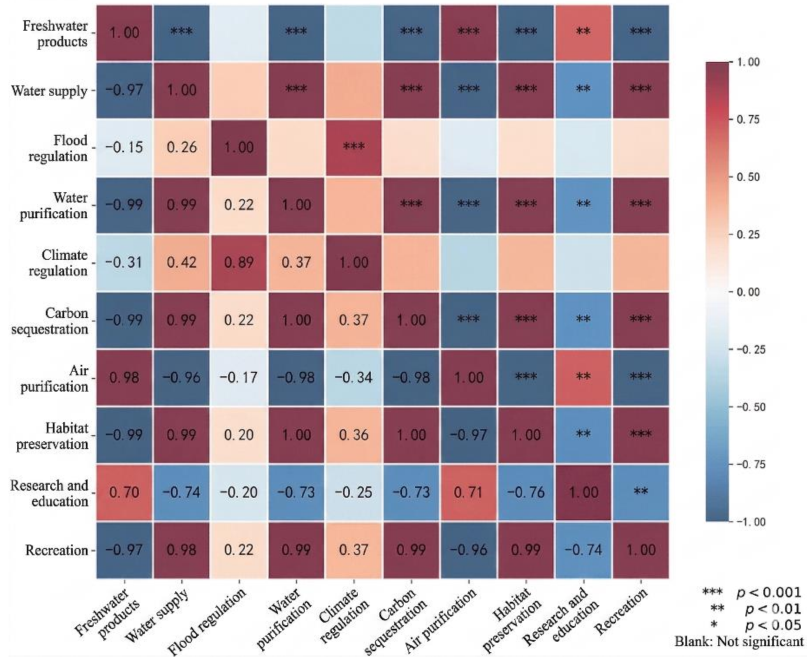

Figure 3. Long-term trade-offs and synergistic relationships of various ecosystem services in East Lake, Wuhan, from 2010 to 2024.

3.3 Comparison of Spatial Functional Division Patterns of Urban Wetlands

To clarify the functional positioning of East Lake in the regional ecological network, this study conducts a horizontal comparison of its ecosystem service value composition with that of Wuhan Jinyinhu, Dugonghu, and Canglong Island. The value proportion structure of each wetland park exhibits significant spatial differentiation characteristics relative to its location.

Located within the urban built-up area, Donghu and Jinyinhu both prioritize cultural services in their value proposition. Donghu, in particular, exhibits a hybrid model of "cultural and regulatory services." Its recreational service value accounts for 74.48%, the highest among the four types of wetlands. Simultaneously, leveraging its vast water area, Donghu maintains a climate regulation value of 23.69%, serving the dual purpose of meeting recreational needs and maintaining the urban microclimate. Jinyinhu, also situated in the core area, has an even higher proportion of recreational services at 89.21%, but limited by its water size, its climate regulation function accounts for only 9.33%, exhibiting typical characteristics of an urban recreational park. In contrast, Dugonghu and Canglong Island, located on the city's outskirts, primarily focus on regulatory and support services. Dugonghu's water purification, carbon sequestration and oxygen release, and flood control services account for 43.39%, 20.30%, and 19.61% respectively, collectively constituting its main functions. Canglong Island's water purification service accounts for 61.71%, and its flood control service accounts for 22.13%, totaling over 80%. The cultural service value of these two wetlands accounts for less than 10% each. Due to their location on the outskirts of the city, these wetlands mainly serve the tasks of intercepting regional water pollution and flood control.

A comprehensive comparison reveals that Wuhan's lakes and wetlands exhibit a spatial functional division of labor: the core area primarily provides cultural services to meet residents' recreational needs, while the peripheral area wetlands mainly provide ecological regulation and support services, together forming a complementary urban wetland ecological network.

Table 2. Value Proportion of Ecosystem Service Functions in Different Wetland Parks.

Service Function Types	East Lake, Wuhan	Dugong Lake, Wuhan	Wuhan Jinyinhu	Wuhan Canglong Island
Freshwater products	0.09	0.00	/	/
Climate Regulation	23.69	1.60	9.33	0.73
Flood regulation	0.95	19.61	0.32	22.13
Carbon fixation and oxygen release	0.34	20.30	0.67	1.84
Air purification	0.01	/	/	/
Purify water quality	0.01	43.39	0.14	61.71
Habitat conservation	0.01	/	/	3.54
Leisure and entertainment	74.48	7.19	89.21	1.84
Scientific Research and Education	0.45	4.75	0.04	0.68
Protecting biodiversity	/	3.16	0.04	7.54
Water conservation	/	/	0.25	/

4. CONSTRUCTION OF ECOLOGICAL COMPENSATION MECHANISM AND CROSS-REGIONAL COLLABORATION

4.1 Calculation of Market-Based Ecological Compensation Amount

This paper analyzes and reveals the dual characteristics of urban lake wetlands in terms of functional evolution and spatial pattern, providing a direct basis for constructing a comprehensive ecological compensation mechanism. At the functional evolution level, a clear service trade-off exists within the East Lake wetland. The continuous rise in the value of cultural services such as leisure and entertainment has objectively squeezed basic ecological functions such as local air purification and climate regulation to a certain extent, increasing the long-term maintenance costs of water environment management and natural habitat restoration. At the spatial pattern level, wetlands in Wuhan exhibit a clear regional division of labor. Core wetlands, represented by East Lake, mainly provide cultural services and obtain direct socio-economic benefits; while peripheral wetlands such as Dugong Lake and Canglong Island mainly undertake regulatory and support functions such as flood control and water purification, bearing the main pressure of maintaining the regional ecological base security. This internal functional substitution and external spatial division of labor leads to an imbalance between ecological protection costs and economic benefits. Therefore, it is necessary to break through the limitations of local management and establish a cross-functional and cross-regional ecological compensation transfer payment mechanism to balance the development and protection relationship of different wetlands within the region through economic regulation.

The collection of ecological compensation funds needs to rely on the quantitative assessment results of specific service functions. This study calculates the funding scale of two market-based compensation pathways-carbon trading and tourism-driven revenue generation-based on the regulatory and cultural service characteristics of Donghu Wetland.

Regarding carbon sequestration trading pathways, based on the material calculation results of carbon sequestration and oxygen release value mentioned earlier, the average annual carbon sequestration of East Lake Wetland is approximately 95,000 tons of $CO2_e$ (carbon dioxide equivalent). Referring to the average price of approximately RMB 45/ton at the Hubei Carbon Emission Trading Center in recent years, the potential annual tradable value of the wetland's carbon sequestration is approximately RMB 4.28 million. Incorporating urban wetland carbon sequestration development into local certified emission reductions (CCERs) or regional carbon market trading systems can directly realize the transformation of regulatory services into economic value, providing a basic source of funding for the daily management and maintenance of wetlands. Regarding tourism-driven development pathways, to address the environmental pressure on water quality and microclimate caused by recreational activities in the core area, a funding extraction mechanism based on the "user-pays" principle needs to be established. Based on the total tourism revenue of East Lake Scenic Area in recent years, if 1% is dynamically extracted and a special ecological protection fund is established, the average annual fundraising scale would be approximately RMB 75.9 million. This portion of the funds needs to be specifically used to compensate for the decline in water environment carrying capacity and degradation of regulatory functions caused by high-intensity cultural and tourism development. By adopting a dynamic extraction ratio linked to total tourism revenue, the compensation amount fluctuates in sync with the regional economic cycle, thereby reducing management costs while ensuring the stability and resilience of the mechanism in the face of sudden public events or economic fluctuations.

4.2 Framework for Diversified Funding Coordination and Cross-Regional Compensation Distribution

A sound ecological compensation mechanism requires a diversified funding source and a scientific allocation system. Taking into account the public nature and market potential of wetland ecosystems, the overall compensation fund framework for urban wetlands should consist of four parts: carbon trading revenue, tourism subsidies, government basic subsidies, and social financing. Among these, carbon trading revenue and tourism subsidies, as market-based incremental funds, establish concrete pathways for "user payment" and "monetization of ecological products," effectively reducing the reliance on single public finances for wetland ecological protection and forming a comprehensive compensation fund pool through multi-party collaboration.

In the funding allocation phase, to address the imbalance between development and protection caused by the functional division of wetland areas within Wuhan, a cross-regional transfer payment system under municipal coordination, whereby the "core area supports the peripheral area," needs to be established. Core wetlands such as East Lake have generated significant economic benefits through intensive cultural services. The tourism support fund and a portion of carbon trading revenue extracted proportionally from these areas, after deducting their own water environment management and natural habitat restoration, should have their remaining balance included in the municipal wetland protection coordination fund [15]. This portion of the coordination fund should be specifically transferred to peripheral regulating wetlands such as Dugong Lake and Canglong Island, primarily to compensate for the direct management costs and opportunity costs incurred by these areas in fulfilling their basic ecological functions such as regional flood control and water purification. This cross-regional funding allocation mechanism breaks the limitations of static compensation based on administrative boundaries and individual lakes, transforming the economic benefits of the core area into ecological compensation for the peripheral area, thereby achieving collaborative governance and regional equity within Wuhan's lake and wetland ecological network.

5. CONCLUSION

Based on long-term data from 2010 to 2024, this study assessed the evolution and trade-off relationships of ecosystem service value in East Lake, Wuhan, and constructed a cross-regional ecological compensation mechanism. The main conclusions are as follows: (1) During the study period, the total value of ecosystem services in East Lake showed non-linear growth, and the value structure tended to be polarized. Cultural services such as leisure and entertainment experienced explosive growth and became absolutely dominant, while basic natural functions such as climate regulation were relatively weakened. The value reconstruction of over-reliance on single cultural services increased the vulnerability of the wetland system to external socio-economic fluctuations. (2) There are significant synergies and trade-offs among various services. Water purification, carbon sequestration and oxygen release, and other regulatory services showed extremely significant synergies with cultural services, while freshwater product supply showed extremely significant trade-offs with most services due to regional ecological restoration. High-intensity cultural tourism development put a reverse squeeze on local air purification and scientific research and education. At the city scale, Wuhan's lakes and wetlands present a spatial division of labor pattern of "core area dominating cultural services and peripheral area undertaking ecological regulation". (3) In response to the spatial mismatch between protection costs and economic benefits, a market-oriented and cross-regional collaborative ecological compensation mechanism was designed. The fundraising scale based on carbon sink CCER trading (approximately RMB 4.28 million/year) and the dynamic extraction of ecological protection fund at 1% of total tourism revenue (approximately RMB 75.9 million/year) was calculated; a fund transfer payment framework of "core area supporting peripheral pure ecological wetlands" under the overall planning of the city was established, providing a quantitative policy tool for regional collaborative governance.

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