

Article

Coupling Coordination of Multi-Dimensional Urbanization and Ecological Security in Karst Landscapes: A Case Study of the Yunnan–Guizhou Region, China

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Abstract: Globally, karst regions face the dual challenges of urbanization and ecological protection, with the coupling coordination of multi-dimensional urbanization (MDU) and ecological security (ECS) being a necessary condition for achieving sustainable development. This study, based on statistical data on MDU and ECS in the Yunnan–Guizhou Region (the YGR) in China, employs the entropy weight TOPSIS model, degree of coupling coordination (CCD) model, and panel Tobit regression model to explore the coupling relationship between MDU and ECS. The main conclusions are as follows. (1) MDU in the YGR increased from 0.299 to 0.305, indicating low-level and sluggish development. Spatially, it is characterized by a “dual-core” structure centered on Kunming and Guiyang. (2) ECS decreased from 0.456 to 0.423, with a spatial pattern of “high in the east, low in the west”. The impact of human activities on ECS increased from 0.579 to 0.631 due to the increase in social and economic activities. (3) CCD increased to 0.579, achieving moderate coordination. The spatial feature evolved into a tri-cluster pattern of “high–low–high” across the “eastern–central–northwestern” regions. (4) Regression results indicate that annual average precipitation has a “both promoting and limiting” dual effect on CCD. The coefficient for the proportion of afforested land area is 0.205, with a significance level of 5%, suggesting that increasing forest cover is a key measure for improving CCD. The study reveals the factors influencing the evolution of MDU and ECS from a negative to a positive correlation, providing a basis for decisions related to sustainable development for urban and ecological management in karst landscapes globally.

Keywords: karst landscapes; sustainable urbanization; ecological sustainability; Tobit regression



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1. Introduction

Karst landscapes cover approximately 15% of the Earth’s surface, and their unique geological and hydrological features make them highly ecologically fragile and unrecoverable once lost [1]. As the level of urbanization in karst regions increases, these ecosystems exhibit high sensitivity to human activities [2]. Multi-dimensional urbanization (MDU) encompasses the comprehensive development and complex changes across various dimensions such as urban population, space, economy, and society during the urbanization process [3]. MDU in global karst regions has driven the development and transformation of population structures, spatial patterns [4], economic systems [5], and social forms [6] in karst cities. In the ongoing process of MDU, highly active economic and human activities in urban areas have led to significant environmental issues, including water pollution, air pollution, and soil contamination [7–9]. These issues not only diminish the quality of the urban ecological environment but also disrupt the overall stability of ecosystems, posing a severe threat to the social and ecological sustainability of karst landscapes [10]. The transformation of urban social structures and the expansion of land use have encroached upon ecological land, directly altering its original properties and vegetation-cover levels. This has led to the fragmentation of ecological land, impaired system functions, and the

degradation of system functions within karst ecosystems [11]. MDU and ecological security (ECS) are two coexisting and interconnected complex systems [12]. The rapid development of MDU can lead to a decline in ecosystem-service functions [13]. However, increasing investment in ECS may reduce investment in MDU construction, and an imbalance in their relationship can constrain the sustainable development of karst regions [14].

Scholars have focused on the interrelationship between MDU and ECS. Some scholars have found that MDU reduces ecosystem stability, leading to a gradual degradation of ECS [15]. This results in a negative correlation between MDU and ECS. However, as urbanization continues to progress, cities face development issues such as declining ecological environment quality and degraded ecosystem functions [16]. In response to these challenges, cities are implementing measures such as low-carbon development and ecological economy, aiming to limit the disorderly expansion of urban land and reduce damage to the natural environment [17]. In this regard, there is a positive correlation. Furthermore, some scholars have found that the relationship between MDU and ECS is not always simply positive or negative [18]. Due to the complex and dynamic development processes involved in urbanization, MDU and ECS may exhibit complex nonlinear relationships, such as an inverted “U” shape [19]. This relationship is mainly influenced by the level of urbanization. At high levels of MDU, it is more likely to exhibit a positive correlation [20]. In summary, research on the relationship between MDU and ECS has yielded rich results. However, the existing research also has the following limitations. (1) Existing studies often analyze the overall characteristics of ECS patterns at different stages of urbanization, lacking a comprehensive understanding of ECS as a complex system under the influence of MDU [21,22]. (2) Moreover, existing studies often adopt urbanization or ECS as separate research perspectives [23,24], indicating a need for further systematic exploration of their complex interactions. (3) Additionally, the current research tends to focus more on the quantitative relationships between urbanization and ECS, while paying less attention to their spatial interactions and spatiotemporal evolution [25,26]. (4) Furthermore, studies mainly focus on coastal and river-basin areas, as well as on economically developed regions [27,28]. In contrast, research in ecologically fragile areas such as karst landscapes is relatively lacking. This gap makes it difficult for research findings to provide scientific references for the orderly coordination of urbanization development and ECS in these ecologically fragile areas.

Based on the above points, this study focuses on the Yunnan–Guizhou Region (the YGR) in China as a typical karst area. The entropy weight–TOPSIS model and the coupling coordination degree model (CCDM) were used to analyze the relationship between MDU and ECS in the YGR. Using the panel Tobit regression model, dependent and independent variables were selected to reveal the factors influencing their relationship. The aim is to enhance the scientific basis of urbanization strategies and ecological protection measures in karst areas, promoting the sustainable development of both urban and ecological environments.

2. Materials and Methods

2.1. Study Area

The YGR is located in southwestern China, encompassing 25 prefectures in Yunnan and Guizhou provinces, with a total area of approximately 570,000 square kilometers (Figure 1). It is one of China’s four major plateaus and contains one of the world’s three highest concentrations of karst landscapes [29]. Positioned at the junction of continental plates, YGR is influenced by the collision and compression of the Indian Ocean plate and the Eurasian plate, resulting in rugged terrain overall. As an important ecological barrier in southwestern China, the region is crisscrossed with rivers and abundant in precipitation, with rainfall concentrated during the rainy season and often coming in heavy downpours. However, due to its unique karst landscape and geological conditions, the ecological environment in this area is extremely fragile, with severe issues of soil erosion and land desertification [30]. YGR is a key focus area for China’s “Western Development Strategy”

and the “Two Horizontal and Three Vertical” strategy, as well as an important node in advancing the One Belt One Road initiative. In 2010, the urbanization level in the YGR was only 34.26%, with a regional GDP of USD 16.28 billion, accounting for approximately 2.94% of the national GDP. By 2022, the urbanization level had increased by nearly 20% to reach 53.27%, with a regional GDP of USD 676.86 billion, accounting for 4.06% of the national GDP. The rapid development of urbanization has placed tremendous pressure on the fragile ecological environment of YGR, making the safeguarding of regional ECS a key and challenging step in effectively enhancing the quality of developing urbanization in the region.

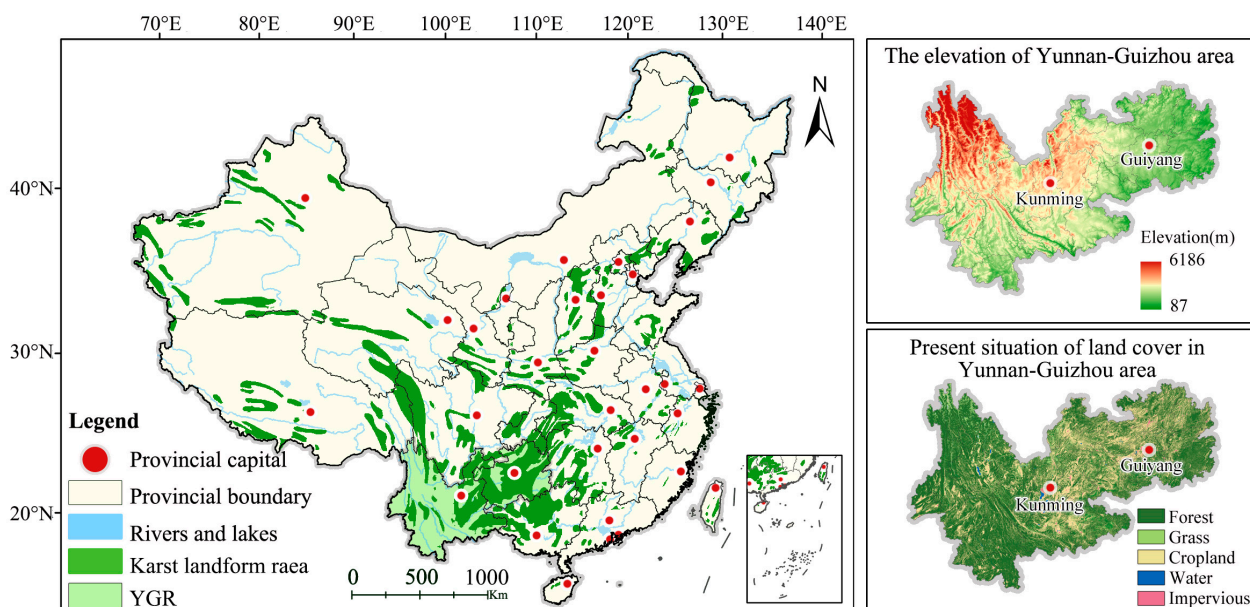


Figure 1. The research area.

2.2. Data Sources

The study period spans from 2017 to 2022, focusing on the 25 prefectures in Yunnan and Guizhou provinces. Data sources include the following. (1) MDU data primarily come from the “China City Statistical Yearbook”, supplemented by statistical yearbooks and bulletins from Yunnan Province, Guizhou Province, and relevant cities and states. (2) ECS data primarily originate from the “Ecological Environment Reports” of Yunnan Province and Guizhou Province. Forest coverage rates and terrain ruggedness were derived from calibrated Landsat TM/OLI satellite remote sensing images and 30×30 DEM data. Rainfall data were sourced from the official website of the China Meteorological Administration (<http://www.nmc.cn>) and the “Water Resources Bulletins” published by Yunnan and Guizhou Provinces. Soil data were obtained from the Second National Soil Survey Database of China. (3) Missing data were interpolated by calculating the average values from adjacent years.

2.3. Research Methodology

As shown in Figure 2, the main research content of this study includes two parts: the analysis of the degree of coupling coordination (CCD) between MDU and ECS and the study of their influencing factors.

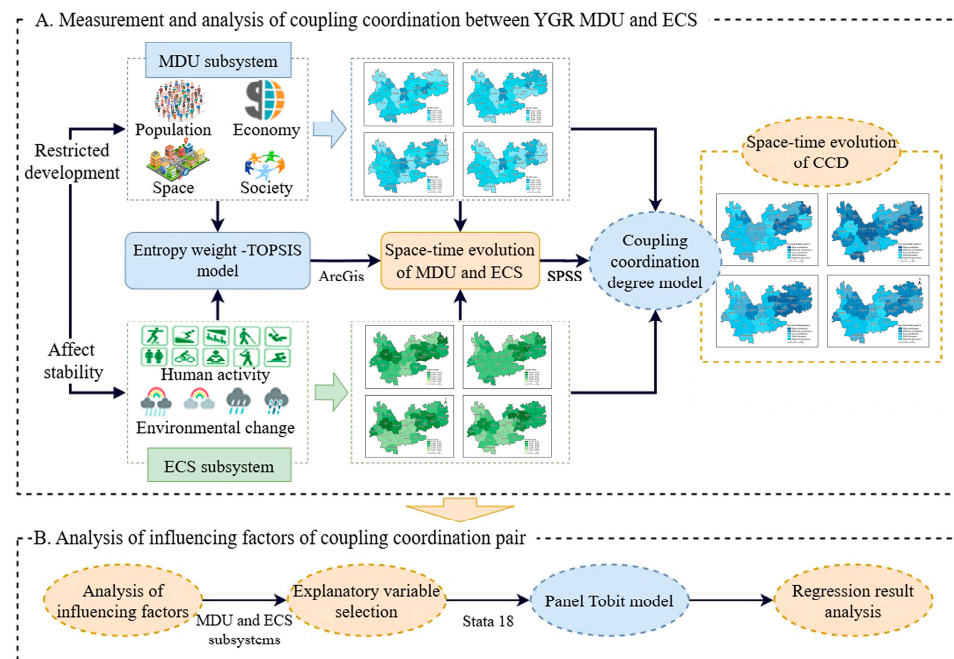


Figure 2. Research framework.

For the quantitative analysis of the degree of coupling coordination, formulas (1) and (2) were used to normalize the raw data of the indicator system. The entropy weight-TOPSIS model was then applied to calculate the MDU and ECS values for YGR. Subsequently, the CCDM was used to calculate the CCD between MDU and ECS, and their spatiotemporal evolution characteristics and mechanisms were analyzed.

In the study of influencing factors, it is necessary to select and process independent variables for the dependent variables. These variables include relevant indicators of urban population, space, economy, society, human activities, and environmental changes. Subsequently, the panel Tobit regression model was used to analyze the factors influencing CCD based on the selected independent variables.

2.3.1. The Evaluation Index System for MDU and ECS

Constructing a scientifically rational evaluation index system is a prerequisite for conducting research. Based on the current status of MDU development and ECS in the YGR, the evaluation index system for MDU and ECS (Table 1) was constructed with reference to the studies of Shaojian Wang et al. (2014) [31], Sheng Xiao et al. (2023) [32], and Qiufeng Zhang et al. (2024) [33]. The system uses population urbanization, spatial urbanization, economic urbanization, and social urbanization as the main indicators for MDU. ECS is a complex concept encompassing two main dimensions: human activities and environmental changes [34].

Table 1. Evaluation index system of MDU and ECS.

Subsystem	Primary Indicator	Secondary Indicator	Unit	Weight	Type
MDU Indicator System	Demographic urbanization	Urbanization rate of permanent residents	%	0.057	Positive
		Proportion of secondary-industry personnel	%	0.086	Positive
		Proportion of tertiary-industry personnel	%	0.068	Positive
		Population density	square kilometer per person	0.071	Positive

Table 1. Cont.

Subsystem	Primary Indicator	Secondary Indicator	Unit	Weight	Type
MDU Indicator System	Spatial urbanization	Per capita road area	square meters per person	0.044	Positive
		Proportion of construction-land area	%	0.180	Positive
		Per capita park and green-space area	m ²	0.064	Positive
	Economic urbanization	Per capita GDP	USD	0.066	Positive
		Proportion of added value of the secondary industry	%	0.025	Positive
		Proportion of added value of the tertiary industry	%	0.018	Positive
		Per capita disposable income of urban residents' households	USD	0.078	Positive
	Social urbanization	Number of beds per thousand urban residents	—	0.059	Positive
		Number of health technical personnel per thousand people	—	0.077	Positive
		Number of mobile phones per one hundred urban households	—	0.03	Positive
		Urban unemployment rate	%	0.036	Negative
		Per capita education expenditure	USD	0.041	Positive
Indicator System	Human activities	Sulfur dioxide emissions per square kilometer	μm/m ³	0.034	Negative
		Urban centralized domestic-sewage-treatment rate	%	0.037	Positive
		Rate of harmless treatment of urban and rural domestic waste	%	0.027	Positive
		Green-space ratio in built-up areas	%	0.054	Positive
		Annual average concentration of PM2.5	μm/m ³	0.077	Negative
	Environmental change	Forest-coverage rate	%	0.069	Positive
		Proportion of days with excellent ambient air quality	%	0.041	Positive
		Annual average precipitation	mm	0.083	Positive
		Proportion of afforested land area	%	0.33	Positive
		Rainfall erosivity	MJ·mm·ha ^{−1} ·h ^{−1}	0.026	Negative
		Soil erodibility	t·hm ² ·h/(hm ² ·MJ mm)	0.15	Negative
		Terrain ruggedness	—	0.072	Negative

Demographic urbanization refers to the process in which the rural population gradually transforms into an urban population and continuously concentrates in cities [35]. Selected indicators to represent the level and concentration of demographic urbanization include the urbanization rate of permanent residents, the proportion of secondary-industry personnel, the proportion of tertiary-industry personnel, and population density.

Spatial urbanization refers to the gradual transformation of non-urban land into urban land and its continuous expansion into surrounding areas, representing the expansion and evolution of urban spatial patterns [36]. The degree and rate of land-use urbanization are reflected by indicators such as per capita road area, the proportion of construction land area, and per capita park and green-space area.

Economic urbanization refers to the process of transforming and upgrading urban industries from traditional agriculture to modern sectors such as manufacturing and

tourism. The transformation of the urban economic structure is measured by the proportion of added value of the secondary industry and the proportion of added value of the tertiary industry. Urban economic changes and upgrading are characterized by per capita GDP and the per capita disposable income of urban residents' households.

Social urbanization refers to the process whereby the development of urban civilization and modern social forms continuously influence and spread to surrounding areas, comprehensively reflecting the levels of development of urban healthcare, culture, education, and other aspects [37]. The development of social urbanization is measured by the number of hospital beds per thousand urban residents, the number of health technicians per thousand people, the number of mobile phones per hundred urban households, the urban unemployment rate, and per capita education expenditure.

The impact of human activities on ecological security is assessed using sulfur dioxide emissions per square kilometer, the urban centralized domestic-sewage-treatment rate, the rate of harmless treatment of urban and rural domestic waste, the green-space ratio in built-up areas, and the annual average concentration of PM_{2.5}.

Changes in regional ecosystems caused by natural environmental conditions include variations in forest cover, the proportion of days with good air quality, and annual average precipitation. Given the risks of desertification and soil erosion in the YGR, it is also essential to enhance assessments of rainfall erosivity, soil erodibility, and terrain undulation [38]. The specific formulas used to calculate rainfall erosivity and soil erodibility were taken from the "Technical Specification for Investigation and Assessment of National Ecological Status—Ecosystem Services Assessment", which was published by the Ministry of Ecology and Environment of China in 2021. Additionally, afforestation is a key measure for YGR, being needed to address land desertification and soil erosion [39]. Therefore, it is necessary to include the proportion of afforestation area as an evaluation indicator.

2.3.2. The Entropy Weight–TOPSIS Model

The entropy weight–TOPSIS model combines the advantages of entropy weighting and TOPSIS, mitigating the subjectivity of evaluation methods such as the Analytic Hierarchy Process and the Delphi method on objective assessment outcomes. It identifies the optimal solution from a pool of alternatives based on their proximity to the ideal solution [40]. The interaction between MDU and ECS arises from intricate relationships among multiple indicators. Therefore, there is a need for an evaluation approach that accommodates diverse data types, is not constrained by the number of indicators, and comprehensively evaluates the impact of all indicators on evaluation subjects to enhance result stability and accuracy [41]. The entropy weight–TOPSIS method not only meets these criteria but also ranks evaluation subjects by their deviation from the ideal solution, providing an objective reflection of the region's actual conditions.

The formulas used for standardization of evaluation indicators are as follows:

$$\text{Positive unit} \quad y_{ij} = [x(i, j) - x_{\min}(j)] / [x_{\max}(j) - x_{\min}(j)] \quad (1)$$

$$\text{Negative unit} \quad y_{ij} = [x_{\max}(j) - x(i, j)] / [x_{\max}(j) - x_{\min}(j)] \quad (2)$$

In Equations (1) and (2), $x(i, j)$ ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$), y_{ij} represents the value of the j -th indicator in region i of the YGR and $x_{\max}(j)$ and $x_{\min}(j)$ represent the maximum and minimum values of the j -th indicator, respectively.

Calculation using the TOPSIS method is done as described below.

First, the information entropy of indicator j , H_j , is calculated through the following equation:

$$H_j = -k \sum_{i=1}^m p_{ij} \ln(p_{ij}) \quad (3)$$

In Equation (3), m represents the number of cities (similarly hereinafter), which is 28; $k = 1/\ln m$; $k > 0$; $\ln$ is a natural logarithm; $p_{ij} = y_{ij} / \sum_{i=1}^m y_{ij}$, and when $p_{ij} = 0$, $p_{ij} \ln p_{ij} = 0$.

Subsequently, the standard deviation of Indicator j , G_j , is calculated using the following equation:

$$G_j = 1 - H_j \quad (4)$$

Finally, the weight of Indicator J , W_j , is calculated as below:

$$W_j = G_j / \sum_{i=1}^n G_j (n = 1, 2, \dots, 30) \quad (5)$$

In Equation (5), n represents the number of indicators in the evaluation system (the same applies hereafter). When the subsystem is MDU, $n = 16$; when the subsystem is ECS, $n = 12$. The steps are as follows:

(1) Establish the weighted normalized matrix V :

$$V = |V_i| m \times n = W_j \times Y_{ij} \quad (6)$$

In Equation (6), Y_{ij} represents the matrix after normalization.

(2) Calculate the positive ideal solution Z^+ and negative ideal solution Z^- for the MDU and ECS of YGR.

$$Z^+ = \left\{ \max_{1 \leq i \leq m} \sum Z_{ij} | i = 1, 2, \dots, m \right\} = \{z_1^+, z_2^+, \dots, z_m^+\} \quad (7)$$

$$Z^- = \left\{ \min_{1 \leq i \leq m} \sum Z_{ij} | i = 1, 2, \dots, m \right\} = \{z_1^-, z_2^-, \dots, z_m^-\} \quad (8)$$

(3) Calculate the distance of each city in the Yunnan–Guizhou region from the optimal solution D_j^+ and the worst solution D_j^- , as follows:

$$D_j^+ = \sqrt{\sum_{i=1}^m (z_{ij} - z_i^+)^2} \quad (9)$$

$$D_j^- = \sqrt{\sum_{i=1}^m (z_{ij} - z_i^-)^2} \quad (10)$$

(4) Calculate the proximity of each region in the YGR to the ideal solution C_i , as follows:

$$C_i = \frac{B_i^-}{B_i^- + B_i^+} (i = 1, 2, \dots, m) \quad (11)$$

In Formula (11), C_i ranges between 0 and 1, representing the distance between the city and the ideal solution. A greater C_i value indicates that the city is closer to the positive ideal solution.

2.3.3. Coupling Coordination Degree Model

CCDM can quantitatively assess the interactions between different systems, measuring the degree of coordination and consistency among different systems during the same period. It has been effectively applied in areas such as regional urban development and ecological

environmental security [42]. Utilizing CCDM allows for an in-depth study of the mutual relationship and degree of coordination between MDU and ECS, as follows:

$$C = \frac{\sqrt{U_1 \times U_2}}{(U_1 + U_2)} / 2 \quad (12)$$

$$T = \alpha U_1 + \beta U_2 \quad (13)$$

$$D = \sqrt{C \times T} \quad (14)$$

Here, U_1 represents the comprehensive value of MDU for each region and U_2 represents the ECS value of each region, where α and β are undetermined parameters satisfying $\alpha + \beta = 1$. In this study, MDU and ECS of the region are equally important, hence $\alpha = \beta = 0.5$. C represents the coupling degree value, which is in the range $[0, 1]$. A greater C value indicates a closer relationship between the two, where T represents the comprehensive evaluation indicator. D represents the degree of coupling coordination, with values ranging from $[0, 1]$. A greater D value indicates a higher level of coordinated development within the system. Referring to the research by Qiufeng Zhang et al. (2023) [33], the degree of coupling coordination and corresponding levels of coordination are categorized into 5 grades (Table 2).

Table 2. Grade classification of CCDM.

Coupling Coordination Degree	Classification Results
High coordination	$0.65 \leq D \leq 1.000$
Moderate coordination	$0.55 \leq D < 0.65$
Low coordination	$0.45 \leq D < 0.55$
Mild dissonance	$0.35 \leq D < 0.45$
Moderate dissonance	$D < 0.35$

2.3.4. The Panel Tobit Regression Model

Due to the minimum threshold of 0 in the output results of CCDM, the study deals with truncated data, so ordinary least squares analysis could lead to biased regression results [33]. The use of panel Tobit regression models is appropriate when the dependent variable is subject to certain constraints [43]. The panel Tobit regression model not only avoids data loss or bias caused by truncation but also quantitatively analyzes various factors. Therefore, the panel Tobit regression model was adopted to analyze the most significant factors affecting the CCD between MDU and ECS, as follows:

$$Y_{it} = \alpha_{it} + \beta_1 X_{it} + e_{it} \quad (15)$$

In Equation (15), Y_{it} denotes CCD, X_{it} represents explanatory variables, β_1 signifies the regression coefficients of the independent variables, and $e_{it} \sim N(0, \sigma^2)$ denote the random disturbance terms. Additionally, α_{it} denotes the constant term. For specific index interpretations, please refer to Table 3.

The variables were categorized based on their roles in the regression model. The dependent variable (CCD) was used to assess the alignment between MDU and ECS. The independent variables were categorized into demographic, spatial, economic, social, human activity, and environmental changes, each providing insights into different dimensions of urbanization and their impacts on ecological coordination. This structured approach allowed for a comprehensive analysis of the factors influencing the coordination between urbanization and ecological safety.

Furthermore, logarithmic transformation was applied to mitigate heteroscedasticity issues in the data. The adjusted panel Tobit model is as follows:

$$Y_{it} = \alpha_{it} + \beta_1 \ln UPA_{it} + \beta_2 \ln UET_{it} + \beta_3 \ln USE_{it} + \beta_4 \ln USW_{it} + \beta_5 \ln DHA_{it} + \beta_6 \ln DEC_{it} + e_{it} \quad (16)$$

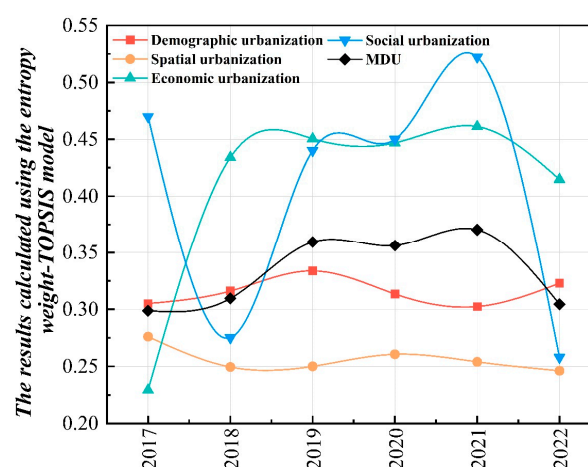
Table 3. Dependent and independent variables in the panel Tobit regression model.

Variable Types	Variable Name	Symbol	Specific Indicators
Dependent variable	CCD	CCD	CCD
Independent variable	Demographic urbanization	UPA	Urbanization rate of permanent residents
	Spatial urbanization	USE	Proportion of construction land area
	Economic urbanization	UET	Proportion of added value of the secondary industry, Proportion of added value of the tertiary industry
	Social urbanization	USW	Number of beds per thousand urban residents, Urban unemployment rate
	Human activities	DHA	Annual average concentration of PM _{2.5}
	Environmental change	DEC	Forest coverage rate, Proportion of afforested land area, Annual average precipitation, Rainfall erosivity, Soil erodibility, Terrain ruggedness

3. Results

3.1. Results of the MDU Subsystem

Based on the results of the entropy weight–TOPSIS model (Figure 3), from 2017 to 2022, the YGR’s MDU remained at a low level and developed slowly, increasing only from 0.299 to 0.305. Economic urbanization and demographic urbanization show a fluctuating upward trend, while social urbanization and spatial urbanization exhibit a fluctuating downward trend. The YGR’s MDU development leans more towards the transition from a rural to an urban population and urban economic growth rather than the enhancement of urban facilities and spatial expansion. This is mainly due to the YGR’s development policies, which encourage rapid urban population growth and economic growth through a series of “catch-up” strategies. Looking at the changes in primary indicators, the growth of demographic urbanization (from 0.305 to 0.323) contrasts with the slowed development of spatial urbanization (decreasing from 0.276 to 0.246). This highlights common challenges in areas with karst terrain, where land suitable for urban development is limited and infrastructure construction is difficult. The rise in economic urbanization (from 0.229 to 0.415), compared to the decline in social urbanization (from 0.450 to 0.258), underscores that the YGR’s economic growth has yet to effectively promote simultaneous improvements in urban facilities. Therefore, coordinating the rate and quality of urbanization development is crucial for allowing the YGR to advance high-quality development.

**Figure 3.** Evolution of MDU level in the YGR from 2017 to 2022.

Based on ArcGIS 10.7 data and using the natural-breaks method to partition the calculation results (Figure 4), the YGR exhibits a distinct “dual-core” structure centered around

Kunming and Guiyang, the provincial capitals. Kunming and Guiyang, as provincial capitals, possess significant advantages in regional resource allocation, labor attraction, infrastructure development, and supportive governmental policy, which place their MDUs ahead of those of other regions. It is noteworthy that the number of regions in the high-value zone has decreased from 13, in 2017, to 10. Among those transitioning to the low-value zone are peripheral cities such as Diqing, Nuijiang, Xishuangbanna, and Tongren, while the newly added Qujing is adjacent to Kunming. This highlights the strong radiating effect of provincial capitals on MDU development in surrounding areas. Lijiang's economic growth, driven by tourism, has propelled its development, placing Lijiang among the top cities by MDU by 2022. However, Lijiang faces challenges in fostering coordinated development in surrounding areas. The MDUs in western YGR lag significantly behind those of other regions, likely due to factors such as geographical location and transportation challenges.

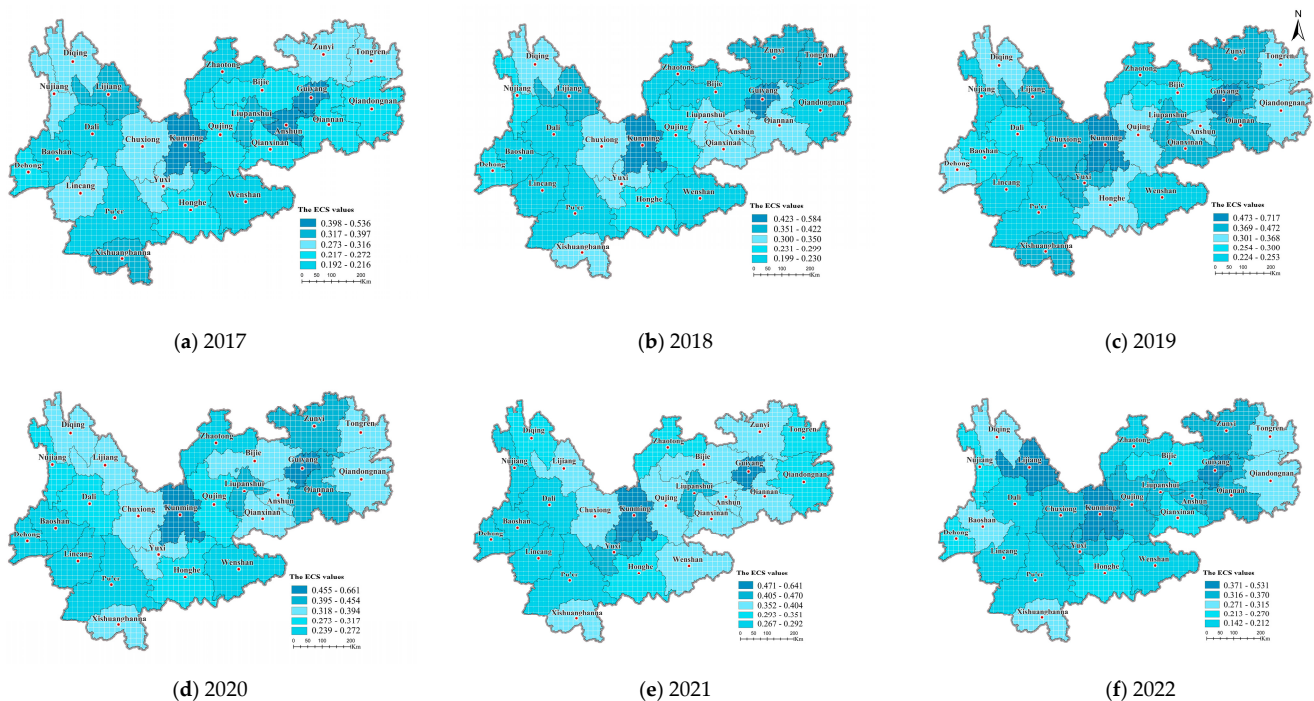


Figure 4. Trend in the spatial evolution of MDU in the YGR from 2017 to 2022.

3.2. Results of the ECS Subsystem

Figure 5 reflects the temporal evolution of the ECS subsystem from 2017 to 2022. During this period, YGR's ECS shows an “M” shaped fluctuating downward trend, declining from 0.456 to 0.423. Comparing this with Figure 3, ECS exhibits a declining trend alongside the increases in MDU in 2019 and 2021, indicating that the development of MDU in the YGR has a significant negative impact on ECS. The MDU model, characterized by demographic urbanization and economic urbanization, has significantly elevated the levels of human social and economic activities in the YGR, leading to increased emissions of pollutants such as $PM_{2.5}$ and SO_2 [44]. Consequently, the impact of human activities on ECS has increased from 0.579 to 0.631. Although social and spatial urbanization is currently on a downward trend, further development in population and economy will increase the demand for land use and various facilities, driving urban spatial expansion and infrastructure growth. Therefore, urban planning in the YGR needs to pay more attention to the scientific and rational development of cities, particularly considering the impact of MDU on the karst ecological environment. Environmental changes have significantly decreased from 0.416 to 0.361, reflecting YGR's long-term efforts in combating land desertification.

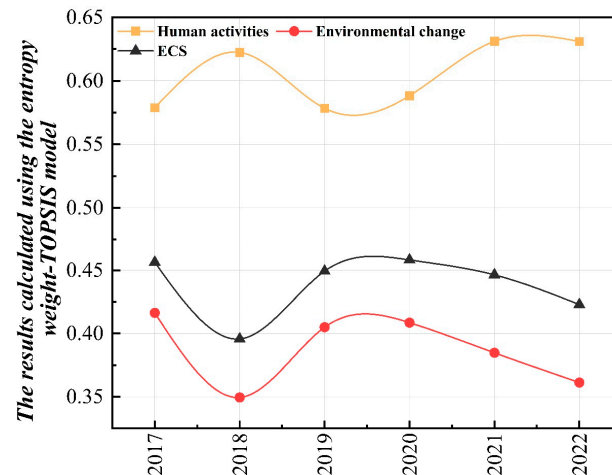


Figure 5. Evolution of ECS level in the YGR from 2017 to 2022.

From a regional perspective, spanning 2017 to 2022, the YGR's ECS exhibits a distinctive “east high, west low” differentiation, as depicted in Figure 6, with eastern Guizhou Province ranking notably higher than western Yunnan Province. In 2016, China issued the “Opinions on Establishing Uniform and Standardized National Ecological Civilization Pilot Zones”, designating Guizhou Province as one of these zones due to its superior ecological foundation and environmental carrying capacity. Green low-carbon initiatives, green finance, and ecological conservation became focal points of development in the province. Against this backdrop, various measures have been implemented by the Guizhou provincial government, society, enterprises, and other sectors to mitigate the negative impacts of MDU development on ECS. Simultaneously, Guizhou Province has continued to increase investment in funds and resources for combating land desertification. These efforts have resulted in a reduction of land desertification area from 24,700 km² in 2017 to 15,500 km² in 2022.

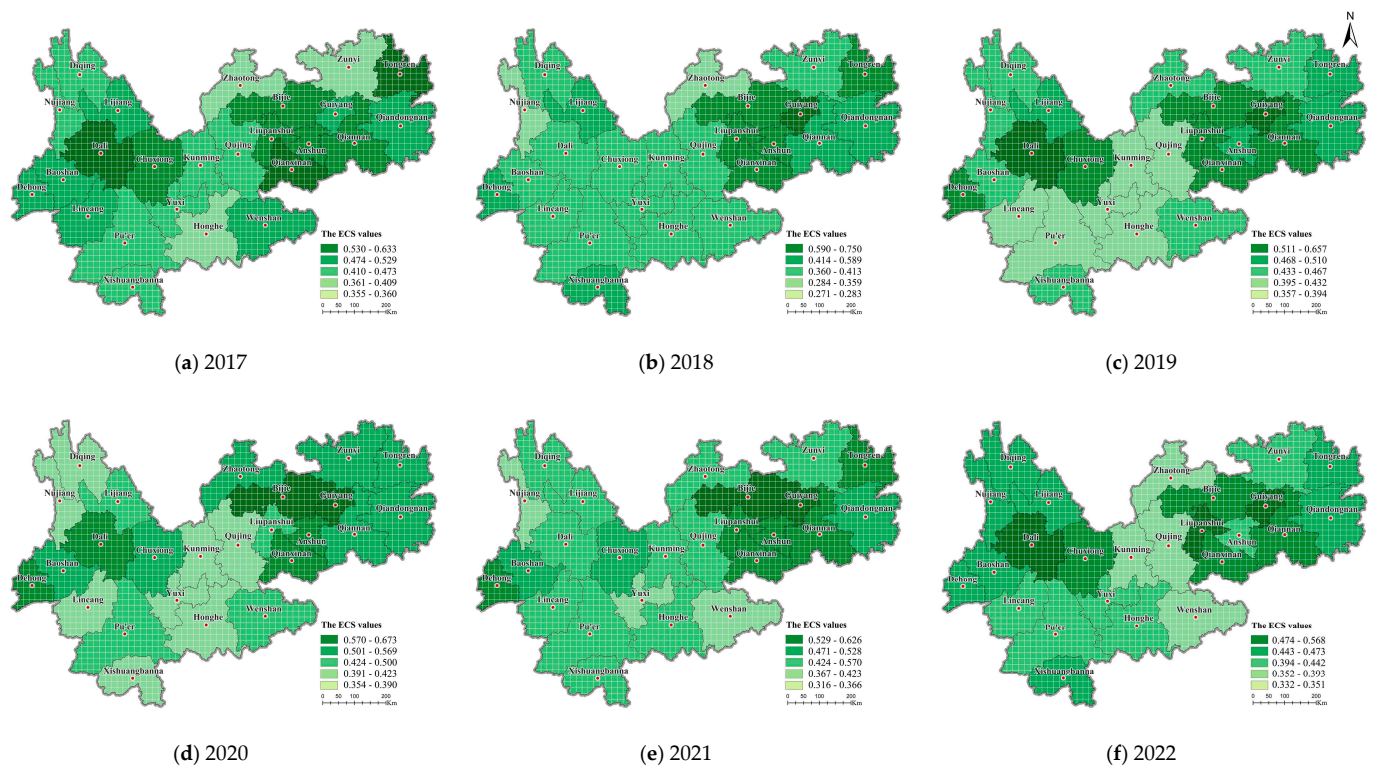


Figure 6. Trend in the spatial evolution of ECS level in the YGR from 2017 to 2022.

Considering various regions, the ECSs of Dali, Chuxiong, Bijie, Liupanshui, Qianxinan, and Qiannan consistently remained in the high-value zone, while Zhaotong, Honghe, and Kunming consistently remained in the low-value zone. Guiyang's ECS underwent a qualitative change from the low-value zone to the high-value zone, whereas ECS in other areas fluctuated but did not achieve a transition to the high-value zone. Anshun experienced a decline from the high-value zone to the low-value zone. Analysis showed that Anshun's urbanization rate, based on registered residents, had increased remarkably from 43% in 2017 to 58% in 2022, a significant 15% increase. However, extensive urbanization requires more ecological resources, leading to a noticeable decrease in Anshun's ECS. Anshun urgently needs to initiate ecological-protection and governance efforts while also reevaluating the relationship between development and ecology.

3.3. Results of the CCD

Table 4 illustrates the dynamic changes in CCD between MDU and ECS in the YGR. The CCD shows a trend of initially decreasing and then increasing, with the average value increasing from 0.512 to 0.579, reaching a moderate coordination level. From 2017 to 2019, the extensive development of MDU significantly stressed ECS, further enhancing their negative correlation. As MDU development began shifting towards an intensive mode in 2020, the synergistic effect between MDUs and ECSs became pronounced, leading to a gradual increase in CCD. This change aligns with the inverted-“U” relationship described by the Environmental Kuznets Curve (EKC), which relates environmental quality to development level. The degree of differentiation in CCD within the YGR has notably narrowed (CV: reduced from 0.363 to 0.308). This outcome is the result of multiple factors such as adjustments in regional development policy, optimization of resource allocation, and ongoing ecologically focused environmental-governance initiatives, including the One Belt One Road, Yangtze River Economic Belt, and the “Two Horizontal and Three Vertical” strategy. Guiyang consistently has the highest CCD, indicating that Guiyang's pattern of MDU development and ECS-focused protection and restoration strategies are exemplars for other regions to reference and learn from, especially for Kunming, which shares the status of provincial capital.

Table 4. Descriptive statistical results for CCD.

Year	Max	Min	Avg	CV
2017	0.827	0.141	0.512	0.363
2018	0.995	0.168	0.461	0.427
2019	0.995	0.117	0.488	0.378
2020	0.995	0.184	0.488	0.377
2021	0.987	0.166	0.535	0.318
2022	0.972	0.195	0.579	0.308

The spatial-distribution pattern of the YGR's CCD has gradually evolved from single clusters into a tri-cluster configuration (Figure 7), indicating a more complex and diverse development trend. The number of regions reaching coordination or higher levels has noticeably increased, while the number of areas in dissonance has decreased. Most regions show improved coordination between urbanization and ecological conservation. However, fluctuations in CCD are evident when examining changes in the number of regions in coordination and dissonance states. Continuous monitoring of the evolution of spatial patterns of CCD is essential and should be accompanied by in-depth analysis of differences and connections among the clusters, to better promote regional coordinated sustainable development. From 2017 to 2019, CCD transitioned gradually from a single cluster centered around Anshun to a dual cluster centered around Anshun and Dali, with low-value areas mainly concentrated in the southern and central YGR. In 2020, CCD in the western regions showed a declining trend, with only Chuxiong achieving a moderate coordination level; others were predominantly in dissonance. A review of the original data revealed

that this was primarily due to variations in precipitation. In 2019, the annual average precipitation in western Yunnan Province was 1008.0 mm, increasing to 1157.2 mm in 2020. This rise in rainfall significantly exacerbated soil erosion and land desertification in karst areas, leading to deterioration of the ecological carrying capacity. Post-2020, a tri-cluster pattern has essentially formed, with high-value clusters in the eastern and northwestern parts and a low-value cluster in the central part. This is mainly attributed to the most typical and concentrated karst areas being in the central YGR, where soil erosion and land desertification are most severe, causing a misalignment between MDU and ECS.

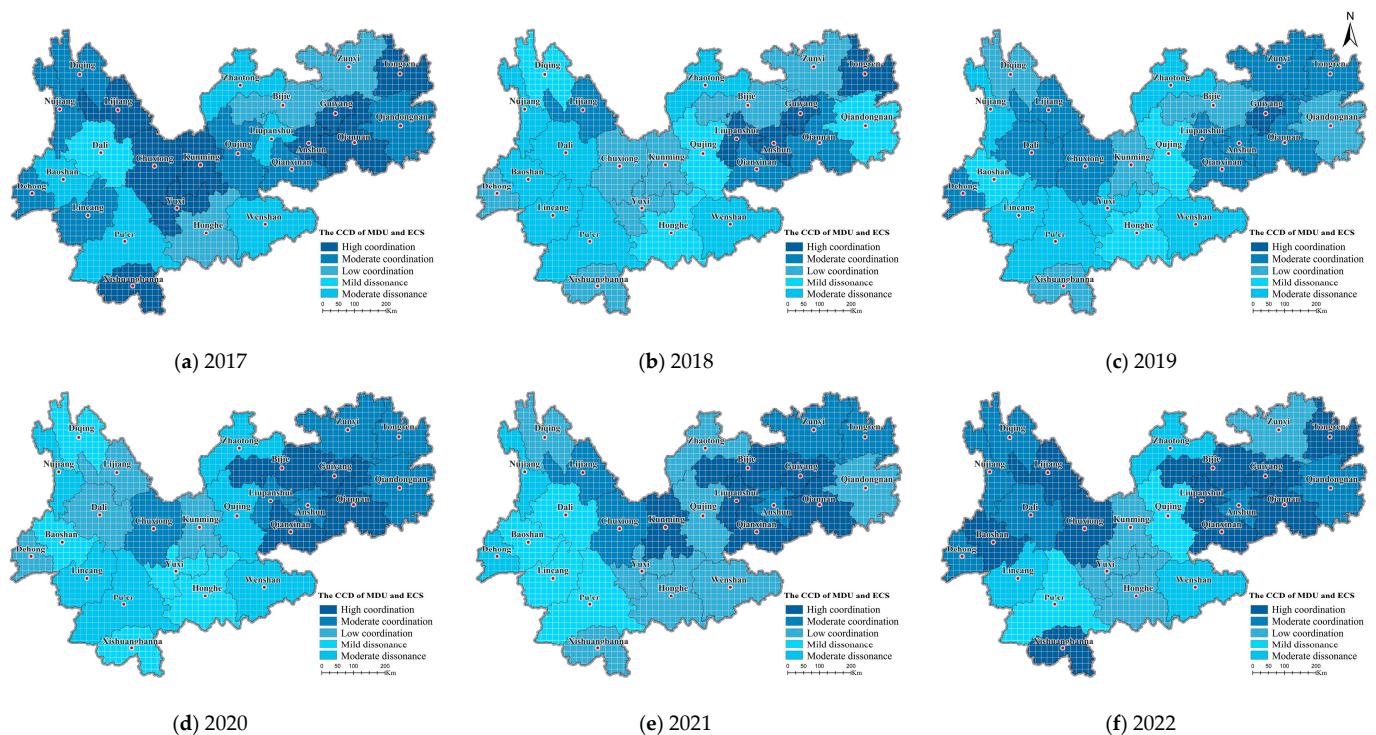


Figure 7. Trend in the spatial evolution of ECS level in Yunnan–Guizhou region from 2017 to 2022.

3.4. Analysis of Driving Factors

The panel Tobit regression results from Stata 18 indicate that seven indicators significantly impact the CCD of MDU and ECSs (Table 5). (1) The coefficient for the urbanization rate of permanent residents is 1.134, which is significant at the 10% level. This suggests that as the urbanization rate of permanent residents increases, the degree of urbanization and the vigor of urban development in the YGR also increase. This enhancement in socioeconomic development and resource-allocation capabilities within cities positively impacts the coupling degree of MDU and ECS, thereby fostering a higher level of coordinated development between them. (2) The coefficient for annual average of PM2.5 concentration is -0.508 , which is significant at the 1% level, reflecting increased human activities such as industrial production, resource exploitation, and pollution emissions. This highlights the necessity for the YGR to formulate responsive plans to manage industrial development, resource exploitation, and pollution control effectively. These measures are crucial in mitigating the adverse impacts of socioeconomic activities on the karst ecological environment. (3) The coefficient for annual average precipitation is 1.208, which is significant at the 5% level. Increased annual average precipitation helps enhance water-resource availability in the YGR [45]. Adequate water resources are fundamental for urban development, supporting socioeconomic growth and thereby promoting higher levels of MDU. Moreover, sufficient precipitation maintains soil moisture, supports vegetation growth, reduces drought impacts on ecosystems, and stabilizes overall ecological conditions [46]. (4) Increased rainfall erosivity can lead to highly eroded land, negatively impacting ecosystems in karst regions.

While annual average precipitation can promote the coordinated development of MDU and ECS subsystems, high rainfall erosivity indicates that excessive precipitation can cause land scouring and erosion, exacerbating ecosystem degradation and increasing the probability of flooding disasters [47]. (5) Both soil erodibility and terrain undulation are significant at the 5% level and are negatively correlated with CCD. Increased soil erodibility affects the safety of urban land use, raises risks of geological disasters, and exacerbates soil erosion and land desertification in karst ecosystems. Relatively minor terrain undulation reduces construction difficulty, improves transportation conditions, and is beneficial for urbanization in the YGR while mitigating risks of soil erosion and land desertification in karst ecosystems.

Table 5. The regression results of the panel Tobit regression model.

Variable	Coefficient	Std. Error	Z-Statistic	p-Value
Urbanization rate of permanent residents	1.134	0.359	3.161	0.098 *
Annual average concentration of PM _{2.5}	−0.508	0.235	−2.164	0.002 ***
Annual average precipitation	1.208	0.615	1.965	0.030 **
Proportion of afforested land area	0.205	0.065	3.175	0.049 **
Rainfall erosivity	−0.443	0.176	−2.518	0.002 ***
Soil erodibility	−1.993	0.924	−2.156	0.012 **
Terrain ruggedness	−0.248	0.149	−1.666	0.031 **

Note: ***, **, * represent significance levels of 1%, 5%, and 10%, respectively.

4. Discussion

4.1. The Spatiotemporal Evolution of MDU and ECS

The development of urbanization and ecological conservation are core topics in economic geography and ecological environmental science, respectively [12]. Coordinating the relationship between urbanization and ecological conservation is crucial for achieving sustainable development in karst landscapes [48]. Therefore, it is necessary to study the interrelationship between the two to enhance the scientific basis for the coordination of urbanization-development and ecological-protection strategies in regions with karst landscapes.

Results of the analysis of the MDU subsystem indicate that rapid population growth and economic development in karst regions have driven the urbanization process. However, this rapid growth has also led to issues such as declining quality and level of urban space and supporting facilities [49]. This may be attributed to a combination of factors, including restrictions on unregulated urban expansion in the National New Urbanization Plans (2014–2020 and 2021–2035), delayed construction of supporting facilities, and land-use restrictions in karst landscapes. On the other hand, assessment of the ECS subsystem shows that human activities are increasingly impacting the karst ecological environment. Impacts include issues such as land-use changes, degradation of ecosystem functions, and overexploitation of water resources [10,11]. It emphasizes the need, during urban planning and development, to protect and restore the capacity of ecosystems. Measures such as rational land-use planning, establishment of ecological protection areas, and implementation of ecological restoration projects are necessary to balance urban construction needs with environmental protection. Furthermore, the evaluation of the ECS subsystem acknowledges significant achievements in controlling soil erosion and land desertification in the YGR.

The MDU and ECS of the YGR exhibit significant spatial heterogeneity, which is driven by varying levels of MDU development and current ECS conditions. To address the potential challenges posed by this heterogeneity, particularly in underdeveloped MDU areas in the west and regions with low ECS values in the central area, targeted regional strategies for urbanization development and ecological-restoration measures are necessary. These strategies aim to narrow the disparities among different regions. This can be achieved through urbanization policies that emphasize sustainability and fairness to reduce spatial disparities in MDU, as well as to ecological-development measures that prioritize both conservation and utilization and emphasize restoration alongside governance.

4.2. CCD and Factors Driving MDU and ECS

In karst landscapes, the development of MDU exerts a compelling influence on ECS, manifested through irreversible conversion of ecological land and sustained, high-intensity demands on ecological resources [50]. Conversely, ECS imposes constraints on the MDU-development process. The ecological resource base of karst landscapes determines the upper limit of development, and land conditions restrict the methods and scale of urban land use [51]. According to the EKC, the relationship between MDU and ECS unfolds in three stages. In the early stage, low levels of MDU development result in minimal impact on ECS, and their coupled coordination relationship is not significant. As MDU rapidly advances and reaches a certain level in the mid-term, the exponential growth in MDU's resource demands increases the overall burden on ECS, leading to a negative correlation between the two. In the later stage, as MDU stabilizes at a certain level, its sustainable development enhances the overall stability of ECS. At the same time, stable ECS provides continuous ecological resources for MDU, resulting in a positive correlation between them. However, in karst landscapes, due to the fragility and unrecoverable quality of the ecological environment, the development stage and extent of the EKC may differ compared to other regions. The negative correlation between MDU and ECS might persist until a higher level of urbanization is reached, at which point it may evolve into a positive correlation.

The CCD between MDU and ECS over time shows an initial decline followed by an upward trend, evolving from a negative correlation to a positive correlation. This indicates that policymakers at the MDU level can mitigate the loss of ecological space and encroachment by promoting intensive use of urban land resources, optimizing economic and industrial structures, and reducing pollutant emissions through various policies and measures. From the ECS perspective, limiting boundaries around urban spatial development ensure the protection of vital ecological functional areas. Increasing investment in ecological restoration, as through afforestation, soil conservation, and other ecological restoration projects, enhances ecosystem stability and service functions. The “three clusters” feature of CCD implies the need for differentiated MDU-development strategies and ecological governance measures. These should be tailored based on the developmental status, potential, and ecological-resource baseline of each region to enhance the scientific appropriateness of development planning. Simultaneously, increased governance funding is crucial in allowing ongoing ecological restoration and management efforts to enhance the ecological resource base and resilience of the YGR.

4.3. The Limitations of This Study

The above research findings reveal the interrelationship between MDU and ECS in karst landscapes, thereby helping urban managers accurately adjust various factors of urbanization and ecology and mitigating conflicts between urban planning and ecological protection in these regions. However, two limitations of this study need to be addressed in future research. The first limitation is the scope of the study, which primarily focuses on macro- and meso-level research on the coupling coordination between MDU and ECS in the YGR. Further refinement to micro-level dimensions, such as counties and townships, could provide more practical and effective strategies and measures for urban development and ecological protection. Secondly, the secondary indicators of human activities primarily consider negative impacts. Due to data availability and confidentiality, positive indicators such as environmental-management resources, as well as investments in funding and manpower, were not included in the evaluation criteria. Future research could explore expanding data sources and incorporating positive indicators into the evaluation framework.

5. Conclusions

Exploring the interrelationship of MDU and ECS and their influencing factors is a key prerequisite for achieving sustainable development in karst landscapes. This study utilized the entropy weight–TOPSIS model, coupling coordination degree model, and panel Tobit

regression model to investigate the coupling coordination of MDU and ECS of the YGR from 2017 to 2022 based on urban-rural statistical data and ecological environment data. The main conclusions are as follows:

(1) From 2017 to 2022, the MDU of the YGR increased from 0.299 to 0.305, indicating low-level and sluggish development. The main characteristics are the urbanization of the population and the economic transformation of urbanization. Spatially, this is manifested in the “dual-core” structure with Kunming and Guiyang as the central cities.

(2) The ECS exhibited a fluctuating downward trend, decreasing from 0.456 to 0.423. Due to the increase in human social and economic activities in the YGR, the impact of human activities on ECS rose from 0.579 to 0.631. Spatially, this was characterized by a distinct “high in the east, low in the west” pattern. Guiyang’s ECS transitioned from a low-value to a high-value area, while Anshun shifted from a high-value to a low-value area, with other regions remaining relatively stable.

(3) Based on the increased CCD of MDU and ECS to 0.579, which reached the level of moderate coordination, the disparities in CCD between cities have significantly decreased. This improvement can be attributed to adjustments in regional policies, optimization of resource allocation, and enhanced ecological environment management. Spatially, the CCD has gradually evolved into a tri-cluster pattern of “high–clow–chigh” across the “eastern–central–cnorthwestern” regions.

(4) Regression results indicate that annual average precipitation has a “both promoting and limiting” dual effect on CCD. An increase in annual average precipitation promotes the coordinated development of MDU and ECS. However, under the combined effects of rainfall erosivity, soil erodibility, and terrain undulation in karst landforms, it also exacerbates the risks of soil erosion and rocky desertification. The coefficient for the proportion of afforested land area is 0.205, which is significant at the 5% level, indicating that increasing the area of forest cover is a key measure to promote the improvement of CCD and achieve the sustainable development of the YGR.

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