

# Coupling Coordination and Driving Mechanisms of Land Use and Ecosystem Service Value in the Central Yunnan Urban Agglomeration

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## ABSTRACT

**Research Content:** This study focuses on the Central Yunnan Urban Agglomeration, analyzing the spatiotemporal evolution characteristics, coupling coordination relationship, and driving mechanisms of land use and ecosystem service value (ESV) from 2010 to 2024. It aims to provide a scientific basis for regional territorial spatial optimization and ecological civilization construction. **Research Methods:** Based on multi-temporal land use data, the study comprehensively employs methods including land use transfer matrix, dynamic degree and comprehensive intensity quantification, ESV equivalent factor assessment, coupling coordination degree model, trend surface model, and geographical detector. **Key findings include:** (1) The overall land use structure remained stable, with ecological land (forest, grassland, and water bodies) dominating. However, construction land continued to expand, primarily at the expense of cultivated land and a small amount of forest land, reflecting the squeezing effect of urbanization on ecological space. (2) The total ESV increased significantly, rising from 1.194 billion yuan in 2010 to 2.288 billion yuan in 2024, with regulating services contributing the most. The spatial distribution of ESV exhibited a pattern of “higher in the south and lower in the north, higher in the west and lower in the east,” with high-value areas distributed along a northeast–southwest corridor. (3) The coupling coordination degree between land use and ESV steadily improved, with most regions transitioning from “uncoordinated” to “coordinated.” However, coordination levels remained relatively low in core urbanized areas such as Kunming, revealing the ongoing tension between intensive human activities and ecological function maintenance. (4) The driving mechanisms showed dynamic evolution: early stages were dominated by natural factors such as NDVI and slope; after 2020, the explanatory power of socio-economic factors like GDP significantly increased; by 2024, a multi-factor synergistic driving pattern had formed, integrating natural constraints (e.g., slope) and human factors (economy, population). Nonlinear interactive enhancement effects were observed among factors. (5) This study reveals a regional development phenomenon in the Central Yunnan Urban Agglomeration where construction land expansion coexists with an increase in total ESV. This phenomenon partly stems from the substantial growth of ecological land (especially water bodies) and their high ESV coefficients achieved through major project interventions. However, it also warns that relying solely on expanding a single land type to boost ESV may entail long-term ecological risks. This highlights the necessity and complexity of achieving a balance between ecological benefits and socio-economic development through refined spatial management during urbanization. (6) The study systematically elucidates the evolution of regional human–land relationships from “natural background dominance” to “natural–socio-economic synergy.” It provides empirical evidence for understanding the interaction between land use and ecosystem services at the urban agglomeration scale and offers reference value for promoting regional sustainable development.

**KEYWORDS:** Land use change; Ecosystem Service Value (ESV); Coupling coordination degree model; Geodetector; Human-land system coordination mechanism; Central Yunnan Urban Agglomeration

## Introduction

Land Use and Cover Change (LUCC) is a critical field in global environmental change and sustainable development research, as well as a core issue in human-land system science. However, driven by urbanization and agricultural expansion, land use change is accelerating<sup>1</sup>. Land use activities profoundly influence the evolution of ecosystem structure, function, and the value of ecosystem services (ESV) by altering surface patterns and ecological processes. This evolution not only reflects changes in ecosystem health but also serves as a vital indicator for assessing regional ecological civilization development and the sustainable use of territorial space<sup>2,3</sup>. Against the backdrop of rapid urbanization and intensive land development, exploring the spatiotemporal coupling mechanisms between land use change and ESV has become a critical scientific issue for assessing regional sustainable development levels and ecological-economic coordination<sup>4</sup>.

Over the past two decades, scholars both domestically and internationally have conducted multidimensional research on the relationship between land use and the value of ecosystem services (ESV). Methodologically, studies have primarily focused on the quantitative analysis of land use and cover change (LUCC) patterns, often employing models such as the land use transition matrix and dynamics degree<sup>5,6</sup>. Concurrently, research has emphasized the estimation of ESV and its spatial evolution patterns, frequently utilizing the unit area value equivalent factor method proposed by Xie Gaudi's team<sup>7</sup>. In recent years, the investigation of system coupling and driving mechanisms has emerged as a prominent research focus, with comprehensive analyses often conducted using diverse models such as the coupling coordination degree model and the InVEST model<sup>8,9</sup>. However, most studies remain confined to watershed or provincial scales, offering insufficient exploration of the multidimensional coupling mechanisms and evolutionary patterns within urban agglomerations—complex human-environment systems<sup>10</sup>. Furthermore, many studies lack in-depth identification of the "dual-factor enhancement" effect between natural and socioeconomic factors, failing to systematically reveal the coupling mechanisms of natural and anthropogenic processes<sup>11</sup>. Notably, existing research on the coordinated relationship between ecosystem services and human well-being has already revealed characteristics such as uneven spatial distribution, fluctuating coupling states, and nonlinear multi-factor influences. This provides an important reference for further identifying system interaction mechanisms within a human-environment coupling framework<sup>12</sup>. Therefore, analyzing the interactive relationships and driving mechanisms between land use change and ecosystem services at the urban agglomeration scale in this paper holds significant scientific and practical importance for enriching theories of human-environment relationship coordination and refining pathways for regional sustainable development.

The Central Yunnan Urban Agglomeration is located at the strategic intersection of the Belt and Road Initiative and the Yangtze River Economic Belt. As the only national-level urban agglomeration in Southwest China, it serves as a core region for both economic and ecological systems in Yunnan Province. Over the past decade, with the advancement of strategies such as the "Central Yunnan New Area Development" and "Integration of Kunming and Chuxiong," the land use pattern has undergone significant changes, while ecosystem services have demonstrated complex spatiotemporal restructuring trends. Against the backdrop of rapid urbanization alongside ecological conservation efforts, there is an urgent need to quantitatively identify the dynamic relationship and spatial coupling mechanisms between land use change and ecosystem service value, in order to provide a scientific basis for regional territorial spatial governance and ecological civilization construction. In terms of scale, this study establishes a coupling coordination

analysis framework for land use and ecosystem services at the urban agglomeration level, extending the spatial scale and systemic boundaries of traditional LUCC-ESV research. In terms of mechanisms, it employs the geographical detector to reveal the "dual-factor enhancement" effect between natural and socio-economic factors. In terms of spatial patterns, trend surface analysis is applied to uncover a spatial differentiation pattern characterized by "higher in the south and lower in the north, higher in the west and lower in the east," reflecting imbalances in regional coordinated development. This research framework systematically elucidates the causal pathway of "land use change → ecosystem service value → coupling coordination degree → driving mechanisms." It reveals the compound driving mechanisms of natural and anthropogenic factors in the system's co-evolutionary dynamics and also provides an analytical perspective for identifying coordination pathways between ecosystem services and human well-being in similar urban agglomeration systems<sup>13,14</sup>.

## 1 Overview of the study area

The Central Yunnan Urban Agglomeration is situated between 100°43'–104°49' E and 24°58'–25°09' N, primarily located in the central part of Yunnan Province. Its scope includes the entire territories of Kunming City, Yuxi City, and Qujing City, as well as the whole of Chuxiong Yi Autonomous Prefecture. It also covers seven counties and cities in the northern part of Honghe Hani and Yi Autonomous Prefecture (Mengzi City, Gejiu City, Jianshui County, Kaiyuan City, Mile City, Luxi County, and Shiping County), as shown in the figure below (Fig.1 Study Area Location Map). With a total area of approximately 111,400 square kilometers, it accounts for about 29% of Yunnan Province's total area. The region has a permanent population of about 21.96 million, representing 46.55% of Yunnan's total population. It serves not only as the geographical center of Yunnan Province but also as a convergence point for population flows, logistics, capital flows, and information flows. Its GDP accounts for approximately 61.5% of the province's total, making it the most economically developed region in Yunnan. The Central Yunnan Urban Agglomeration features relatively flat terrain and a pleasant climate, conducive to agricultural production and human habitation. Its overall ecological environment remains well-preserved, offering a uniquely advantageous geographical location, abundant resources, and a solid foundation for development. However, intensive human activities have led to a continuous decline in ecological land such as farmland and forest land. The land use structure faces adjustment pressures, and the coordination between ecosystem service functions and urbanization development urgently requires optimization. Against this backdrop, scientifically identifying the spatiotemporal interaction mechanisms between land use and ecological value holds significant practical importance for promoting regional sustainable development.

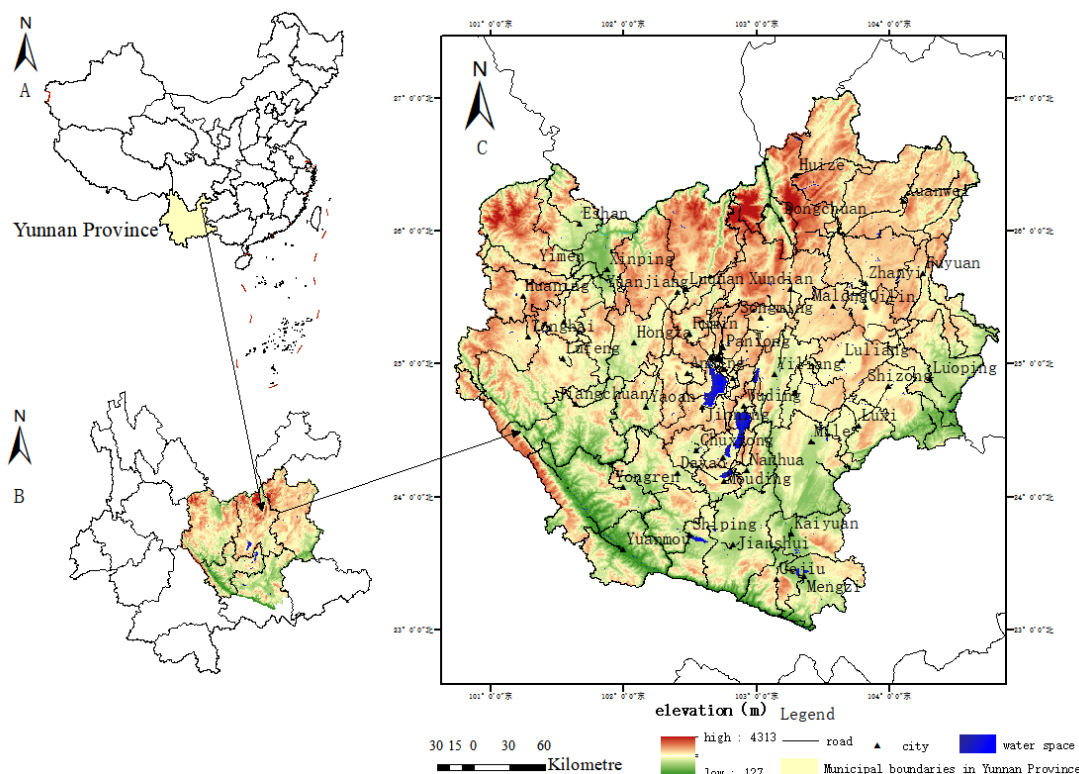


Figure 1. Study Area Location Map

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## 2 Data Sources and Research Methods

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### 2.1 Data Sources

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The data involved in this study mainly include the following three categories, as shown in Table 1. Land use data includes the current land use status of the central Yunnan urban agglomeration for the years 2010, 2015, 2020, and 2024. These data are derived from the CLCD (China Land Cover Dataset) published by Professor Huang Xin of Wuhan University. Based on 335,709 Landsat images on Google Earth Engine, Professor Huang constructed spatiotemporal features and applied a random forest classifier to obtain classification results. The overall accuracy of CLCD reaches 80%, validated through 5,463 visually interpreted samples. Since the dataset generation process already includes rigorous accuracy validation, subsequent analyses in this study are based on this foundational data product with known accuracy. Administrative boundary data are sourced from the 1:1 million National Basic Geographic Database of the National Geomatics Center of China and calibrated using the standard map service GS(2024)0650, ensuring an accurate representation of China's national boundaries and administrative regions. The data adopt the WGS 84 geographic coordinate system and are displayed in plan view using the Albers equal-area conic projection in ArcGIS software. Socioeconomic data include the sown area, yield, and price information for corn, rice, and potatoes. These data are derived from the Yunnan Statistical Yearbook and the China Agricultural Product Price Survey Yearbook. The data required for the geographical detector include elevation, slope, aspect, annual average temperature, annual precipitation, GDP, MNDWI, and NDVI. Among these, terrain and meteorological data are sourced from the National Tibetan Plateau/Third Pole Environment Data Center. GDP data are derived from the Yunnan Statistical Yearbook. MNDWI data are calculated using Sentinel-2 MSI, Landsat 8 OLI, and MODIS imagery on the Google Earth Engine platform. NDVI data are based on Landsat series satellite imagery, obtained and calculated from the Geospatial Data Cloud

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platform.

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**Table 1. Categories and Sources of Research Data**

Data type	Specific Name	Source
Land Use Data	Land Use Data for the CentralYunnan Urban Agglomeration in 2010, 2015, 2020, and 2024	Yang Jie and Huang Xin from Wuhan University, "30m Annual Land Cover and Its Dynamics in China from 1990 to 2022". (Updated to 2024)
Map Data	Administrative division boundaries	National Geomatics Center of China, 1:1 million National Basic Geographic Database; Map Approval Number: GS(2024)0650
Socioeconomic Data	Planting area, yield, and price of corn, rice, and potatoes	Yunnan Statistical Yearbook, China Agricultural Product Price Survey Yearbook
Data required for the geodetector	Elevation, slope, aspect, annual average temperature, annual average precipitation, GDP, NDVI, MNDWI data	Terrain and meteorological data are from the National Tibetan Plateau Data Center; GDP data are from the Yunnan Statistical Yearbook; NDVI is calculated based on Landsat imagery (Geospatial Data Cloud); MNDWI is calculated based on Sentinel-2/Landsat/MODIS imagery (Google Earth Engine).

## 2.2 Research Methods

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### 2.2.1 Land Use Transition Matrix

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The Markov model can determine the initial probability matrix P. The operational process of this model is as follows: Suppose there exist multiple land use types E1, E2, ..., En. Each state update can only reflect one land use condition, and each state has n possible transitions (including self-transitions E1→E2, E1→E3, ..., E1→En). The probability of transitioning from land use type Ei to Ej is Pij (1≤i,j≤n)<sup>15</sup>.

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$$P = \begin{pmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{pmatrix} \quad (1)$$

### 2.2.2 Land Use Dynamics

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Evaluation of Land Use Dynamics. Land use dynamics quantify the rate of change for a specific land use category, enabling quantitative description of regional land use transformation speeds<sup>16</sup>. This calculation method is expressed as Equation (2).

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

In Equation (2), K represents the dynamic degree result for a specific land use type during the study period; Ua and Ub denote the area of that land use type at the beginning and end of the study period, respectively, while T is the duration of the study period.

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### 2.2.3 Land use intensity

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Comprehensive Land Use Intensity Index. The land use intensity index reflects the degree of human development of land resources within a region, while the comprehensive land use intensity index reflects the level of land development and utilization<sup>17</sup>. Its calculation formula is:

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$$L_X = 100 \sum_{i=1}^n (W_i \times X_i) \quad (3)$$

In equation (3),  $W_i$  denotes the land use index for land use type  $i$ ,  $X_i$  represents the area-normalized value for land use type  $i$ , and  $n$  indicates the land use type. The  $L_X$  value reflects the intensity level of land use. For the land use index  $W_i$ , referencing to existing research., the land use index is categorized into four levels: unutilized land is assigned a value of 1, forest land, grassland, and water bodies are assigned a value of 2, cultivated land is assigned a value of 3, and construction land is assigned a value of 4. These values undergo standardization, with the sum of weights equaling 1<sup>18</sup>. Based on the aforementioned calculation method, previous literature, and the actual conditions of the study area, the classification criteria for land use intensity in the study area were established, as detailed in Table 2.

**Table 2. Land Use Intensity Classification Criteria**

Land Use Intensity Standardized Value	Grade
1.0-2.0	Low Intensity
2.0-3.0	Low-to-Moderate Intensity
3.0-5.0	Moderate Intensity
5.0-8.0	Moderate-to-High Intensity
8.0 and above	High Intensity

#### 2.2.4 Ecosystem Service Value Assessment Methodology

To scientifically assess the spatiotemporal evolution of ecosystem service value (ESV) in the Central Yunnan Urban Agglomeration and account for regional characteristics and economic development influences, this study builds upon the equivalent factor method proposed by Xie Gaodi et al. (2015) and introduces two key modifications: (1) Temporally, by accounting for the economic value of grain crops annually to dynamically adjust the value per unit equivalent factor, thereby reflecting market price fluctuations and regional agricultural development levels; and (2) Spatially, by incorporating net primary productivity (NPP) as a biomass indicator to regionally adjust the equivalent factor table, capturing differences in ecological productivity between the Central Yunnan Urban Agglomeration and the national average. The specific steps are as follows:

##### (1) Dynamic Determination of the Economic Value per Unit Equivalent Factor

To address potential issues arising from using a fixed value coefficient, such as ignoring monetary value changes and regional agricultural productivity imbalances, this study, with reference to related research<sup>19,20</sup>, calculates the economic value of grain output per unit area annually based on the annual yields of major grain crops (corn, rice, potatoes) in the study area. This value serves as the benchmark value for one standard equivalent factor. The calculation formula is as follows:

$$E = \frac{1}{7} \frac{\sum (C_i \times P_i)}{F} \quad (4)$$

In the formula:  $E$  represents the economic value per unit equivalent factor;  $C_i$  is the annual total yield of the  $i$ -th grain crop (kg);  $P_i$  is the average market price of that crop in that year (yuan/kg);  $F$  is the total sown area of grain crops. The coefficient  $1/7$  originates from the proportion of farmland natural capital's contribution to economic output

determined by Xie Gaodi's team. 173

## (2) Regional Adjustment of Ecosystem Service Equivalent Factors 174

The national average equivalent factor table by Xie Gaodi does not fully reflect regional differences in ecosystem biomass and key service capacities. This study introduces NPP as a proxy indicator for biomass to calculate a regional adjustment coefficient for spatially scaling the equivalent factors<sup>21,22</sup>. The formula is as follows: 176 177

$$\rho = \frac{D_m}{D_n} \quad (5)$$

In the formula:  $\rho$  is the regional adjustment coefficient;  $D_m$  is the average NPP value of the study area (Central Yunnan Urban Agglomeration) (kg C/m<sup>2</sup>);  $D_n$  is the average NPP value of China for the same period (kg C/m<sup>2</sup>). NPP for each period is obtained via remote sensing data inversion, and the adjustment coefficient  $\rho$  for the study area relative to the national level is calculated. Subsequently, this coefficient is applied to adjust Xie Gaodi's original equivalent factor table ( $E_{oi}$ ) to obtain the equivalent factors ( $E_i$ ) applicable to this study area: 179 180 181 182

$$E_i = \rho \times E_{oi} \quad (6)$$

## (3) Calculation of Ecosystem Service Value 183

Integrating the dynamically determined unit equivalent value ( $E$ ) and the regionally adjusted equivalent factors ( $E_{oi}$ ) described above, the total ecosystem service value and the value of each category for the study area were calculated using the following formula: 185 186

$$ESV = \sum_{h=1}^n (A_h \times \sum_{j=1}^{11} (E \times E_{hj})) \quad (7)$$

ESV is the total ecosystem service value (yuan); "h" is the ecosystem type (corresponding to land use type);  $A_h$  is the area of the "h"-th type ecosystem (hm<sup>2</sup>);  $E_{hj}$  is the regionally adjusted equivalent factor for the "j"-th service provided by the "h"-th type ecosystem. Finally, the spatially and temporally adjusted ecosystem service value coefficients per unit area for each land use type across different periods were calculated. The average annual yield of the three major grain crops in the Central Yunnan Urban Agglomeration from 2010 to 2024 was 3050 kg/hm<sup>2</sup>. Using the 2024 price level as the benchmark, the standard equivalent value for each year was adjusted using the CPI index. After averaging, the final average adjusted standard equivalent value for the study area for the period 2010-2024 was determined to be 3017.81 yuan/hm<sup>2</sup>. Using ArcMap 10.3, the average NPP for China from 2010 to 2024 was calculated as 408 g C/m<sup>2</sup>, while the average NPP for the Central Yunnan Urban Agglomeration for the same period was 870 g C/m<sup>2</sup>. This resulted in a regional adjustment coefficient ( $\rho$ ) of 2.13. In summary, based on the above, the ESV coefficients for the Central Yunnan Urban Agglomeration were derived, as presented in Table 3. 188 189 190 191 192 193 194 195 196 197

**Table 3. Unit area ecosystem service value coefficient ( yuan· hm<sup>2</sup>)**

Primary Category	Secondary Category	Arable Land	Forest Land	Grass land	Water Areas	Construction Land	Unutilized Land
Supply Services	Food Production	6669.36	3023.85	2752.24	9656.99	0.00	1539.08
	Raw Material Production	1478.73	6874.57	4055.94	2776.39	0.00	1508.91
	Water Supply	-7876.49	3536.87	2245.25	106589.07	0.00	7816.13
Regulating Services	Gas Regulation	5371.70	22591.33	14268.21	9838.06	0.00	5794.20
	Climate Regulation	2806.56	67689.49	37734.70	29272.76	0.00	10864.12
	Environmental Purification	814.81	20171.05	37734.70	67478.25	0.00	11165.90
	Hydrological Regulation	9023.25	50162.05	27667.29	1256224.03	0.00	73212.09
Support Services	Soil Conservation	3138.52	27582.79	17382.59	11226.26	0.00	7031.50
	Maintain nutrient cycling	935.52	2082.29	1303.69	844.99	0.00	543.21
	Biodiversity	1026.06	25102.15	15789.19	30811.85	0.00	23810.53
Cultural Services	Aesthetic landscape	452.67	11039.15	6953.04	23086.25	0.00	14304.42
Total		23840.70	239855.59	167886.84	1547804.90	0.00	157590.07

#### (4) Accuracy Verification and Sensitivity Analysis

To examine the degree of dependence and robustness of the above ecosystem service value (ESV) assessment results on the value coefficients (VC), this study introduces the Coefficient of Sensitivity (CS) for analysis<sup>23</sup>. This index adopts the concept of elasticity coefficient from economics to judge the reliability of the assessment results. The calculation formula for the sensitivity index is as follows:

$$CS = \left| \frac{(ESV_v - ESV_u) / ESV_u}{(ESV_{vj} - VC_{uj}) / VC_{uj}} \right| \quad (8)$$

Where: CS represents the sensitivity index.  $ESV_v$  and  $ESV_u$  are the total ecosystem service values (yuan) after and before adjustment, respectively.  $VC_{vj}$  and  $VC_{uj}$  are the ecosystem service value coefficients per unit area ( $\text{yuan} \cdot \text{hm}^{-2}$ ) for the “j”-th land use type after and before adjustment, respectively. The interpretation criterion for the sensitivity index is: If  $|CS| < 1$ , it indicates that the ESV is inelastic to changes in the value coefficient (VC). This means the ESV estimation result is insensitive to changes in the VC setting, suggesting that the research findings are relatively robust and credible<sup>24</sup>.

For a unified comparison, the range standardization method was employed to eliminate dimensional differences in the data. Based on previous studies<sup>25</sup> and the actual conditions of the study area, the standardized ESV values were constrained within the range of 0 to 1. The total ESV for each land type was then calculated using ArcGIS. Finally, the resulting values were normalized and classified into five levels. The specific classification criteria are presented in Tab. 4.

**Table 4. Classification Criteria for ESV**

ESV Standardized Value	Grade
$0.6 < \text{ESV} \leq 1.0$	High
$0.4 < \text{ESV} \leq 0.6$	Moderate
$0.2 < \text{ESV} \leq 0.4$	Medium
$0 < \text{ESV} \leq 0.2$	Low

2.2.5 Land Use and Ecosystem Coupling Coordination Model

Coupling originated as a concept in physics, referring to the phenomenon where two or more systems or forms of motion influence each other through various interactions within themselves and with their external environment. It was later introduced into economics to represent the level of coordination between systems.

$$C = 2 \left[ \frac{L_x \times E_y}{(L_x + E_y)(L_x + E_y)} \right]^{\frac{1}{2}} \quad (9)$$

In the formula, C represents the coupling degree, LX denotes the normalized comprehensive land use index, and Ey signifies the normalized ESV. However, in certain scenarios, the coupling degree model fails to fully reflect the overall coordination of the system. Therefore, the coupling coordination degree model is introduced to capture the holistic coupling coordination status among indicators, as expressed by the following formula:

$$D = \sqrt{C \times T} \quad (10)$$

$$T = aL_x \times bE_y \quad (11)$$

In the formula, D represents the coupling coordination degree, T denotes the comprehensive evaluation index, and a and b are the weights assigned to land comprehensive utilization and ESV. Since land comprehensive utilization and ESV are considered equally important, therefore, following previous research weights a and b were both set to 0.5. The classification criteria for the coupling coordination degree D are shown in Table 5.

**Table 5. coordination degree classification criteria**

Category	Coupling Coordination Index	Grade
Balanced Development	$0.8 < D \leq 1.0$	Highly Coordinated Development
Over development	$0.6 < D \leq 0.8$	Moderately Coordinated Development
	$0.4 < D \leq 0.6$	Barely Coordinated Development
Unbalanced Development	$0.2 < D \leq 0.4$	Moderately Unbalanced Development
	$0 < D \leq 0.2$	Severely Unbalanced Development

2.2.6 Trend Surface Analysis

Trend surface analysis, based on the ArcGIS platform, employs mathematical methods to reveal spatial change trends and distribution patterns of the study subject. This paper uses coupling coordination as the observation value and applies trend surface analysis to simulate the spatiotemporal differentiation characteristics of the coupling coordination relationship between land use and ecosystem service value in the Central Yunnan Urban Agglomeration from 2010 to

2024.

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### 2.2.7 Geographic Detector Model

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To reveal the driving mechanisms behind the spatial differentiation pattern of the coupling coordination degree (D-value) between land use and ecosystem service value in the Central Yunnan Urban Agglomeration, this study employed the geographical detector model for factor detection. The factor detector module within the model quantifies the explanatory power (q-value) of each driving factor (X) on the spatial distribution differences of the coupling coordination degree D-value (Y). For the selection of driving factors, based on the coupled human-environment systems framework<sup>28,29</sup>, and by synthesizing previous research, the actual conditions of the study area, and data availability, a total of 12 indicators were selected across two dimensions: the natural environment and socio-economics. The specific indicators are as follows:

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In selecting driving factors, we integrated prior research, the actual conditions of the study area, and the scientific validity and operational feasibility of data acquisition. Based on the human-land coupling system framework<sup>30</sup>, factors were selected from both natural environment and socioeconomic dimensions. This comprehensive approach ensures a holistic understanding of underlying mechanisms. Specific indicators include: Natural factors: Elevation, Slope, Aspect—elements constraining land use suitability; Annual mean temperature and Annual precipitation—fundamental climatic drivers of ecosystem processes; and MNDWI—Represents the distribution of surface water bodies and serves as a key indicator for water-related ecosystem services (e.g., hydrological regulation). NDVI—Represents vegetation coverage and primary productivity; it is a fundamental indicator of ecosystem structure and function<sup>31,32</sup>. Socioeconomic factors: Land use type itself reflects human decision-making; GDP represents economic development levels; nighttime light serves as a reliable proxy for human activity and economic intensity<sup>33,34</sup>; population density and urbanization rate reflect population pressure and urban expansion dynamics<sup>35</sup>.

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This module can be used to detect the spatial heterogeneity of the coupling coordination degree (D) and to quantify the explanatory power of each driving factor. The specific formula is as follows:

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$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} \quad (12)$$

In the formula,  $h = 1, 2, \dots, L$  denotes the classification of Y and X;  $\sigma_h^2$  and  $\sigma^2$  represent the variance of Y at layer h and across the entire area, respectively;  $N_h$  and N denote the number of units in each category. The analytical nature of the model can be verified based on the magnitude of the q value; a larger value indicates higher analytical capability.

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### 2.2.8 Screening and Processing of Driving Factors

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Although the Geodetector model exhibits strong statistical robustness to multicollinearity among factors and does not rely on linear assumptions<sup>36</sup>, a systematic screening and processing procedure was implemented before inputting factors into the Geodetector. This was done to prevent factors with highly overlapping information from diluting the independent explanatory power of individual factors and to ensure clear identification of core driving mechanisms. As

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land use type is a categorical variable, it was not included in the Variance Inflation Factor (VIF) calculation. Therefore, VIF analysis was performed on the 11 continuous factors excluding the categorical land use type. VIF quantifies the extent to which the variance of a dependent variable is inflated due to multicollinearity and is a commonly used indicator for testing collinearity. Consequently,  $VIF < 10$  was set as the empirical threshold for determining the absence of severe multicollinearity<sup>37</sup>. The principle for factor removal was prioritized as follows: retaining indicators that have clear geographical significance, have been widely validated as key driving factors in similar studies, and are closely related to the actual conditions of the study area.

Screening Results: Following the VIF testing and screening process, the initial factors aspect and nighttime light index exhibited high collinearity with elevation and GDP, respectively ( $VIF \geq 10$ ). Furthermore, the information they conveyed could be partially represented by other factors, leading to their removal. Ultimately, a total of 10 driving factors were retained for the Geodetector model, including: Elevation ( $X_1$ ), Slope ( $X_2$ ), Annual Mean Temperature ( $X_3$ ), Annual Precipitation ( $X_4$ ), MNDWI (Modified Normalized Difference Water Index,  $X_5$ ), NDVI (Normalized Difference Vegetation Index,  $X_6$ ), Land Use Type ( $X_7$ ), GDP ( $X_8$ ), Population Density ( $X_9$ ), and Urbanization Rate ( $X_{10}$ ). The VIF values for all retained factors were below 10, indicating that the issue of multicollinearity had been effectively controlled. This screening process ensures the credibility and interpretability of subsequent factor detection and interaction analysis results.

**Table 6 Multicollinearity Test Results for the Final Driving Factors**

Driving Factor	VIF Value	Tolerance (1/VIF)
Elevation ( $X_1$ )	2.15	0.465
Slope ( $X_2$ )	1.89	0.529
Annual Mean Temperature ( $X_3$ )	3.42	0.292
Annual Precipitation ( $X_4$ )	2.78	0.360
MNDWI ( $X_5$ )	1.23	0.813
NDVI ( $X_6$ )	2.95	0.339
GDP ( $X_8$ )	5.67	0.176
Population Density ( $X_9$ )	6.23	0.161
Urbanization Rate ( $X_{10}$ )	4.81	0.208

### 3 Results

#### 3.1 Characteristics of Land Use Structure and Spatial Pattern Evolution

The area and proportion of various land-use types in the Central Yunnan Urban Agglomeration were derived by analyzing the four-phase land-use data from 2010, 2015, 2020, and 2024 using ArcGIS 10.3 software. The specific details are presented in Table 7.

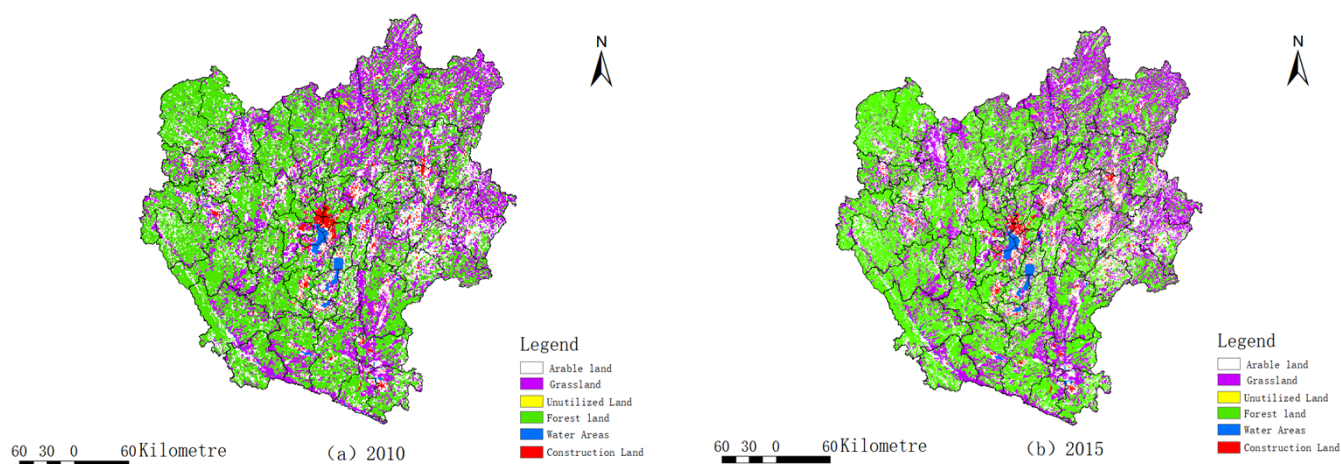
**Table 7. Land Use Structure of the Study Area from 2010 to 2024 (km<sup>2</sup>)**

Land Use Type		2010	2015	2020	2024
Arable land	Area	22816	22644	22511	21995
	Percentage	20.49%	20.34%	20.22%	19.76%
Forest land	Area	54912	54850	54796	54343
	Percentage	49.32%	49.27%	49.22%	48.82%

Grassland	Area	29881	29791	29725	29612
	Percentage	26.84%	26.76%	26.7%	26.6%
Water Areas	Area	1422	1427	1464	2147
	Percentage	1.27%	1.28%	1.36%	1.93%
Construction Land	Area	2143	2445	2677	3017
	Percentage	1.92%	2.19%	2.41%	2.71%
Unutilized Land	Area	156	173	157	205
	Percentage	0.14%	0.15%	0.15%	0.19%

Figure 2 illustrates the distribution of land use changes in the Central Yunnan Urban Agglomeration from 2010 to 2024, showcasing the structural shifts in land use. Overall, the land use pattern remained relatively stable, with woodland and grassland dominating the landscape, consistently accounting for the largest proportions of area. Figure 3 presents a Sankey diagram depicting the transfer of land use changes in the Central Yunnan Urban Agglomeration from 2010 to 2024, revealing the conversion dynamics among various land types over the study period.

Combining the observations from Figure 2 and Figure 3, the following trends are evident: Woodland occupied the largest area, reaching 54,912 km<sup>2</sup> (49.32%) in 2010. However, it exhibited a continuous declining trend, decreasing to 54,343 km<sup>2</sup> (48.81%) by 2024, primarily converting to construction land and water bodies. The area of cropland experienced an overall reduction, declining from 22,816 km<sup>2</sup> (20.49%) in 2010 to 21,995 km<sup>2</sup> (19.75%) in 2024, with notable mutual conversions between cropland and construction land. Grassland area showed relatively minor fluctuations, with its proportion slightly decreasing from 26.84% to 26.60%. In contrast, both construction land and water bodies demonstrated significant expansion. Construction land increased from 2,143 km<sup>2</sup> (1.92%) to 3,017 km<sup>2</sup> (2.71%), with its expansion mainly sourced from the occupation of cropland. Water bodies also grew from 1,422 km<sup>2</sup> (1.27%) to 2,147 km<sup>2</sup> (1.92%), partly due to conversions from woodland. Unused land consistently represented the smallest proportion, with insignificant changes. In summary, the region maintained a land use structure predominantly composed of ecological land (woodland, grassland, and water bodies). However, the continuous expansion of construction land has exerted pressure on both cropland and a portion of ecological land.



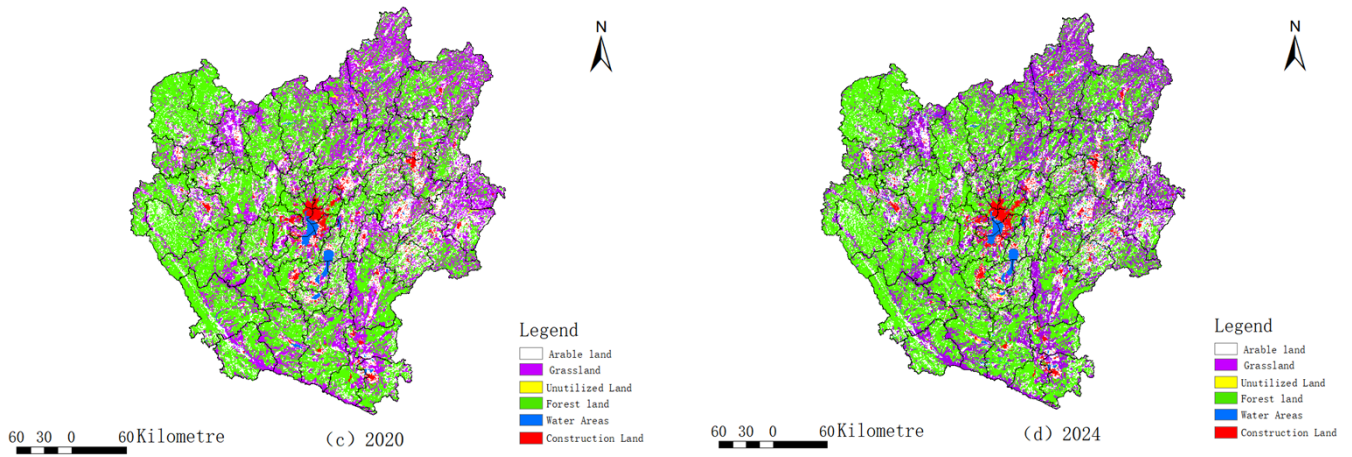


Figure 2. Distribution Map of Land Use Changes in the Central Yunnan Urban Agglomeration from 2010 to 2024.

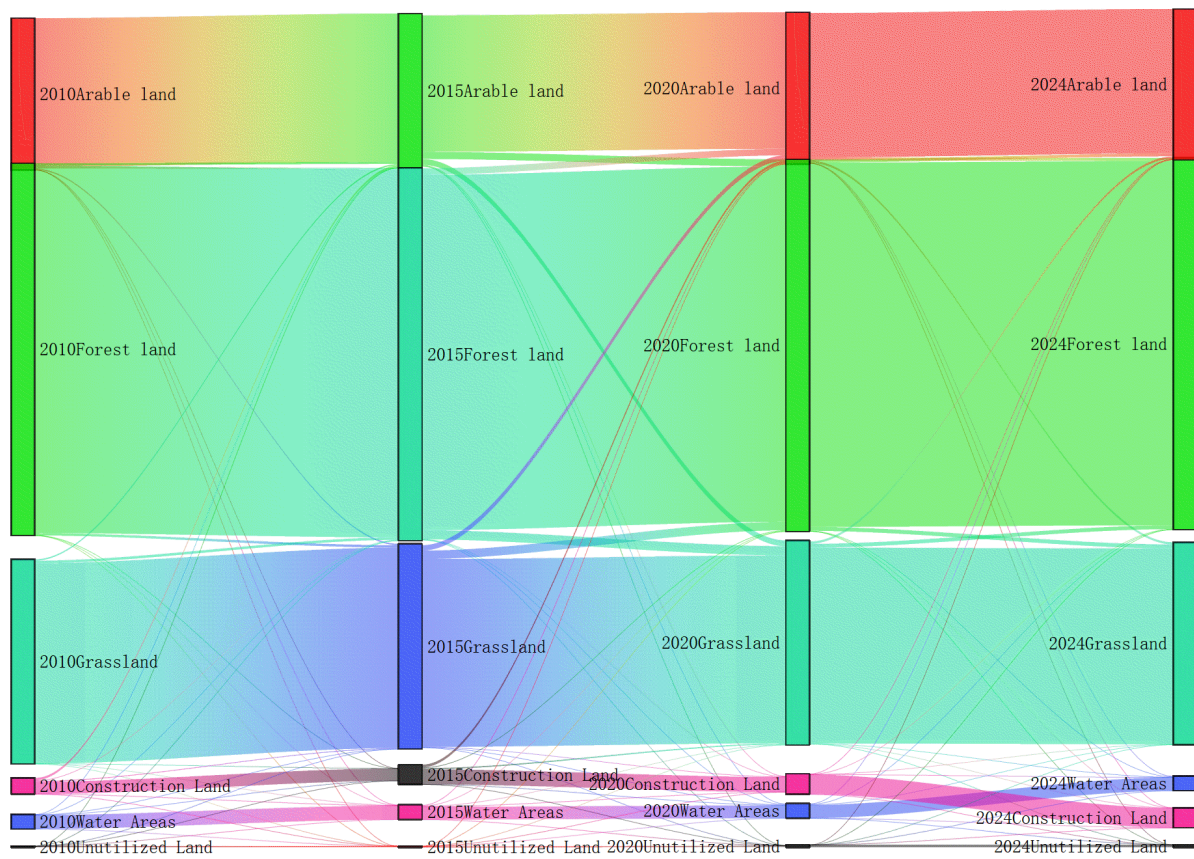


Figure 3. Sankey diagram of land use transfer changes in the Central Yunnan Urban Agglomeration from 2010 to 2024.

### 3.2 Land Use Change Rates and Transformation Characteristics

Figure 4 shows the land use dynamic degree map for the Central Yunnan Urban Agglomeration from 2010 to 2024,

revealing the varying change rates and transformation characteristics of different land types. During this period, cropland, woodland, and grassland all exhibited a continuous decreasing trend. Among them, the reduction rate of cropland was relatively gentle, with its dynamic degree ranging between -0.15% and -0.57% across different intervals. Woodland decreased the least and most stably, with a dynamic degree of approximately -0.02% in each stage. Grassland declined at a slightly higher rate than woodland, with its dynamic degree ranging from -0.06% to -0.09%. In contrast, water bodies and construction land (urban, industrial, mining, and residential land) showed continuous growth. The dynamic degree of construction land remained consistently high, staying within the range of 2.5% to 3.2%. The dynamic degree of water bodies increased significantly over time, particularly reaching 11.67% during the 2020–2024 period. Unused land exhibited the most volatile changes: it increased by 2.32% from 2010 to 2015, decreased by 1.85% from 2010 to 2020, and then rose sharply by 7.76% from 2020 to 2024. Overall, regional land use changes were dominated by the expansion of construction land and the growth of water bodies. During the study period, farmland and forest land played a major role in providing ecological functions. Although their areas gradually decreased, their substantial proportions meant they remained the foundation for regional ecological stability.

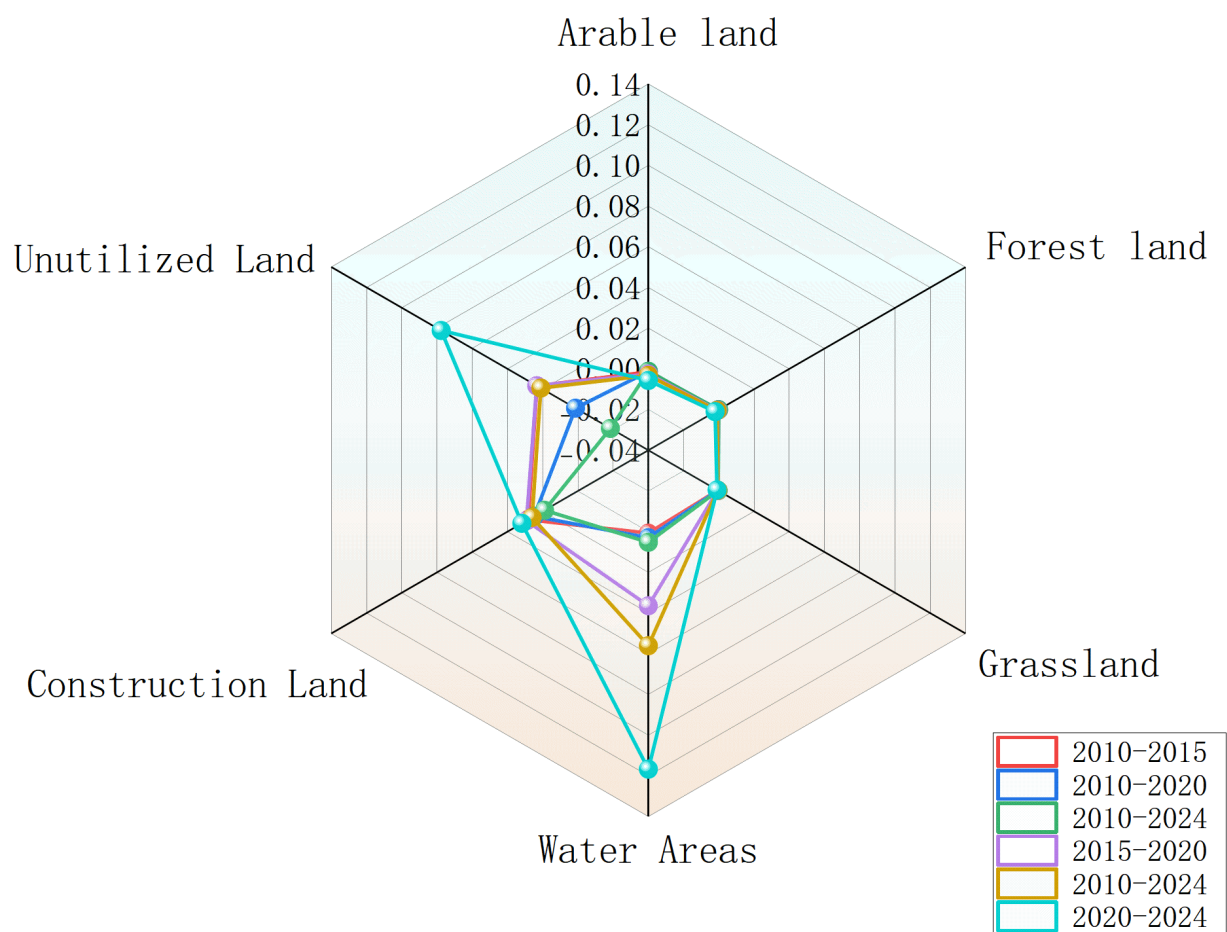


Figure 4. Land Use Dynamics in the Central Yunnan Urban Agglomeration, 2010–2024

### 3.3 Changes and Spatial Differentiation Characteristics of Land Use Intensity

From 2010 to 2024, the comprehensive land use intensity in the Central Yunnan Urban Agglomeration showed an overall increasing trend, reflecting an improvement in the level of regional land intensive use. Significant internal disparities were observed, presenting clear spatial differentiation. As shown in Figure 5, in 2010, areas of high land use intensity were concentrated in the economically developed eastern part of central Yunnan, such as Wuhua District and Panlong District of Kunming City, Qilin District of Qujing City, and Luliang County. By 2015, noticeable shifts in intensity levels occurred in the central-eastern regions, transitioning from low intensity to low-medium or medium intensity, indicating an overall increase in regional development intensity. During the 2020-2024 period, the overall pattern of intensity levels tended to stabilize, although significant local changes persisted. For instance, Guandu District and Chenggong District escalated to high intensity by 2024, with their surrounding counties and districts also rising to medium-high intensity. Areas like Chuxiong City and Lufeng County maintained medium-high intensity levels, but the rate of increase slowed down. Notably, the intensity in ecologically sensitive zones and some peripheral counties and cities (e.g., Jianshui, Kaiyuan) consistently remained at low-medium levels with minimal fluctuation. In summary, the land use intensity in the Central Yunnan Urban Agglomeration exhibits a tiered distribution characterized by "continuous intensification in the core areas, steady growth in the peripheral regions, and stable low levels in ecological zones." This pattern reveals significant spatial heterogeneity in the intensity of human activities.

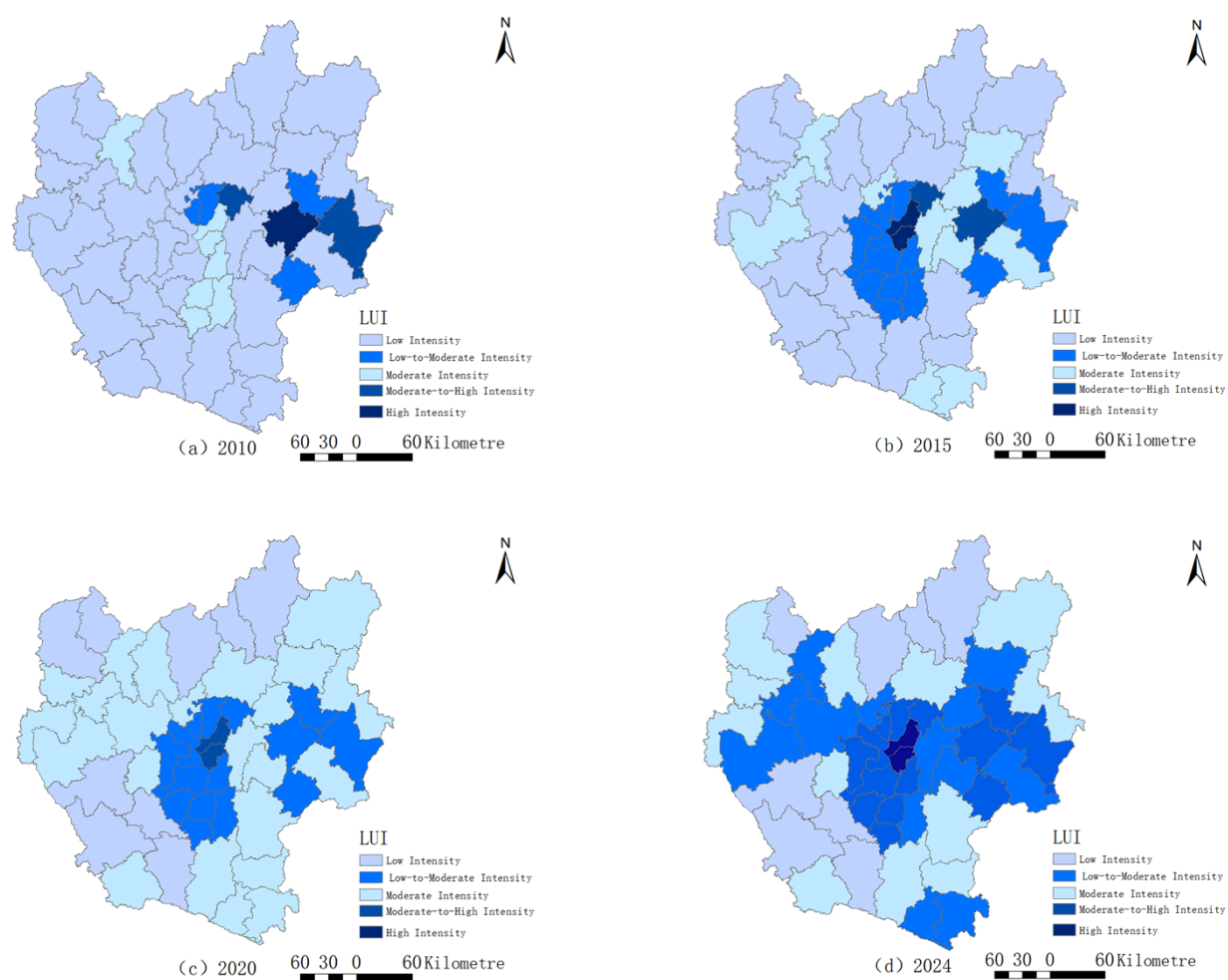


Figure 5. Distribution Map of Comprehensive Land Use Intensity in Central Yunnan Urban Agglomeration from 2010 to 2024

### 3.4 Spatio-temporal Evolution Characteristics of Ecosystem Service Value (ESV)

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As shown in Figure 6 (Ecosystem Service Types in Central Yunnan Urban Agglomeration, 2010-2024), the Ecosystem Service Value (ESV) in the Central Yunnan Urban Agglomeration showed a consistent and significant increasing trend, rising from 1.194 billion yuan to 2.288 billion yuan. Classified by service type, the value of regulatory services consistently dominated, increasing from 0.884 billion yuan to 1.886 billion yuan. Supporting services (0.94 → 1.80 billion yuan), provisioning services (0.85 → 1.63 billion yuan), and cultural services (0.31 → 0.59 billion yuan) also achieved steady growth. The period 2010–2015 marked the initial growth stage for ESV, while 2015–2020 entered a phase of rapid enhancement, with the growth in regulatory service value being particularly prominent. In terms of spatial distribution, ESV exhibited significant regional heterogeneity (As shown in Figure 7). The eastern and northern districts/counties (such as Guandu District, Xundian County, Malong District, etc.) showed the most notable increases, generally rising from the 0.3–0.4 billion yuan range in 2010 to 0.6–0.7 billion yuan in 2024. Central and some southern districts/counties (e.g., Wuhua District, Fumin County, Shizong County, etc.) maintained steady growth, increasing from approximately 0.3 billion yuan to 0.5–0.6 billion yuan. In contrast, most southern and scattered central districts/counties (such as Panlong District, Chenggong District, Jinning District, etc.) remained consistently around 0.1 billion yuan, with limited growth.

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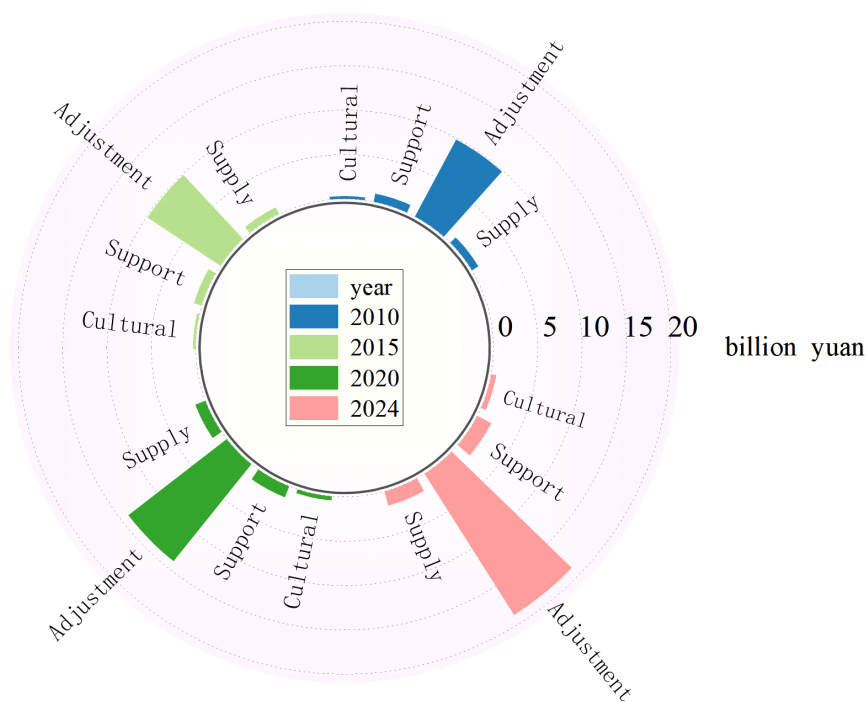


Figure6. Ecosystem Service Types in Central Yunnan Urban Agglomeration, 2010-2024.

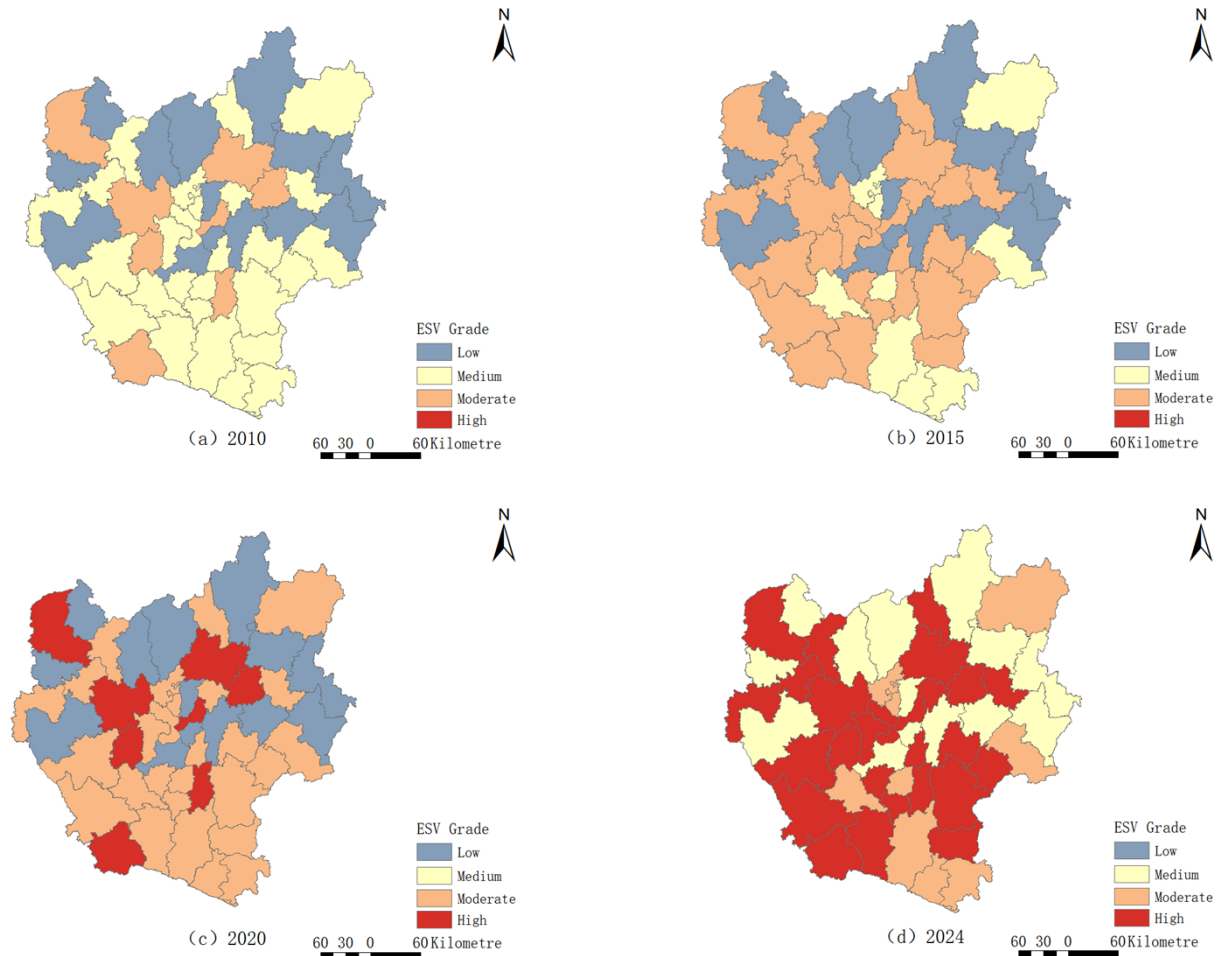


Figure7. Spatial Distribution of Ecosystem Service Value (ESV) in Central Yunnan Urban Agglomeration from 2010 to 2024.

### 3.5 Sensitivity Analysis of Ecosystem Service Value

To examine the reliability of the ecosystem service value assessment results, this study calculated the corresponding Sensitivity Index (CS) with reference to relevant methods (Table 8). The results indicate that the CS values for all land cover types within the study area from 2020 to 2024 were less than 1. This demonstrates that the Ecosystem Service Value (ESV) is inelastic to changes in the value coefficients, confirming that the assessment results possess high stability and credibility. The CS values varied among different land cover types due to differences in their area proportions and unit value coefficients. Forest land, which had the highest area proportion (approximately 49%) and a relatively high unit value coefficient, consistently exhibited the highest CS (0.6645 in 2024). This indicates that forest land plays a critical role in maintaining regional ecological balance and providing ecosystem services. Grassland, with both its area proportion and value coefficient lower than those of forest land, ranked second in terms of CS (0.2208 in 2024), signifying its significant contribution to ecological regulation. Although water areas had the highest unit value coefficient, their CS remained relatively low (0.0605 in 2024) due to their small area proportion. However, the slight increase in its CS over time reflects a growing recognition of its ecological importance. Cropland, with low values for both area proportion and unit value coefficient, consistently showed a low CS level (0.0543 in 2024). The CS values for construction land and unutilized land were close to zero, suggesting their minimal impact on the regional ESV. Overall,

the CS values for all land use/cover types changed only gradually between 2020 and 2024. This suggests that the structure of ecosystem service values in the Central Yunnan Urban Agglomeration was relatively stable during this period, with forest land and grassland playing a dominant role in maintaining the region's ecological functions. This analysis provides a scientific basis for regional ecological conservation and land use planning.

**Table 8. Sensitivity Index (CS) of ESV for Different Land Cover Types in the Central Yunnan Urban Agglomeration from 2020 to 2024**

Year	Arable land	Forest land	Grassland	Water Areas	Construction Land	Unutilized Land
2010	0.0559634	0.6669659	0.2257386	0.0512673	0	0.0000647
2015	0.0554772	0.6662249	0.2242893	0.0539445	0	0.0000646
2020	0.054991	0.6654839	0.2228401	0.0566207	0	0.0000645
2024	0.0542528	0.6644819	0.2208420	0.0604541	0	0.0000643

### 3.6 Spatiotemporal Coupling Characteristics of Land Use and Ecosystem Service Value (ESV)

As shown in Figure 8, depicting the temporal changes in the coupling coordination degree between land use and ecosystem service value (ESV) in the Central Yunnan Urban Agglomeration, the level of coupling coordination showed a steady improvement trend from 2010 to 2024. In 2010, the overall coordination level across the region was relatively low, with the vast majority of counties/districts in a state of severe or mild imbalance ( $D \leq 0.4$ ). The coordination degree in core urban areas of Kunming, such as Panlong and Guandu, was even below 0.2. By 2015, most counties/districts had entered a barely coordinated development stage ( $0.4 < D \leq 0.6$ ), with significant improvements observed in places like Songming County and Qilin District. The coordination level further increased in 2020. Areas like Wuhua District and Jiangchuan District reached a moderate coordination level ( $0.6 < D \leq 0.8$ ), while counties/cities such as Shilin and Xuanwei achieved a high level of coordination ( $D > 0.8$ ). By 2024, the scope of counties/districts with high coordination continued to expand. Areas like Dongchuan District, Xundian County, and Dayao County saw their coordination degree exceed 0.9, indicating a strengthening synergistic effect between ecological protection and land use management.

The spatial distribution of the coupling coordination degree between land use and ESV in the Central Yunnan Urban Agglomeration from 2010 to 2024 reveals distinct regional differentiation. Areas with high coordination were concentrated in the southwestern region, which boasts a superior ecological baseline, such as Shuangbai and Xiping. Their abundant forest resources supported a consistently high coordination level ( $D > 0.9$ ). In contrast, highly urbanized areas, like the rapidly expanding central urban zone of Kunming, remained at a medium-low coordination level, highlighting the ongoing pressure urban sprawl exerts on ecological service functions. Overall, most areas within the Central Yunnan Urban Agglomeration have fundamentally transitioned from a state of "imbalance" to "coordination."

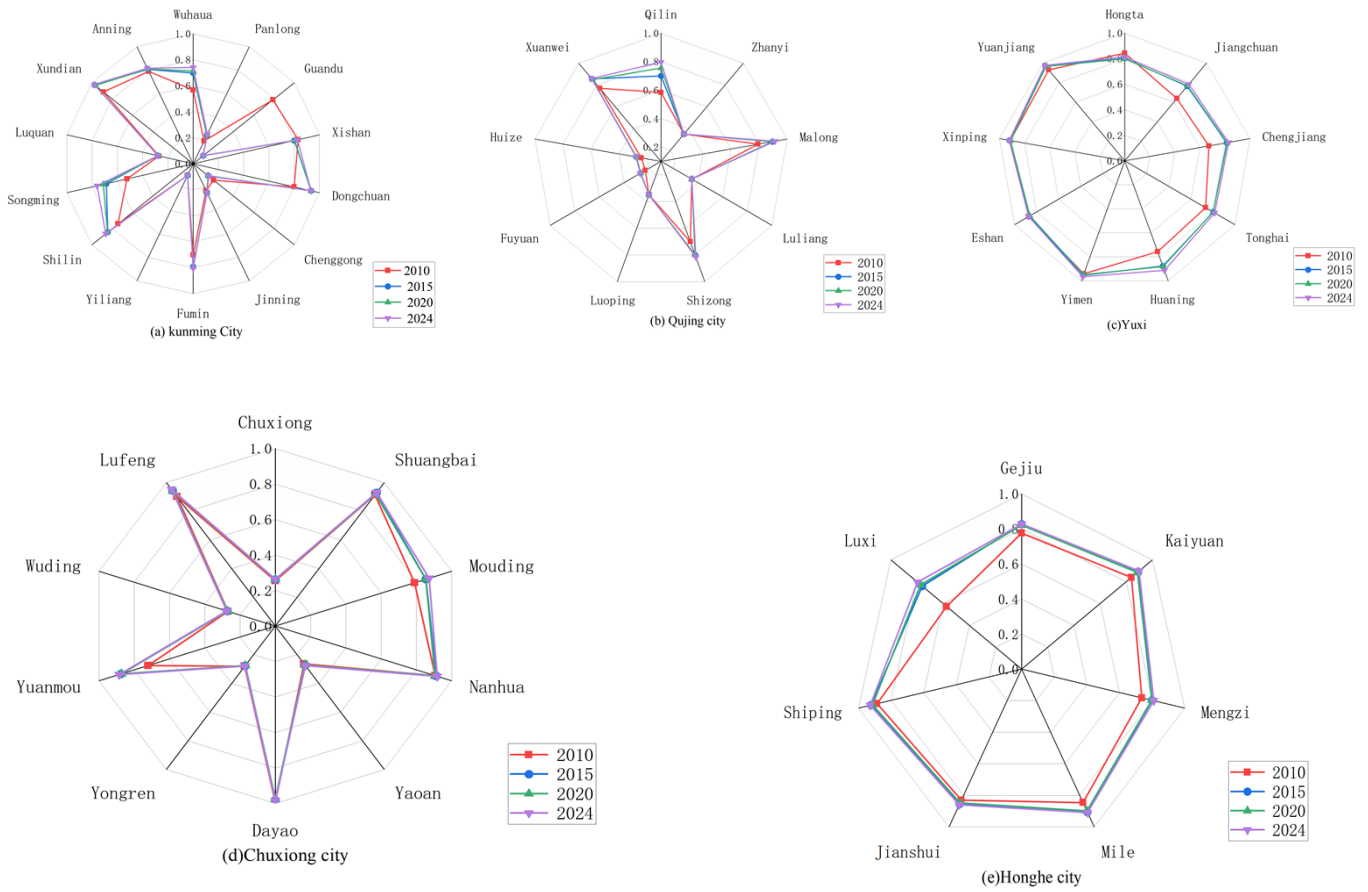
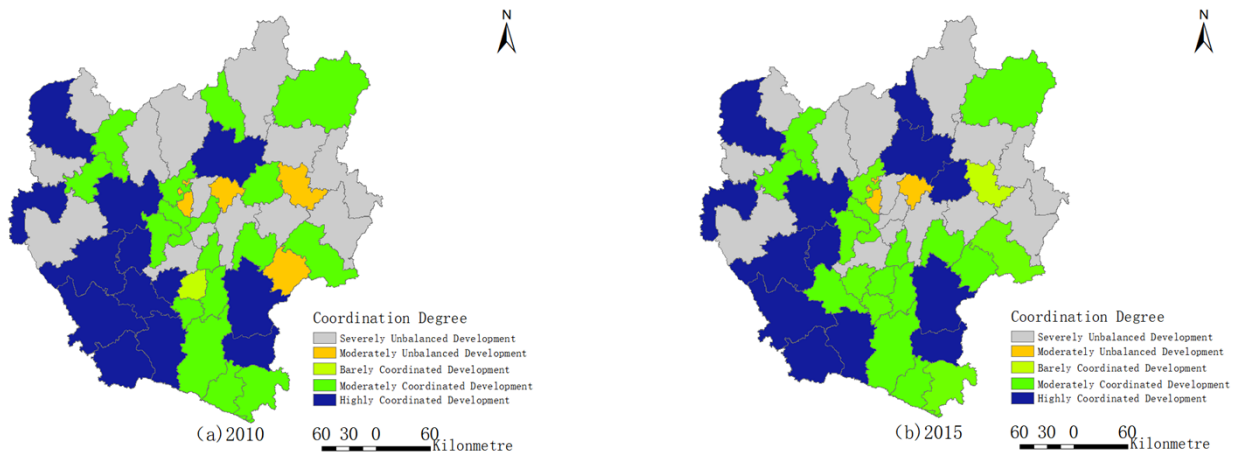


Figure 8 Temporal Variation of the Coupling Coordination Degree between Land Use and Ecosystem Service Value in the Central Yunnan Urban Agglomeration, 2010-2024

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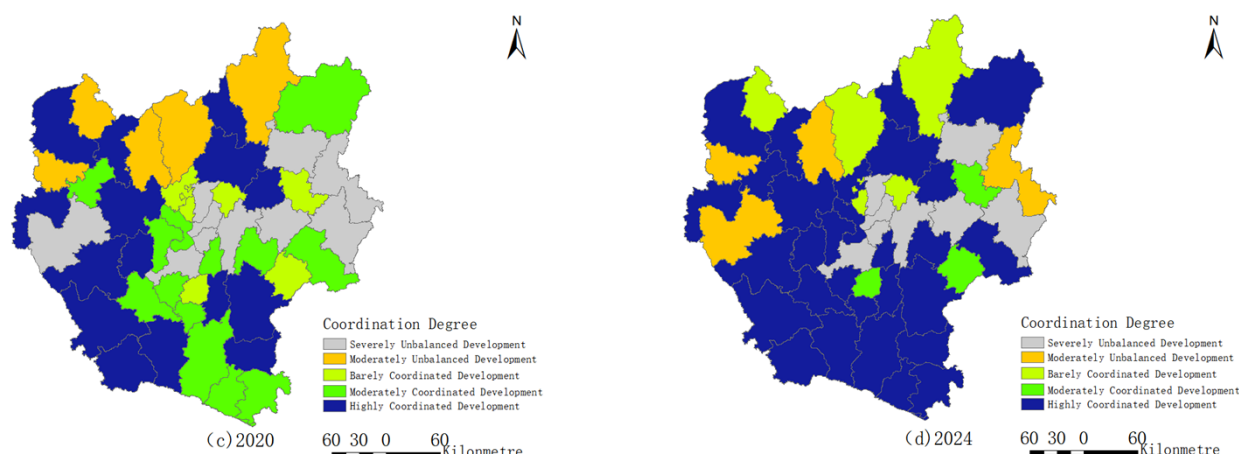


Figure 9. Spatial Distribution of the Coupling Coordination Degree between Land Use and Ecosystem Service Value (ESV) in the Central Yunnan Urban Agglomeration, 2010-2024

### 3.7 Spatial Differentiation Characteristics of the Coupling Coordination Relationship between Land Use and Ecosystem Services

Based on the coupling coordination degree data of counties (districts) in the Central Yunnan Urban Agglomeration from 2010 to 2024, the spatial evolution characteristics of the coordination relationship between land use and ecosystem service value (ESV) were simulated using trend surface analysis. A spatial coordinate system was established with the X-axis oriented due east and the Y-axis oriented due north. The fitting results, as shown in Figure 10 (Trend surface map of the coupling coordination degree between land use and ecosystem service value in the Central Yunnan Urban Agglomeration from 2010 to 2024) reveal that the coupling coordination degree exhibits an inverted U-shaped pattern in the east-west direction and a U-shaped pattern in the north-south direction. Overall, a spatial differentiation pattern characterized by "higher values in the south than in the north, and higher values in the west than in the east" is observed. This pattern reflects a typical "core-periphery" spatial structure. Areas with high coordination are concentrated along the Kunming-Yuxi-Chuxiong axis, while peripheral regions in the north and east exhibit lower coordination levels. In terms of evolutionary trends, the north-south U-shaped structure has been continuously strengthening, indicating a further widening of the north-south disparity and highlighting an increasingly prominent regional imbalance. Specifically, highly coordinated areas ( $D > 0.8$ ) are mainly located in the western and southern parts. Counties and districts in the central region and some northern areas remain in a state of barely coordinated or even uncoordinated development. Overall, the coordination pattern of the Central Yunnan Urban Agglomeration demonstrates an evolutionary trend shifting from "core agglomeration and peripheral diffusion" towards "intensified differentiation and structural stabilization."

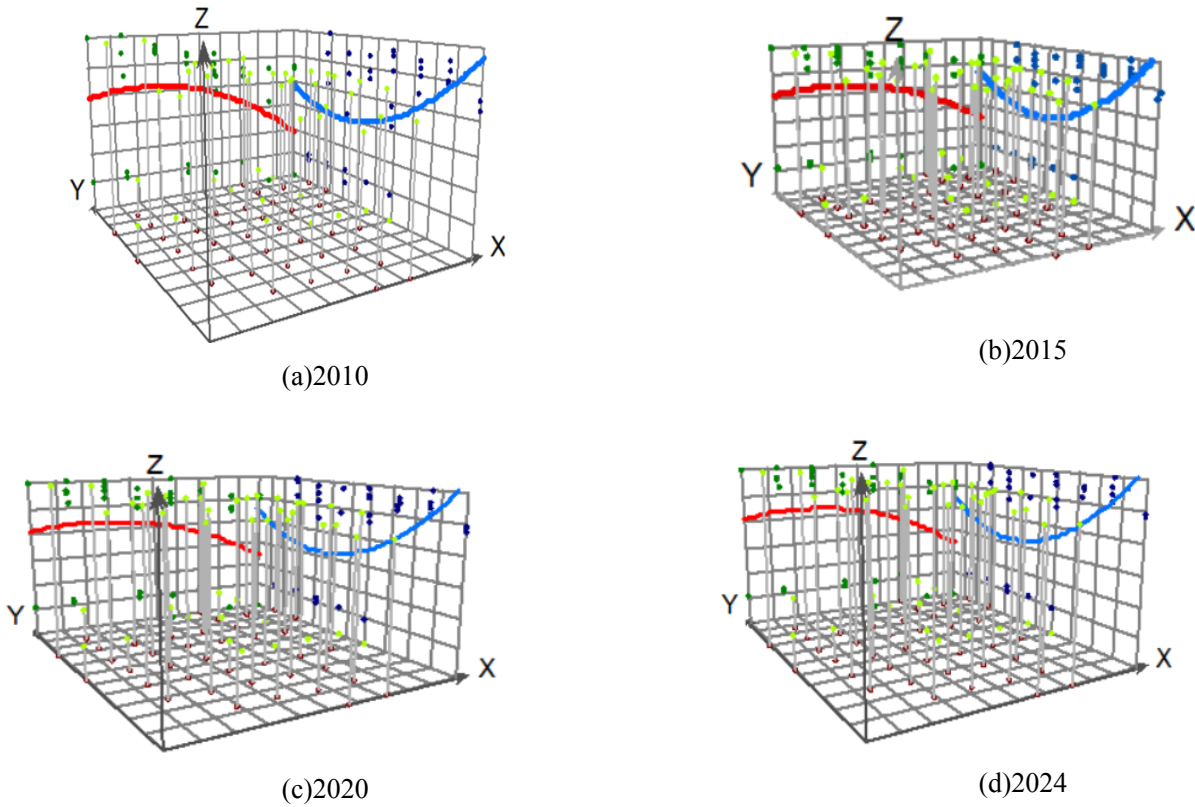


Figure 10. Trend surface map of the coupling coordination degree between land use and ecosystem service value in the Central Yunnan Urban Agglomeration from 2010 to 2024.

### 3.8 Analysis of Driving Mechanisms for the Coupling Coordination between Land Use and Ecosystem Services

#### 3.8.1 Temporal Evolution Characteristics of Dominant Driving Factors

Analysis based on Figure 11 indicates that from 2010 to 2024, the driving factors for the coupling coordination degree (D value) between land use and ecosystem service value in the Central Yunnan Urban Agglomeration exhibited a dynamic evolutionary characteristic of shifting from "nature-dominated to human-enhanced, then towards explanatory multi-factor equilibrium." In 2010, the spatial differentiation of system coordination was primarily explanatory natural factors. The top five factors in terms of explanatory power (q value) were all natural elements: NDVI ( $X_6$ ,  $q=0.749$ ), slope ( $X_2$ ,  $q=0.698$ ), MNDWI ( $X_5$ ,  $q=0.696$ ), land use type ( $X_7$ ,  $q=0.692$ ), and elevation ( $X_1$ ,  $q=0.615$ ). Their q values were all greater than 0.6, indicating that the regional natural background was the foundation for pattern formation during this stage. Between 2015 and 2020, the driving structure changed significantly. The explanatory power of core natural factors such as NDVI ( $X_6$ ) and slope ( $X_2$ ) remained at a relatively high level above 0.69. However, the influence of socio-economic factors increased markedly. Notably, the q value for GDP ( $X_8$ ) reached 0.760 in 2020, making it the single most explanatory factor for that year. This signifies that economic development had become a crucial factor influencing the coupled development of land use and ecosystems in the Central Yunnan Urban Agglomeration. By 2024, the driving system evolved into a pattern of multi-factor synergy between natural and human factors. Among the natural factors, slope ( $X_2$ ) exhibited the most prominent explanatory power ( $q=0.769$ ), while the role of NDVI ( $X_6$ ) relatively declined ( $q=0.552$ ). Meanwhile, GDP ( $X_8$ ) and population density ( $X_9$ ) continued to exert significant influence. Overall, the driving forces transitioned from an initial stage dominated by natural conditions, through a phase where the influence

of socio-economic factors significantly strengthened, and ultimately developed into a state of multi-factor equilibrium. 450  
 This final state involves the combined effects of various factors, including topographic constraints, economic 451  
 development, and population distribution. 452

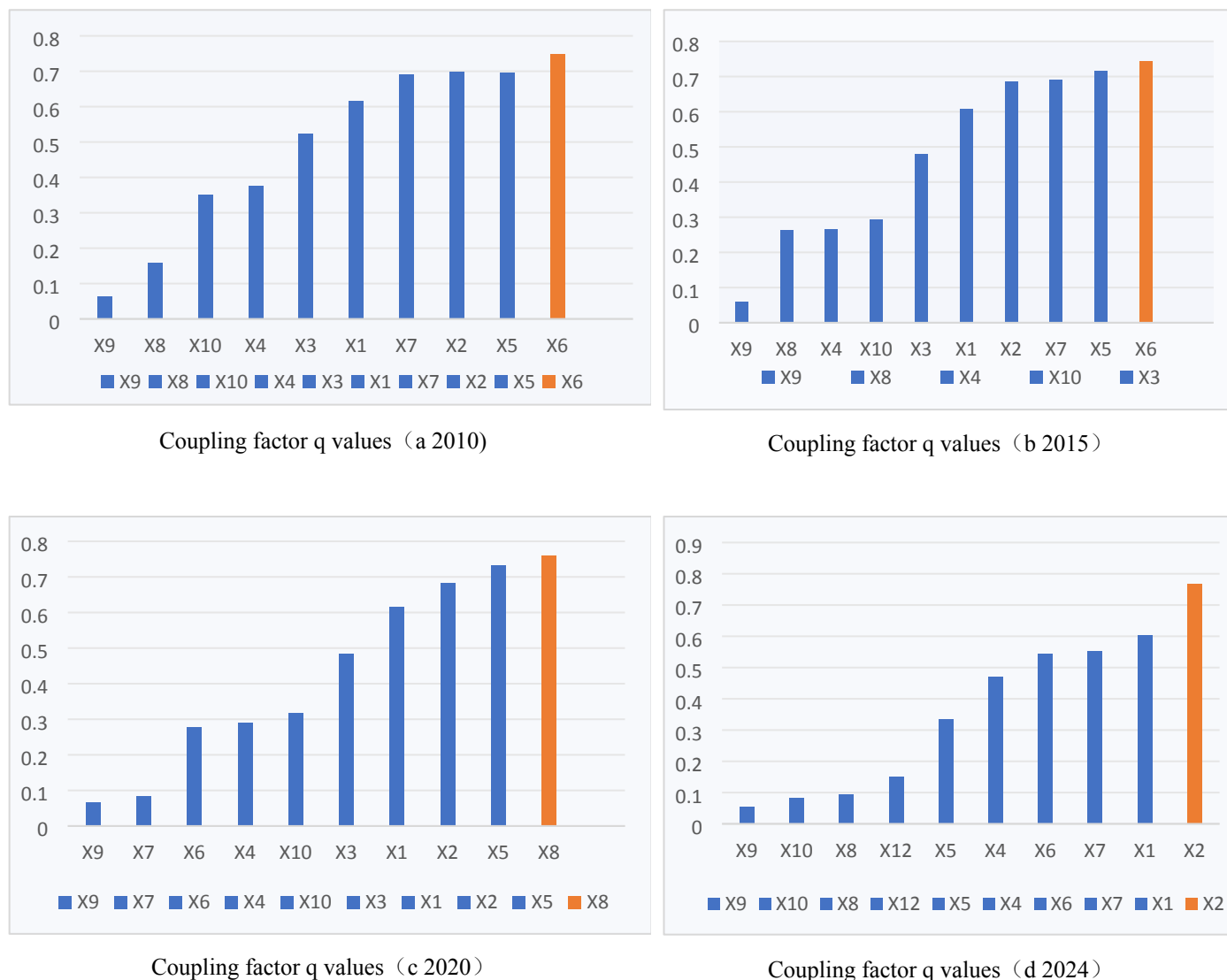


Figure 11. Ranking of q-values for factors influencing the coupling coordination degree between land use and ecosystem service value in the Central Yunnan Urban Agglomeration from 2010 to 2024. 454

### 3.8.2 Synergistic Enhancement Effects of Natural and Socioeconomic Factors 455

Based on the interaction detection results of the geographical detector from 2010–2024 (Figure 12), interactive enhancement effects were prevalent among the various driving factors of the coupling coordination degree (D value) in 457  
 the Central Yunnan Urban Agglomeration. The interactions among natural factors themselves maintained high intensity 458  
 throughout the entire study period, exerting a strong influence on the spatial patterns. Specifically, the interactive q- 459  
 values between factors such as elevation ( $X_1$ ), slope ( $X_2$ ), and mean annual temperature ( $X_3$ ) remained consistently 460  
 high. For instance, the interactive q-value for  $X_1 \cap X_3$  was 0.961 in 2010 and still reached 0.963 by 2024; the interactive 461  
 q-value for  $X_2 \cap X_3$  was as high as 0.966 in 2024. The interactions between NDVI ( $X_6$ ) and the aforementioned 462  
 topographic and climatic factors were also strong, although their intensity fluctuated over time. For example, the q-value 463  
 for  $X_1 \cap X_6$  decreased from 0.920 in 2010 to 0.670 in 2024. The interactive effects between socioeconomic factors and 464

natural factors were significant and exhibited dynamic changes. On one hand, the interaction intensity between GDP (X<sub>8</sub>), population density (X<sub>9</sub>), and core natural factors (e.g., X<sub>1</sub>, X<sub>2</sub>) consistently remained at a very high level (with q-values mostly above 0.85), indicating a profound coupling effect between economic development/population distribution and the geographical background. On the other hand, the strength of some interactions evolved. For example, the interactive q-value between NDVI (X<sub>6</sub>) and GDP (X<sub>8</sub>) decreased from 0.819 in 2010 to 0.602 in 2024, suggesting a weakening of their synergistic enhancement effect. In contrast, the interactive q-value between land use type (X<sub>7</sub>) and natural factors (e.g., X<sub>2</sub>) still exceeded 0.818 in 2024, indicating that the combination of human land use patterns and topographic constraints continues to yield strong explanatory power. In summary, the interactive effect of any two factors was greater than the q-value of their individual effects, confirming that the system is driven nonlinearly and synergistically by multiple factors. The driving pattern is not determined by a single factor but is jointly shaped by the complex interactions among natural background constraints, ecological conditions, and human socioeconomic activities.

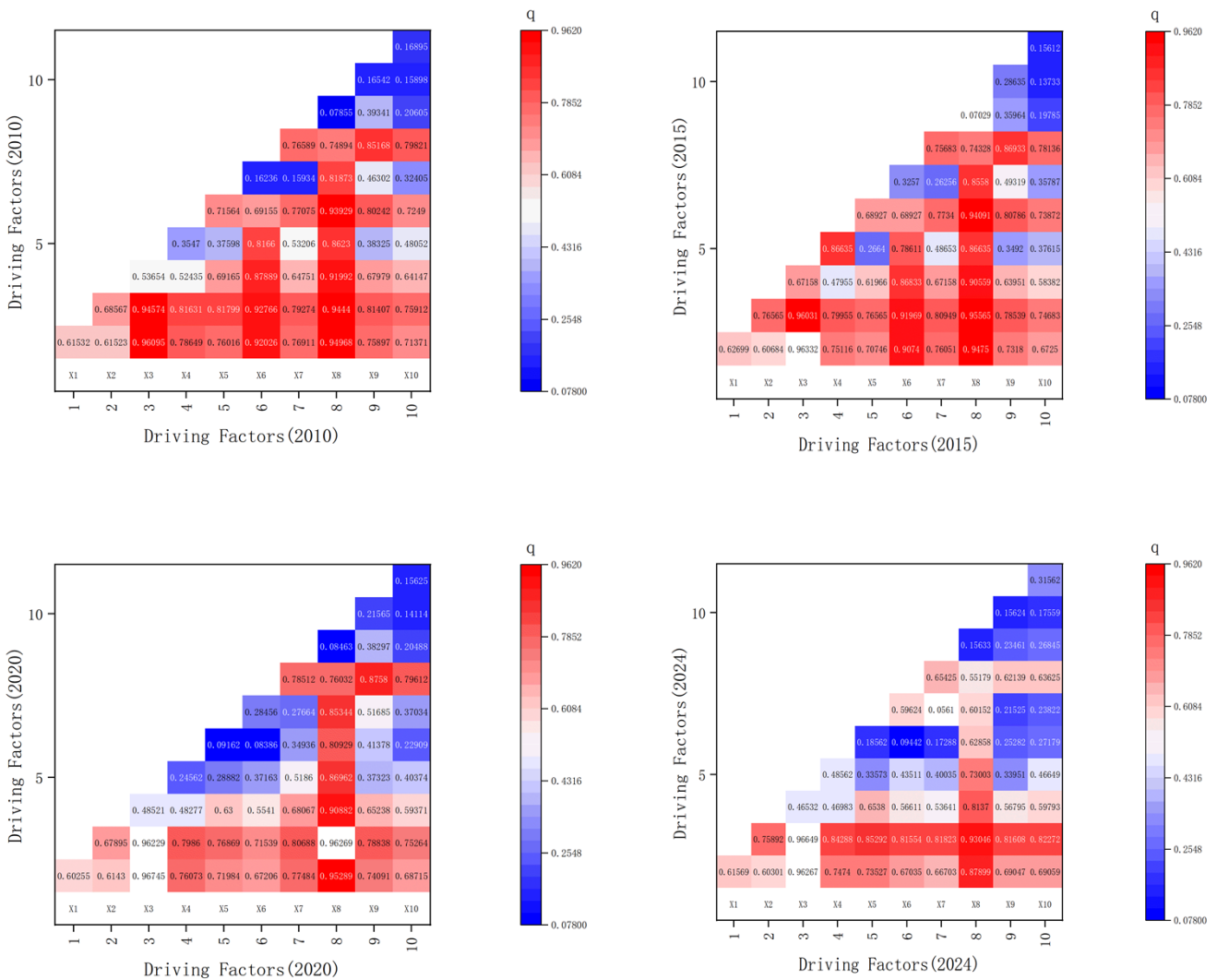


Figure 12. Interaction Effects of Influencing Factors on the Coupling Coordination Degree between Land Use and Ecosystem Service Value in the Central Yunnan Urban Agglomeration, 2010-2024

## 4 Discussion

### 4.1 Ecological Effects in Land Use Transformation: Co-occurrence of Construction Land Expansion and Total ESV Growth

The findings of this study indicate that from 2010 to 2024, the total ecosystem service value (ESV) in the Central Yunnan Urban Agglomeration showed a growth trend despite the continuous decrease in forest and cultivated land areas. This phenomenon is primarily attributed to the substantial concurrent increase in water body area, which has the highest unit value coefficient. The high marginal value gain from water bodies effectively offset the losses from the former land types<sup>38,39</sup>.

Data show that water bodies were the land type with the highest dynamic degree, especially during 2020–2024, with an average annual change rate of 11.67% and a net area increase of 683 km<sup>2</sup>. This change is directly related to human interventions in recent years, such as the construction of regional large-scale water conservancy projects (e.g., the "Central Yunnan Water Diversion Project"), reservoir expansions, and ecological restoration of rivers, lakes, and wetlands. These projects have altered the regional hydrological pattern, increased water body area, and thereby driven the increase in total ESV<sup>40,41</sup>. (It should be noted that this explanation is based on the widely accepted equivalent factor valuation method, and its results depend on the preset value coefficients for each land type. Although the magnitude of the coefficients directly affects the calculation, the ESV in this study showed low elasticity to the value coefficients (CS<1), supporting the robustness of the assessment results.)

The foundation for the growth in total ESV lies in the relative stability of the macro-structure of land use<sup>42</sup>. Throughout the study period, the combined proportion of forest and grassland consistently exceeded 75%, forming a stable ecological baseline for the region. Although their areas have slowly decreased (with dynamic degrees both below -0.1%), their dominant status remained unchanged, ensuring the continuity of basic ecological functions. However, potential risks associated with the current ESV growth pattern must be addressed. The continuous and rapid expansion of construction land (with dynamic degrees maintained between 2.5% and 3.2%) mainly occupied parts of cultivated land, forest, and grassland. This may directly lead to habitat loss, reduced carbon sequestration capacity, and generate hidden ecological costs through consequences like fragmented landscape connectivity<sup>42,43</sup>. The current ESV growth relies, to some extent, on the recent expansion of water bodies driven by water conservancy projects. Whether this growth is sustainable and whether it can compensate for the long-term value loss caused by ecosystem degradation and fragmentation induced by rapid construction land expansion remains to be observed. Therefore, future land management needs to strictly control the scale and spatial layout of construction land expansion while maintaining the reasonable growth of ecological land such as water bodies, to promote healthy and sustainable changes in ESV<sup>44,45</sup>.

### 4.2 Spatial Differentiation of Coupling Coordination and Evolution of Its Driving Mechanisms

Another key finding of this study is its characterization of the spatiotemporal transition of the coupling coordination between land use and ESV from an "uncoordinated" to a "coordinated" state within the Central Yunnan Urban Agglomeration, revealing the dynamic evolution of its driving mechanisms from "nature-dominated" to "natural-socioeconomic synergy." The coupling coordination degree exhibited a spatial pattern characterized as "higher in the south and lower in the north, higher in the west and lower in the east." This pattern is related to the region's "core-periphery" socioeconomic structure and its natural geographical endowments. Highly coordinated areas ( $D > 0.8$ ) were

consistently distributed in southwestern counties such as Shuangbai and Xinning throughout the study period. These regions are rich in forest resources, have low development intensity, and experience relatively minor human disturbance to natural ecosystems<sup>45,46</sup>. In contrast, the core development area of Kunming's main urban district exhibited high land use intensity, and its coordination degree remained at a medium-to-low level for most of the study period. This indicates that local ecological service functions still face certain pressures during rapid urbanization and construction land expansion, necessitating further reconciliation between the socioeconomic benefits and ecological benefits of land use<sup>45,47</sup>. The temporal evolution of the driving mechanisms further elucidates the causes of this spatial pattern. In 2010, natural factors such as NDVI and slope ( $q$ -value  $> 0.6$ ) dominated the pattern differentiation, suggesting that in the early developmental stages, natural conditions like topography and vegetation cover were the fundamental constraints limiting coordinated local development<sup>48,49</sup>. By 2020, the explanatory power of the GDP factor ( $q=0.760$ ) rose to the top, marking economic development as a key driving force. This also reflects a shift in the driving mechanism: from a state of "passive coordination" primarily determined by natural endowment towards a state of "proactive coordination" co-shaped by human interventions and the natural base. Notably, the interactive effects between factors like land use type (a human-modified factor) and slope (a natural factor) were significant, indicating that the interplay between human activity patterns and geographical constraints profoundly shapes the coordination status. Future spatial governance should be informed by this multifaceted interactive mechanism, strengthening protection in ecologically advantageous areas and promoting land use optimization alongside ecological space integration in areas under development pressure, thereby enhancing the overall synergistic level of the system<sup>50,51</sup>.

#### 4.3 Research Limitations and Future Prospects

While our study reveals the complex and dynamic interrelationship between land use structure and ecosystem service value (ESV) in the Central Yunnan Urban Agglomeration, it also has the following limitations: 1. The land use data used in this study are sourced from the publicly available CLCD (China Land Cover Dataset). Although the overall national accuracy of this dataset has been verified, an independent localized accuracy assessment specific to our study area was not conducted, constituting a potential limitation of the research. Future studies could enhance accuracy by collecting and validating more localized samples. 2. The conclusion that "total ESV showed an increasing trend despite the decrease in forest and cultivated land area" is primarily attributed to the significant expansion of water bodies, which have a high unit value coefficient. This explanation is based on the widely accepted equivalent factor valuation method, the results of which depend on the preset value coefficients for each land type. While the magnitude of these coefficients directly influences calculations, the low elasticity of ESV to value coefficient changes ( $CS < 1$ ) in this study supports the robustness of the assessment results. 3. The research relies on remote sensing image interpretation and various statistical datasets. Inherent data uncertainties, such as consistency in statistical caliber across different periods or sources, may influence the precision of the analytical findings.

Future research can be deepened in the following directions: First, by employing higher-resolution land use data and localized parameters to improve the precision of the ESV assessment model. Second, in analyzing driving mechanisms, factors such as policy interventions and ecological projects could be incorporated, and tools like structural equation modeling could be used to elucidate the interaction pathways and causal relationships among various factors. Finally, conducting simulation and prediction studies under multiple scenarios would provide more forward-looking and actionable decision support for optimizing regional territorial spatial patterns and ensuring ecological security.

#### 5 Conclusions

This study comprehensively analyzes the spatiotemporal evolution patterns of land use and ecosystem service value (ESV) in the Central Yunnan Urban Agglomeration from 2010 to 2024, revealing their coupling coordination relationship and underlying driving factors. The main conclusions are as follows:

(1) During the study period, the land use structure remained relatively stable, with ecological land (forest, grassland, and water bodies) constituting the dominant categories. However, significant internal dynamic shifts occurred within this structure. Construction land expanded continuously throughout the period, primarily at the expense of cultivated land and some forest land. This reflects the substantial pressure exerted by urbanization and industrialization on agricultural production and ecological space.

(2) The total value of regional ecosystem services increased significantly, with regulating services consistently contributing the most. This indicates that ongoing water conservancy projects, ecological restoration efforts, and water resource management initiatives—such as the Central Yunnan Water Diversion Project, the Niulan River–Dianchi Lake Water Supplement Project, and ecological restoration of abandoned slag sites—have yielded notable outcomes. Spatially, ESV exhibited a pattern characterized by high-value corridors oriented northeast–southwest and a stepwise growth pattern. Overall, despite the occupation of some ecological land by construction expansion, the sound ecological foundation of the agglomeration—marked by a high proportion of forest and grassland and the enhanced ecological function of water bodies—has effectively promoted the appreciation of regional ecological assets.

(3) The coupling coordination degree between land use and ESV steadily improved, with most areas transitioning from an uncoordinated to a coordinated state. Areas of high coordination are concentrated in the southwestern region, which possesses a superior ecological base, while core areas experiencing rapid urbanization, such as Kunming's main urban district, exhibited relatively lower coordination levels. This reveals the persistent tension between intensive human activities and the maintenance of ecological functions. The spatial pattern displays a "core–periphery" differentiation characterized as "higher in the south and lower in the north, higher in the west and lower in the east."

(4) Analysis of the driving mechanisms indicates that the evolution of the coordination relationship between land use and ESV in the Central Yunnan Urban Agglomeration underwent a dynamic process. It shifted from initial dominance by natural factors (vegetation, topography), to a phase where socio-economic factors (e.g., GDP) exerted significantly increased influence, and finally progressed towards a state of multi-factor synergistic driving involving both natural constraints (e.g., slope) and human factors (economy, population). Non-linear interactive enhancement effects were prevalent among factors, indicating that the coordination pattern is the integrated outcome of complex feedback between natural geographical conditions, ecological status, and human socio-economic activities.

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## Author contributions

J.L.Z. Conceptualization; Investigation; Validation; Formal analysis; Writing-original draft. L.D.N. Supervision; 706  
Resources; Project administration; Writing-review & editing. Y.Z provided experimental guidance, and M.J.Z provided 709  
language polishing assistance. 710

## Declarations

### Competing interests

The authors declare no competing interests.

### Data Availability

All data included in this study are available upon request by contact with the corresponding author J.L.Z. or L.D.N.

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