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Dual-scale Spatiotemporal Correlation Analysis of Ecosystem Service Value and Land Use Carbon Emissions in the Yangtze River Basin

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Abstract: The spatiotemporal correlation between ecosystem service value (ESV) and land use carbon emissions is of great significance for coordinating regional ecological protection with socio-economic development and promoting the implementation of the "dual carbon" goals. Taking the Yangtze River Basin as the case study area, based on multi-source data from 2002 to 2022, this study employs the equivalent factor method, carbon emission coefficient method, and bivariate spatial autocorrelation analysis. From both grid (20 km) and county-level scales, we systematically analyze the spatiotemporal evolution characteristics and spatial correlation patterns of ESV and land use carbon emissions in the Yangtze River Basin. The results show that: (1) During the study period, the ESV of the Yangtze River Basin remained stable with a slight increase, exhibiting a spatial distribution pattern of "high in the west and low in the east, high in mountainous areas and low in plains"; forestland was the primary contributor to ESV, with its contribution rate increasing from 65.17% to 68.22%, while the negative impact of construction land continued to intensify. (2) The total land use carbon emissions increased from 261 million tons to 738 million tons, with construction land as the dominant carbon source and forestland as the largest carbon sink; high carbon emission areas were concentrated in the Yangtze River Delta in the lower reaches, urban agglomerations in the middle reaches, and the Chengdu-Chongqing region, while high carbon sink areas were located in the upstream mountainous regions and mid-reach forest areas, showing a significant pattern of "carbon sources in the east and carbon sinks in the west". (3) The bivariate spatial autocorrelation analysis reveals a significant negative correlation between ESV and land use carbon emissions, and the degree of negative correlation continuously strengthened during the study period; the negative correlation at the county scale was significantly stronger than that at the grid scale; the Low-High concentration areas were stably distributed in the upstream ecological functional areas, while the High-Low concentration areas were concentrated in the downstream urban agglomerations and agricultural core areas, reflecting the high spatial separation between ecological service supply areas and carbon emission hotspots.

Keywords: Yangtze River Basin; Ecosystem Service Value; Land Use Carbon Emissions; Dual-Scale Analysis; Spatiotemporal Evolution

1. Introduction

Ecosystem service value (ESV) is a core indicator for monetizing the provisioning, regulating, supporting, and cultural services that ecosystems provide to human society. It can directly reflect the capacity of ecosystems to support human well-being and regional sustainable development. Conducting ESV research can not only reveal the importance and spatial differences of ecosystems but also provide a scientific basis for ecological protection and restoration, territorial spatial planning, and ecological compensation mechanism formulation. This has important theoretical and practical significance for coordinating ecological protection with socio-economic development and promoting green and low-carbon transformation. Climate, as a basic condition for human survival and development, is also an important support for sustainable economic and social development [1].

In this context, scholars at home and abroad have explored the impacts of land use carbon emissions and ESV from multiple scales such as national [2], provincial administrative regions [3-4], and cities [5-6]. In terms of carbon emissions, researchers mostly use methods such as the carbon emission coefficient method [7], model simulation method [8] to calculate regional total carbon emissions, and then examine topics such as spatiotemporal evolution patterns, influencing factor analysis, and future change trends. In terms of ESV, the equivalent factor method and model evaluation method are commonly used accounting methods. Related research focuses on the spatiotemporal dynamic characteristics of ESV, multi-scenario simulation and prediction [9] and the exploration of relationships with different driving factors [10]. In the research on spatiotemporal relationships between carbon emissions and ESV, bivariate spatial autocorrelation analysis [11] is a widely used method. Some studies introduce geographically weighted regression models [12] to explore the local heterogeneity of spatial correlations between carbon emissions and ESV and their driving factors. Some scholars also combine coupling coordination degree models [13] to analyze the evolution of coordinated development levels of the two systems from a temporal perspective. Overall, existing methods focus on statistical description and pattern identification of the spatial relationships between the two variables, and the quantitative characterization of their interaction intensity, direction, and scale effects remains insufficient. The above achievements have laid an important foundation for understanding the spatial coupling relationship between carbon emissions and ESV. However, existing research is mostly concentrated at the provincial, urban agglomeration, or small-to-medium basin scales. For large river basin systems like the Yangtze River Basin that span multiple provinces and cover three terrain ladders, there is still a significant lack of comparative analysis using both grid and county-level dual scales.

In recent years, China has attached great importance to ecological protection and restoration in the Yangtze River Basin, taking "jointly focusing on major protection and avoiding major development" as the core strategic direction, and the ecological environment quality of the basin has been gradually improved. In this context, exploring the intrinsic relationship between ESV and land use carbon emissions in the Yangtze River Basin can provide scientific reference for the precise implementation of carbon peak and carbon neutrality goals in the Yangtze River Basin, as well as for green and low-carbon transformation of industrial structure and optimization of high-quality regional economic development paths. It has important practical significance for various regions in the basin to respond to the national "dual carbon" policy, deepen ecological civilization construction, and promote green development models of harmonious coexistence between humans and nature. This study takes the Yangtze River Basin as the case area, attempting to analyze the spatiotemporal evolution characteristics and spatial correlation patterns of land use carbon emissions and ESV from both grid and county-level scales, with a view to providing scientific reference for synergistic governance of carbon reduction and ecological protection at the basin level.

2. Study Area and Data Sources

2.1 Study Area Overview

The Yangtze River Basin spans eastern, central, and western China, with geographical coordinates roughly between 24°30′N to 35°45′N latitude and 90°33′E to 122°25′E longitude (Fig. 1). It flows through 11 provinces (autonomous regions and municipalities): Qinghai, Tibet, Sichuan, Yunnan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, and Shanghai. It is one of the regions with the largest basin area, largest population, and most active economy in China. The terrain of the basin is high in the west and low in the east, showing a three-tier ladder distribution: the upper reaches are plateau and alpine canyon areas, the middle reaches are hilly and plain interleaving areas, and the lower reaches are alluvial plains and estuarine deltas. The basin extends about 3,000 km from east to west and about 1,000 km in width from north to south, with a total area of approximately 1.8 million square km, accounting for 18.8% of China's land area. The main stream of the Yangtze River runs through the entire basin from west to east, with numerous tributaries forming a huge water system network. It is an important transportation and economic link connecting southwestern, central, and eastern China.

2.2 Data Sources

The land use dataset used in this study is the

CLCD (Annual China Land Cover Dataset), obtained from the National Scientific Data Center for Cryosphere, Permafrost and Desert (https://www.ncdc.ac.cn). Natural environmental data such as net primary productivity, soil erosion, and precipitation were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn). Data on three major crops (wheat, rice, and corn) from 2002 to 2022 were sourced from the "Compilation of Cost and Benefit Data of Agricultural Products in China".

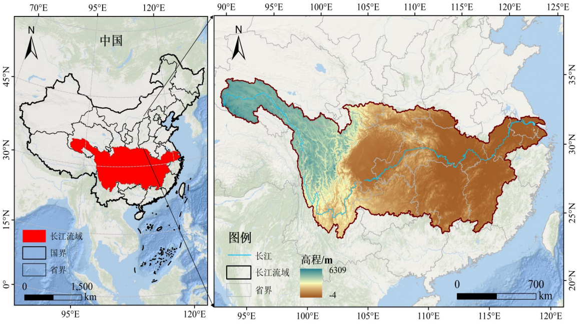

Figure 1. Schematic Diagram of the Yangtze River Basin

3. Research Methods

3.1 Ecosystem Service Value Calculation

The equivalent factor method based on unit area value covers direct and indirect ecological values and provides comprehensive statistics on ecosystem service functions. The equivalent factor method for calculating ESV is suitable for regional and large-scale areas. Therefore, this paper takes the Chinese ecosystem service value unit area equivalent factor table proposed by Xie Gaodi et al. [14-15] as the research foundation, with 1/7 of the average grain market value representing the economic value of one ecosystem service value equivalent factor. Comprehensively considering the actual conditions of the Yangtze River Basin ecosystem, this study selected three major crops (rice, wheat, and corn) and used their sowing area, unit yield, and grain price as basic data to calculate the economic value of grain production in the Yangtze River Basin from 2002 to 2022 as 1,634.30 yuan/hm², and further calculated the ecosystem service value coefficients for the Yangtze River Basin.

Table 1. Ecosystem Service Value Coefficient per Unit Area in the Yangtze River Basin (Unit: Yuan/hm²)

Primary Classification	Secondary Classification	Cultivated Land	Forestland	Grassland	Water Area	Construction Land	Unused Land
Provisioning Services	Food Production	2096.89	472.27	434.49	831.20	18.89	9.45
	Raw Material Production	472.27	1095.67	642.29	453.38	0.00	28.34
	Water Resource Supply	-2474.71	566.73	358.93	8217.54	-14187.06	18.89
Regulating Services	Gas Regulation	1681.29	3608.16	2285.80	1794.64	-4571.60	122.79
	Climate Regulation	887.87	10786.70	6026.20	4042.65	0.00	94.45
	Environmental Purification	264.47	3154.78	1983.54	5856.18	-4647.16	387.26
	Hydrological Regulation	2833.63	7065.20	4420.47	84121.16	0.00	226.69
Supporting Services	Soil Retention	395.68	1765.36	1118.57	821.81	15.22	57.07
	Nutrient Cycling	261.49	294.17	179.77	130.74	0.00	8.17
	Biodiversity	277.83	3464.72	2189.96	5687.37	555.66	114.40
Cultural Services	Aesthetic Landscape	162.12	1884.68	1195.66	4539.44	20.27	60.80

Since the proportion of dryland and paddy fields in the Yangtze River Basin is similar, the equivalent factor for cultivated land uses the average of dryland and paddy fields; forestland uses the average of coniferous forest, coniferous-broadleaf mixed forest, broadleaf forest, and shrubland; grassland uses the average of grassland, shrub-grass, and meadow; water areas use the average of wetlands, water systems, and glacial snow; construction land mainly consists of urban and various construction land, with dense population and negative impacts on ecosystem services, with its value equivalent determined based on existing research [16]; unused land uses the average of desert and unused land.

To suit the actual conditions of the Yangtze River Basin, four indicators (net primary productivity, precipitation, soil erosion, and transportation convenience) are introduced for spatial correction of the equivalent factor table. Among them, net primary productivity has a direct impact on food production, raw material production, gas regulation, climate regulation, and environmental purification; precipitation has a significant correlation with water resource supply functions; soil erosion degree is closely related to soil retention functions; transportation convenience is directly related to aesthetic landscape functions [17].

$$ESV = E_a \times \sum_{k=1}^{n} \sum_{f=1}^{n} \left(V_{kf}^{a} \times A_k \right) \quad (1)$$

Where ESV is the ecosystem service value of the study area (yuan); Ea is the economic value provided by the ecosystem (yuan/hm^2); Ak is the land type area (hm^2); Vaf is the corrected equivalent factor of land type f (yuan/hm^2). The final ecosystem service value coefficients for the Yangtze River Basin are shown in **Table 1**.

3.2 Land Use Carbon Emission Calculation

Referring to relevant research [18], this paper uses carbon emission coefficients to calculate carbon emissions from forestland, grassland, water areas, unused land, and cultivated land. The calculation formula is as follows:

$$E_d = \sum e_i = \sum \delta_i \times S_i \qquad (2)$$

Where Ed represents carbon emissions (tons); ei represents carbon emissions from land use type i (tons); Si represents the area of land use type i (hectares); δi represents the carbon emission coefficient of land use type i. The carbon emission coefficients for cultivated land, forestland, grassland, water areas, and unused land are shown in Table 2.

Table 2. Carbon Emission Coefficients

Land Use Type	Forestland	Grassland	Cultivated Land	Water Area
Carbon Emission Coefficient (t/hm^2)	-0.644	-0.022	0.422	-0.253

Carbon emissions from construction land cannot be directly calculated using carbon emission coefficients and need to be indirectly estimated through energy consumption and related socio-economic data. Nine types of energy consumption were selected: raw coal, coke, kerosene, crude oil, diesel, gasoline, fuel oil, natural gas, and electricity. Combined with standard coal conversion coefficients and carbon emission coefficients, construction land carbon emissions were estimated. Due to the large area of the Yangtze River Basin, some county-level data could not be obtained, so the ratio of county GDP to provincial GDP was used to indirectly estimate energy consumption for each county. Based on statistical data, the CO_2 emissions from energy consumption were calculated using the "Carbon Emission Calculation Guide" published by IPCC. The calculation formula is as follows:

$$Ce = (44/12) \times \sum_{k=1}^{n} K_i E_i \qquad (3)$$

Where Ce represents the statistical value of carbon sources for construction land; i is the energy type; Ki is the carbon emission coefficient of energy i (in carbon/standard coal); Ei is the consumption of energy i, calculated in standard coal. The standard coal conversion coefficients and carbon emission coefficients for various energy sources are shown in Table 3.

Table 3. Carbon Emission Coefficients of Various Energy Sources

Energy Type	Standard Coal Conversion Coefficient	Carbon Emission Coefficient
Raw Coal	0.714	0.756
Coke	0.971	0.855
Kerosene	1.471	0.571
Crude Oil	1.425	0.586
Diesel	1.457	0.592
Gasoline	1.471	0.554
Fuel Oil	1.429	0.619
Natural Gas	1.214	0.448
Electricity	0.404	0.794

3.3 Bivariate Spatial Autocorrelation Analysis

Bivariate spatial autocorrelation is used to analyze whether the values of two variables in space exhibit clustering characteristics, thereby determining whether there is spatial correlation between the two variables and the degree of correlation. Based on GeoDa software, the bivariate spatial autocorrelation model is employed, comprehensively using the global bivariate Moran's I, local bivariate Moran's I, and bivariate LISA maps to visually analyze local spatial correlations, so as to explore the spatial correlation characteristics between land use carbon emissions and ecosystem service value (ESV) in the Yangtze River Basin. The model calculation formulas are as follows:

$$I = \left[\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})\right] / \left[S^2 \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}\right] \qquad (4)$$

$$I_i = \left[(x_i - \bar{x}) \sum_{j=1}^{n} W_{ij}(x_j - \bar{x})\right] / S^2 \qquad (5)$$

Where I and Ii represent the global and local bivariate Moran's I, respectively; n is the number of counties/districts or grid cells in the study area; Wij is the n × n spatial weight matrix; xi and xj refer to the attribute values of the i-th and j-th counties or grid cells, respectively; $\bar{x}$ and S^2 are the mean and variance of the attribute values, respectively.

4. Results and Analysis

4.1 Spatiotemporal Evolution Analysis of Ecosystem Service Value

Based on the 20 km × 20 km grid data and county-level ESV intensity in the study area from 2002 to 2022, this paper uses the natural breakpoint classification method to classify the study area into five categories: low, relatively low, medium, relatively high, and high ecosystem service value over the 20-year period. The numerical value is positively correlated with the level of ecosystem service value. The specific results are shown in Fig. 2 and Fig. 3. Land use patterns are the core carrier of ecosystem service value changes. By aggregating and calculating the ESV and proportions of various land use types from 2002 to 2022, the results are shown in Table 4.

From 2002 to 2022, the ESV contribution of various land use types in the Yangtze River Basin showed temporal characteristics of forestland dominance, cultivated land contraction, and expanding negative contribution from construction land. Forestland is the main body of basin ESV, with its value contribution continuously increasing. From the overall spatial pattern, high and relatively high value areas of ecosystem service value in the Yangtze River Basin are distributed in a contiguous, strip-like pattern in the western, southern, and eastern peripheral mountainous areas of the basin, while low and relatively low value areas are concentrated in the plains, basins, and densely urbanized areas in the hinterland of the basin. High value areas are mainly distributed in the eastern edge of the Qinghai-Tibet Plateau, Hengduan Mountains, Min Mountains, Qionglai Mountains, Wuling Mountains, southern Anhui mountains, and western Zhejiang hilly areas. These areas are dominated by natural ecosystems such as forestland, grassland, and wetlands, with outstanding service functions such as water conservation, soil retention, biodiversity maintenance, and carbon fixation. They are important ecological barriers and ecological service supply areas in the Yangtze River Basin. In contrast, the Sichuan Basin, Jianghan Plain, Dongting Lake Plain, Poyang Lake Plain, and Yangtze River Delta have concentrated cultivated land, dense urbanization, and high-intensity human activities, resulting in generally low ecosystem service value. These areas become low-value zones for ecological service value in the Yangtze River Basin.

From a regional perspective, the upper reaches of the Yangtze River are the core support area for the ecosystem service value of the entire basin. High ESV values are contiguously distributed in the Jinsha River Basin, the northwest Sichuan Plateau, and the northern Yunnan-Guizhou Plateau, with complete ecosystem structure, weak human disturbance, and high ecological service function value. The interior of the Sichuan Basin has high urbanization and agricultural intensification, forming a clear low-value closed area, contrasting sharply with the surrounding high-value mountainous areas, showing a "basin low-value effect." The middle reaches have the most significant spatial differentiation in ecosystem service value. Low-value areas are concentrated in the Jianghan Plain and the two-hubei plains (traditional farming areas), while relatively high-value areas are located in mountainous and hilly areas such as Wuling Mountains and Dabie Mountains, forming a circular distribution pattern of "low in plains and high in mountains." Large lake wetlands such as Dongting Lake and Poyang Lake form point-like high-value patches within low-value areas due to their functions in flood regulation, water purification, and habitat provision, becoming key nodes of ecosystem services in the middle reaches. The lower reaches show highly differentiated characteristics of ecosystem service value. The hilly mountainous areas in southern Anhui and western Zhejiang maintain relatively high levels, while the Yangtze River Delta urban agglomeration on the plain has become one of the lowest areas of ecological service value in the entire basin due to construction land expansion; the coastal wetlands at the Yangtze River estuary form local high-value areas against a low-value background due to their unique ecological functions, playing an irreplaceable role in maintaining basin ecological security.

From the perspective of scale effects, the analysis results at grid scale and county scale are both consistent and significantly complementary. Grid-scale data can break through administrative boundary restrictions, finely depicting the continuous changes in ecosystem service value, accurately identifying value fluctuations in sensitive areas such as urban-rural fringes, mountain-plain transition zones, and river-lake system surroundings. This more aligns with the spatial continuity characteristics of ecological processes. County scale uses administrative units as statistical units, directly reflecting differences in ecosystem service supply capacity among different counties, providing direct basis for regional ecological compensation, main function zoning, and territorial spatial control. The dual-scale results jointly indicate that the spatial differentiation of ecosystem service value in the Yangtze River Basin is mainly driven by four factors: terrain and landform, land use structure, human activity intensity, and ecological protection policies. Terrain controls the value base pattern by determining the distribution of natural ecosystems, land use structure is the direct cause of value differentiation, and human activity intensity has a significant inhibitory effect on ecosystem services.

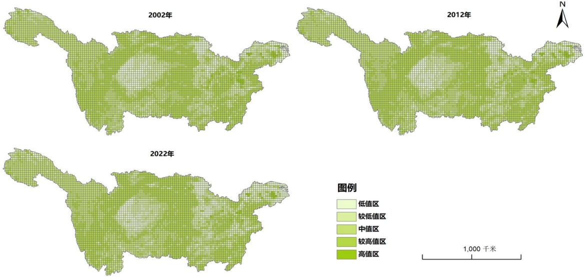

Figure 2. Spatial Distribution Map of ESV at Grid Scale in the Yangtze River Basin

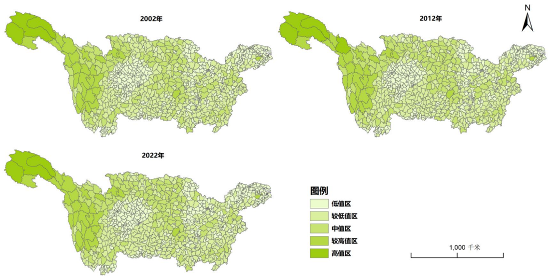

Figure 3. Spatial Distribution Map of ESV at County Scale in the Yangtze River Basin

Table 4. ESV and Its Proportion of Different Land Use Types

Land Use Type	Cultivated Land	Forestland	Grassland	Water Area	Construction Land	Unused Land
2002 Value (10^8 yuan)	3706.05	28371.77	7253.96	4703.63	-517.34	19.15
Proportion (%)	8.51%	65.17%	16.66%	10.80%	-1.19%	0.04%
2007 Value (10^8 yuan)	3671.95	28534.42	7105.02	4731.56	-636.36	21.29
Proportion (%)	8.46%	65.71%	16.36%	10.90%	-1.47%	0.05%
2012 Value (10^8 yuan)	3614.96	28674.44	7038.53	4833.42	-786.50	21.23
Proportion (%)	8.33%	66.08%	16.22%	11.14%	-1.81%	0.05%
2017 Value (10^8 yuan)	3559.79	28724.03	7008.36	4872.63	-942.73	22.19
Proportion (%)	8.23%	66.42%	16.21%	11.27%	-2.18%	0.05%
2022 Value (10^8 yuan)	3509.16	29166.33	6844.21	4270.20	-1063.10	24.67
Proportion (%)	8.21%	68.22%	16.01%	9.99%	-2.49%	0.06%

4.2 Spatiotemporal Evolution Analysis of Land Use Carbon Emissions

The spatial distribution of land use carbon emissions in the Yangtze River Basin is shown in Fig. 4 and Fig. 5, which highly matches the basin's geographical pattern, socio-economic development level, and ecological protection layout, showing spatial characteristics of "high in the east and low in the west." Moreover, the spatial differentiation of land use types further intensifies regional differences in land use carbon emissions.

Carbon emissions from different land use types from 2002 to 2022 are shown in Table 5. The Yangtze River Basin shows an overall trend of continuous expansion of carbon sources, a slight increase in carbon sinks, and rapid growth in net carbon emissions. The basin is dominated by carbon sources, and the degree of carbon emission imbalance continues to intensify. At the grid scale, land use carbon emissions in the Yangtze River Basin show spatial characteristics of continuous gradient changes, patchy agglomeration, and differentiation along geographical boundaries. The boundaries between high and low land use carbon emission grids are clear, highly matching the terrain, landform, and land use patterns. The Yangtze River Delta urban agglomeration forms the largest contiguous high carbon source area in the basin, with grid land use carbon emission values ranking first in the basin, high proportion of construction land, and large industrial and transportation energy consumption. The Chengdu-Chongqing urban agglomeration (Chengdu, Chongqing main city and surrounding city grids) is the largest carbon source agglomeration area in the upper reaches, with basin terrain and industrial concentration leading to carbon emission agglomeration. The middle reaches urban agglomeration (Wuhan, Changsha, Nanchang core urban area grids) forms a central carbon source high-value patch. The three major urban agglomerations form a carbon source corridor along the main stream of the Yangtze River, running through the middle and lower reaches. These grids are dominated by construction land and cultivated land, with high-intensity human activities, and land use carbon emissions are mainly positive, generally higher than the basin average.

At the county scale, land use carbon emissions in the Yangtze River Basin are dominated by the economic structure of administrative units, land development intensity, and ecological function positioning, with more concentrated spatial differentiation and clearer boundaries. County areas dominated by carbon sinks are concentrated in the upper and middle mountainous areas: in the upper reaches, counties such as Ganzi, Aba, and Liangshan in Sichuan, Diqing and Nujiang in Yunnan, and Chengkou and Wuxi in Chongqing have forestland coverage generally exceeding 65%, construction land proportion below 3%, small industrial and urban scale, and land use carbon emissions are negative throughout the year, making them stable carbon sink supply areas in the basin. In the middle reaches, counties such as Enshi in Hubei, Ganzhou in Jiangxi, and Huangshan in Anhui are dominated by mountain forest ecosystems, with outstanding ecological protection functions and strong carbon sink capacity, with land use carbon emissions mainly negative. Many of these counties are key ecological functional areas and core carriers of ecological security and carbon sink guarantee in the Yangtze River Basin.

Overall, county-scale land use carbon emissions clearly present characteristics of "low carbon and high sink in ecological counties, high carbon and low sink in economic counties, stable carbon source in agricultural counties, and peak carbon source in urban clusters." The spatial imbalance of land use carbon emissions between upper and lower reaches and between urban and rural areas is significant, providing a clear spatial basis for differentiated carbon control and cross-regional ecological compensation.

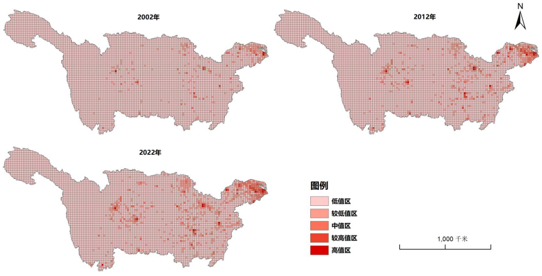

Figure 4. Spatial Distribution Map of Carbon Emissions at Grid Scale in the Yangtze River Basin

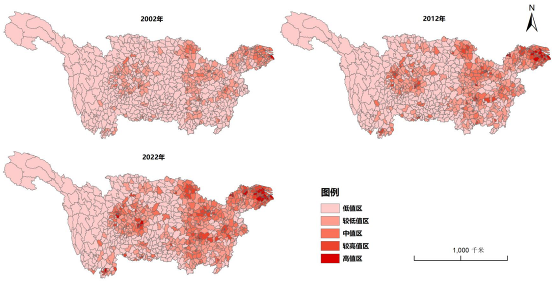

Figure 5. Spatial Distribution Map of Carbon Emissions at County Scale in the Yangtze River Basin

Table 5. Carbon Budget of Different Land Use Types (10^4 t)

Year	2002	2007	2012	2017	2022
Cultivated Land	2280.15	2259.17	2224.11	2190.16	2159.01
Forestland	-5349.09	-5379.75	-5406.15	-5415.50	-5498.89
Grassland	-73.11	-71.61	-70.94	-70.64	-68.98
Water Area	-102.15	-102.76	-104.97	-105.82	-92.74
Construction Land	23779.62	41960.99	60993.71	62323.79	71687.32
Unused Land	-0.85	-0.94	-0.94	-0.98	-1.09
Carbon Source	26059.77	44220.16	63217.82	64513.95	73846.33
Carbon Sink	-5525.20	-5555.06	-5583.00	-5592.94	-5661.70

4.3 Analysis of ESV and Land Use Carbon Emissions Correlation

Bivariate spatial correlation analysis of land use carbon emissions and ecosystem service value in the Yangtze River Basin was conducted, with results shown in Table 6, Table 7, Fig. 6, and Fig. 7. From 2002 to 2022, the bivariate Moran's I values of ecosystem service value and land use carbon emissions at both grid and county scales in the Yangtze River Basin were negative and showed an overall continuous decline. At the grid scale, Moran's I decreased from -0.0900 to -0.1559, while at the county scale, it showed a trend of "slight rise followed by steep decline," reaching -0.2382 in 2022. This indicates that there is a significant spatial negative correlation between the two, and this negative agglomeration characteristic is continuously intensifying. The degree of negative correlation at the county administrative scale is much higher than that at the grid scale. The spatial coupling of the two is not randomly distributed but shows obvious regular heterogeneity characteristics.

Table 6. Global Moran's I Statistics at Grid Scale

Year	Moran's I	P-value	Z-value
2002	-0.0900	<0.001	11.6423
2012	-0.1435	<0.001	18.5227
2022	-0.1559	<0.001	20.1152

Table 7. Global Moran's I Statistics at County Scale

Year	Moran's I	P-value	Z-value
2002	-0.2156	<0.001	12.5432
2012	-0.2234	<0.001	12.8956
2022	-0.2382	<0.001	13.7854

The local spatial correlation between the two is mainly characterized by Low-High and High-Low agglomeration, while High-High and Low-Low agglomeration are only sporadically distributed. The pattern highly matches the basin's natural conditions and human development activities. Low-High agglomeration areas are concentrated in mountainous forest areas such as western Sichuan and northern Yunnan in the upper reaches of the Yangtze River, where forests and grasslands are widely distributed, natural conditions are superior, and service values are high. At the same time, terrain barriers limit high-intensity development, stabilizing this agglomeration pattern of high ecological services and low carbon emissions. High-Low agglomeration areas focus on the middle-lower Yangtze plains and Yangtze River Delta urban agglomeration in the lower reaches, where the degree of urbanization and industrialization is high. Industrial development and energy consumption increase land use carbon emissions, while the continuous expansion of construction land compresses natural ecological space, directly leading to relatively low ecosystem service value, forming typical characteristics of low ecological services and high carbon emission agglomeration.

High-High agglomeration areas are sporadically distributed in wetlands along the Yangtze River main and tributary streams and areas with coordinated ecological and economic development. Relying on the carbon fixation and service functions of aquatic ecosystems, these areas achieve coexistence of high ecosystem service value and high land use carbon emissions. However, the two are in a fragile equilibrium state, facing dual challenges of ecological protection and carbon reduction. Low-Low agglomeration areas appear in small numbers in the ecologically fragile transition zones of the middle and upper reaches of the basin. These areas have low-intensity human activities and low land use carbon emissions. However, due to scarce biodiversity and single ecosystem structure, ecosystem service value is also relatively low, falling into a dual-low situation of ecology and carbon sinks. The continuous decline of the bivariate Moran's I also reflects the intensifying contradiction between protection and development in the upper and lower reaches of the basin. The increasingly intensified negative correlation between ecosystem service value and land use carbon emissions also highlights that the coordinated development of ecological protection and economic growth in the basin urgently needs solutions.

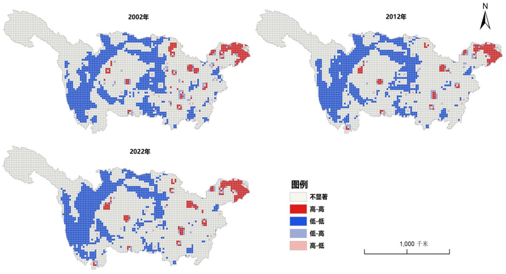

Figure 6. LISA Cluster Map of Carbon Emissions at Grid Scale in the Yangtze River Basin

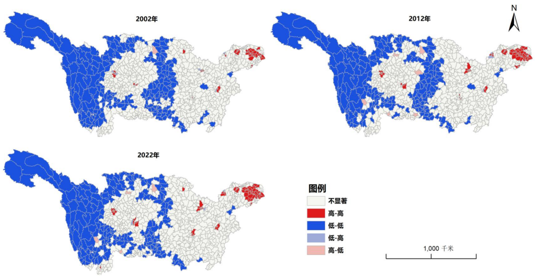

Figure 7. LISA Cluster Map of Carbon Emissions at County Scale in the Yangtze River Basin

5. Discussion and Conclusion

5.1 Discussion

Based on the spatiotemporal relationship evolution characteristics of land use carbon emissions and ESV in the Yangtze River Basin from 2002 to 2022, the discussion is as follows:

The spatial patterns of ESV and land use carbon emissions in the Yangtze River Basin show an obvious inverse symmetrical relationship, which can be explained by natural conditions and land use structure. In the upper mountainous reaches, altitude is high and terrain is undulating, with land use mainly consisting of forestland and grassland, and ecosystems experience less human disturbance. Therefore, they simultaneously exhibit characteristics of high ESV and low carbon emissions. In the middle-lower plains and basins, terrain is flat and hydrothermal conditions are favorable, with concentrated cultivated land and dense urbanization, high proportion of construction land, low ESV, and high carbon emissions. Table 1 further supports this judgment from the perspective of land type composition: forestland, with an absolute advantage in area share, simultaneously contributes 65%-68% of total

ESV and over 95% of total carbon sink. Construction land, with a relatively small area proportion, drives the main body of carbon source growth and continuously generates negative contributions to ESV. It can be seen that land use structure is a common link connecting changes in ESV and land use carbon emissions.

From 2002 to 2022, the bivariate Moran's I of ESV and land use carbon emissions in the Yangtze River Basin was negative at both grid and county scales and continuously declined, indicating that the spatial negative correlation between the two continuously intensified during the study period. From the perspective of spatial pattern stability, the upper mountainous areas are constrained by both terrain conditions and ecological protection policies, making it difficult for large-scale development activities to proceed. The pattern of high ESV and low carbon emissions has been maintained for a long time. The lower plains and urban agglomerations have high economic density and long development history, and the state of high carbon emissions and low ESV also has strong continuity. From the perspective of change process, construction land expansion is a direct factor promoting the deepening of negative correlation. The increase in construction land not only raises carbon emissions from energy consumption but also directly weakens the carbon sequestration capacity and service functions of ecosystems by occupying cultivated land, forestland, and wetlands. At the same time, it reduces the efficiency of surrounding ecological land through indirect approaches such as habitat fragmentation. The "Low-High" agglomeration in the LISA cluster map is stably distributed in upstream ecological functional areas, and the "High-Low" agglomeration is concentrated in downstream urban agglomerations and agricultural core areas. This further indicates that this spatial negative correlation has strong structural characteristics and is not caused by short-term fluctuations.

The negative correlation intensity between ESV and land use carbon emissions at the county scale is significantly higher than that at the grid scale, and the trend of negative strengthening is more significant. The main reason for this difference is the different ways the two spatial units handle internal heterogeneity. The grid scale can reflect continuous changes inside and outside administrative boundaries, preserving more local information. The county scale uses administrative boundaries as units for aggregation, internal land use differences are averaged, and the overall opposition relationship between ESV and land use carbon emissions is highlighted, with a more intense negative correlation signal. This finding indicates that when analyzing carbon-ecological spatial relationships, relying solely on a single scale may lead to biased judgments. Multi-scale verification helps improve the reliability of conclusions. At the same time, county units directly correspond to governance subjects, and their higher response sensitivity makes them an appropriate scale for implementing differentiated control measures and cross-regional ecological compensation.

5.2 Conclusion

(1) From 2002 to 2022, the ESV of the Yangtze River Basin remained stable with a slight increase, exhibiting a spatial distribution pattern of "high in the west and low in the east, high in mountainous areas and low in plains." High ESV areas are concentrated in the upper reaches' Hengduan Mountains, northwest Sichuan Plateau, middle reaches' Wuling Mountains, and lower reaches' southern Anhui and western Zhejiang hilly areas. Low-value areas are concentrated in the Sichuan Basin, Jianghan Plain, and Yangtze River Delta urban agglomeration. Forestland has always been the core component of ESV, with its contribution rate continuously increasing from 65.17% to 68.22%, while the negative contribution of construction land is continuously increasing, reflecting the continuous compression of ecological service functions by development intensity.

(2) During the study period, total carbon source increased from 261 million tons to 738 million tons, with construction land contributing an absolutely dominant share. Forestland is the largest carbon sink, but the increase in total carbon sink is far from sufficient to offset the growth of carbon source. The net carbon emission pressure of the basin continues to increase. Spatially, high carbon source areas are concentrated in the lower reaches' Yangtze River Delta, middle reaches' urban agglomerations, and Chengdu-Chongqing region, while high carbon sink areas are concentrated in upstream mountainous areas and mid-reach forest areas, with the "carbon sources in the east and carbon

sinks in the west" pattern strengthening.

(3) The two show significant negative spatial correlation at both grid and county scales, and the degree of negative correlation continuously strengthened during the study period, with county scale correlation stronger than grid scale. Low-High agglomeration areas are stably distributed in upstream ecological functional areas, High-Low agglomeration areas are concentrated in downstream urban agglomerations and agricultural core areas, and High-High and Low-Low agglomeration are only sporadically distributed. This reflects the practical difficulty of coordinating ecological protection and carbon reduction at the basin scale: ecological service supply areas and carbon emission hotspots are highly separated in space, and the regional transfer of ecological products and carbon emission costs has not yet been effectively compensated and regulated.

References

[1] Schaefer K, Lantuit H, Romanovsky VE, et al. The impact of the permafrost carbon feedback on global climate. Environmental Research Letters, 2014, 9(8): 085003.
[2] Zhao S, Yu Z, Liu W. Revealing the spatio-temporal coupling coordination characteristics and influencing factors of carbon emissions from urban use and ecosystem service values in China at the municipal scale. Frontiers in Ecology and Evolution, 2025, 13: 1539909.
[3] Xie XJ, Huang A. Spatiotemporal relationship between carbon emissions and ecosystem service value in Sichuan Province based on LUCC. Resources and Environment in the Yangtze Basin, 2025, 34(10): 2352-2365.
[4] Wei H, Li AJ, Yin X, et al. Spatiotemporal relationship evolution between county-level land use carbon emissions and ecosystem service value in Hebei Province. Research of Soil and Water Conservation, 2026, 33(02): 274-282.
[5] Zhao WJ, Wang CW. Interactive characteristics of land use carbon emissions and ecosystem services in Urumqi metropolitan area. Journal of Earth Science and Environment, 2025, 47(02): 260-273.
[6] Zhao XC, Tian YD, Zhang XX. Spatiotemporal relationship between land use carbon emissions and ecosystem service value in Changsha-Zhuzhou-Xiangtan urban agglomeration. Journal of Soil and Water Conservation, 2023, 37(05): 215-225.
[7] Tang WB, Liu HQ, Liu Y. Spatiotemporal differentiation and influencing factors of county-level land use carbon emissions in Wuhan urban circle. Economic Geography, 2026, 46(02): 92-102.
[8] Hou K, Huang LH, Dong H, et al. Multi-scenario prediction of energy carbon emissions in Shaanxi Province based on STIRPAT-SD coupled model. Journal of Xi'an Shiyou University (Social Science Edition), 2026: 1-17.
[9] Tong AQ, Liang JY, Li JC, et al. Multi-scenario simulation of ecosystem service value in Jining City based on PLUS. Environmental Science & Technology, 2025, 48(S2): 217-227.
[10] Liu ZH, Cai J, Wu J, et al. Spatiotemporal evolution and driving factors of ecosystem service value in Beijing-Tianjin-Hebei region. Geological Bulletin of China, 2025, 44(12): 2278-2290.
[11] Tang F, Yin YL, Zhang PT, et al. Ecosystem service value and carbon emission risk based on land use change in Gaoyang County. Research of Soil and Water Conservation, 2019, 26(04): 265-271.
[12] Shi T, Xu H. Study on ecosystem service values of urban green space systems in Suzhou City based on the extreme gradient boosting geographically weighted regression method. Land, 2025, 14(3): 564.
[13] Li A, Niu L, Zhou Y, et al. Study on coupling coordination between ecosystem service value and carbon reserve based on land use change: taking Chengdu-Chongqing economic circle as an example. International Journal of Global Energy Issues, 2024, 46(5): 522-541.
[14] Xie GD, Zhang CX, Zhang LM, et al. Improvement of ecosystem service value valuation method based on unit area value equivalent factor. Journal of Natural Resources, 2015, 30(08): 1243-1254.
[15] Zhang RJ, Yu KH, Luo PP. Spatio-temporal relationship between land use carbon emissions and ecosystem service value in Guanzhong, China. Land, 2024, 13(1): 118.
[16] Wang YY. Evaluation and prediction of ecosystem service value in Guanzhong Plain urban agglomeration based on land use. Xi'an University of Technology, 2024.
[17] Liu YL. Coupling coordination and

important influencing factors of ecosystem service value and new urbanization in the Yellow River Basin. Inner Mongolia University of Finance and Economics, 2025.

[18] Zhang Y, Dai Y, Chen Y, et al. The study on spatial correlation of recessive land use transformation and land use carbon emission. China Land Science, 2022, 36(6): 100-112.