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Coupled and Coordinated Development of New Urbanization and Ecological Vulnerability: Evidence from Counties in the Upper Reaches of the Yangtze River

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Abstract: Achieving coupled and coordinated development of new urbanization (NU) and ecological vulnerability (EV) is the key to promoting high-quality development. Focusing on 345 counties in the upper reaches of the Yangtze River, which have vulnerable ecological condition and experience rapid urbanization in recent years, this study assessed the levels of NU and EV base on multi-dimensional indicator systems, quantitatively analyzed the coupling coordination degree (CCD) between NU and EV from 2010 to 2020 and predicted their future development trends, using entropy weight TOPSIS method, coupling coordination model, Dagum Gini coefficient and ARIMA model with county-level multi-sourced data. The results showed a positive trend of

CCD between NU and EV; however, the overall level remains low, and highly vulnerable areas accounted for a large proportion. It is expected that the study area will reach the intermediate CCD between NU and EV by 2030 with intensive ecological recovery and protection measures.

Key words: new urbanization, ecological vulnerability, coupling coordination degree, county-level analysis, the upper reaches of the Yangtze River

1 Introduction

Urbanization is a vital force in shaping the global socio-economic and environmental structure, especially in developing countries. Since the reform and opening in 1978, China has experienced unprecedented urbanization, which is expected to accelerate (Lv et al., 2019). Such rapid urbanization has brought significant economic and social changes, while also intensifying the conflict between humans and nature. Studies have shown that there are complex interactions between urbanization and the ecological environment. On one hand, the ecological environment provides resource support for urbanization, while environmental pollution and ecological degradation cause economic loss and may severely restrict development (He et al., 2018). On the other hand, rapid population growth, land use changes, and infrastructure extension during the traditional economy-centered urbanization processes have led to severe ecological and environmental issues, including ecosystem degradation, frequent natural disasters, air pollution, and climate change (Dadashpoor et al., 2019; Liu et al., 2023; Xu et al., 2016).

In response to the challenges posed by economy-centered urbanization, in 2014, the Chinese government proposed new urbanization (NU), promoting coordinated development and alleviating the contradiction between economic growth and the deterioration of resources and environment (Chen et al., 2019; Feng et al., 2023; Guan et al., 2018). NU is a human-centered development model that emphasizes ecological protection, environmental friendliness, and resource conservation, being oriented toward low-carbon, intelligent, and green development (Xu et al., 2024). New-type urbanization redirects its emphasis from land-centered expansion toward a cohesive, resident-focused model, with the fundamental goal of reconciling urban development with eco-efficiency (Wang et al., 2025). It aims to achieve synergies between urbanization and the environment through socioeconomic and ecological systems (Zhao et al., 2024). As the NU strategy has been implemented for about 10 years, it is essential to evaluate whether it has promoted the coordination between urban development and ecological conditions.

Previous studies have unfolded the interrelationship between urbanization and ecological environment through ecological environment efficiency (Chen et al., 2023), ecological total factor energy efficiency (Ren and Yu, 2021), ecological security (Zhang et al., 2023), and coupling coordination between urbanization and ecological elements (Li et al., 2023), from the national, provincial, and urban agglomeration scopes (Chen et al., 2023; Lei et al., 2024; Ren et al., 2022; Sui et al., 2024; Zhang et al., 2023). Although extensive research has examined the coupling coordination between urbanization and the ecological environment at national, provincial, and urban

agglomeration scales (Zhang et al., 2022; Zhu et al., 2024), empirical evidence remains insufficient in ecologically fragile areas at the county level. In such areas, urbanization tends to exacerbate ecological vulnerability (EV), which is characterized as a combination of an ecosystem's sensitivity and its degradation degree within specific spatial and temporal scales in response to external disturbances (Wei et al., 2020; Xie et al., 2024). In areas with high EV, urbanization is a double-edged sword that may enhance environmental adaptive capacity through resource agglomeration at the early stage while exacerbating system vulnerability once the excessive expansion exceeds the ecological threshold (Ma et al., 2023).

The current study raises attention for the dynamic relationship between NU and EV (Nie et al., 2023; Zou et al., 2022), and their coupling coordination needs to be further clarified. The upper reaches of the Yangtze River, characterized by rich biodiversity and complex ecosystems, embody both the vision of urbanization and face ecological challenges such as habitat degradation and deteriorating water quality. Therefore, it is essential to explore the interaction between NU and EV. This study aims to identify interaction patterns between NU and EV through empirical analysis of 345 counties in the upper reaches of the Yangtze River, to provide references for coordinated development for the study area and broader areas with similar conditions.

Following the introduction, Chapter 2 establishes the evaluation indicator systems for NU and EV, Chapter 3 details the study area and data sources, Chapter 4 explains the methodology, Chapter 5 presents the results on the spatio-temporal patterns of NU and EV, their coupling coordination degree (CCD) and the future trends, Chapter 6

discusses the findings and policy implications, and Chapter 7 concludes the study with limitations and outlooks.

2 Construction of indicator systems

Following the principles of scientificity, representativeness, and data accessibility, this study constructs the evaluation indicator systems for NU and EV, considering the regional-specific situations, based on previous studies (Cai et al., 2021; Cao et al., 2023; Fang and Liu, 2009; Hua et al., 2024; Nie et al., 2023; Wang et al., 2023; Zhang et al., 2022; Zhang et al., 2023)

2.1 Evaluation indicator system for NU

Unlike traditional urbanization that focused on economic growth and spatial expansion, NU is human-centered that emphasizing the coordinated integration of industry and agriculture development, and harmony of economic and social systems, aiming to achieve high-quality, sustainable, and inclusive growth (Xu et al., 2024). Consistent with the multi-dimensional nature of new-type urbanization emphasized by recent studies (Wang et al., 2025; Zhu et al., 2024), our evaluation system incorporates not only economic and social dimensions but also urban-rural integration. As listed in Table 1, this study constructs an evaluation indicator system from four dimensions, namely industrial structure, agricultural development, economic development, and social development, measured by ten indicators to reflect the multifaceted nature.

Table 1 Evaluation indicator system for NU

Target Layer	Indicator	Effect	Literature Citation
Industrial structure	X_1Proportion of added value of primary industry (%)	-	Zhang et al., 2022
	X_2Proportion of added value of secondary industry (%)	+	Li et al., 2022; Hua et al., 2024; Zhang et al., 2022
	X_3Proportion of added value of the tertiary industry (%)	+	Li et al., 2022; Hua et al., 2024
Agricultural development	X_4Per capita grain production (tons/person)	-	Cao et al., 2023; Fang and Liu, 2009
Economic development	X_5Per capita GDP (yuan/person)	+	Li et al., 2022; Nie et al., 2023; Wang et al., 2023; Zhang et al., 2023
	X_6Per capita total output value of industrial enterprises above designated size (yuan/person)	+	Zhang et al., 2023
	X_7Per capita retail sales of consumer goods (yuan/person)	+	Wang et al., 2023
Social development	X_8Hospital beds per 10,000 people (beds/person)	+	Nie et al., 2023; Wang et al., 2023; Zhang et al., 2023
	X_9Number of students in secondary schools per 10,000 people	+	Zhang et al., 2023

X_{10}Per capita savings deposit balance of urban and rural residents (yuan/person)	+	Zhang et al., 2023	

2.2 Evaluation indicator system for EV

With population growth and the acceleration of urbanization, the resource and environmental carrying capacity in ecologically-fragile areas is approaching its limit (Hou et al., 2020). EV assessment and impact analysis are crucial for achieving sustainability (Chen et al., 2024), while EV evaluation at China's county level remains scarce due to the complexity of the index systems and data limitations. In line with recent regional ecological risk assessments that employ nighttime light data and PM2.5 concentration as proxies for human disturbance (Wang, 2021; Wiredu et al., 2024; Ghosh et al., 2023), we incorporate these indicators to capture the pressure dimension of ecological vulnerability. As listed in Table 2, this study comprehensively reflects EV in the upper reaches of the Yangtze River by considering multiple factors such as natural environment, ecological status and human activities from the perspective of "exposure-sensitivity-adaptability" (Jiang et al., 2023; Bao and Xi, 2023; Wang et al., 2024; Li et al., 2022; Yi et al., 2023).

Table 2 Evaluation indicator system for EV

Target layer	Sub-layer	Indicator	Effect	Literature Citation
Exposure	Air quality	$Y_1PM_{2.5}$	+	Bao and Xi, 2023; Jiang et al., 2023

	Surface structures	Y_2Land use type	+	Li et al., 2022; Wang et al., 2024
	Economic pressures	Y_3Nighttime light index	+	Li et al., 2022; Wang et al., 2024
Sensitivity	Terrain factor	Y_4DEM	+	Bao and Xi, 2023
		Y_5Slope gradient	+	Bao and Xi, 2023; Cai et al., 2021; Jiang et al., 2023
		Y_6Terrain undulation	+	Jiang et al., 2023
	Meteorology	Y_7Annual average temperature	-	Li et al., 2022; Wang et al., 2024
		Y_8Annual average precipitation	-	Bao and Xi, 2023; Jiang et al., 2023; Wang et al., 2024
	Vegetation	Y_9NDVI	-	Bao and Xi, 2023; Cai et al., 2021; Wang et al., 2024
Adaptability	Landscape structure	Y_{10}Landscape Diversity Index (SHDI)	-	Cai et al., 2021; Jiang et al., 202
		Y_{11}Landscape Aggregation Index (AI)	-	Jiang et al., 2023

3 Study areas and data sources

As the largest geographical component of the Yangtze River Economic Belt, the upper reaches of the Yangtze River cover 345 counties in Sichuan Province, Yunnan Province, Guizhou Province, and Chongqing Municipality (Figure 1), playing a vital role in promoting the high-quality development of the Yangtze River in terms of resource supply, ecological support, production exchange, and consumption processes. The terrain in the study area is complex and diverse, with mountains, hills, and rivers interlaced, forming a unique ecosystem with high biodiversity in terms of forest vegetation and aquatic ecosystems. In addition, the ecological red line in the study area spans 7.66×105km^2, accounting for 67.8% of the total ecological red line area of the Yangtze River Economic Belt and 47.3% of its total ecological service value (Xu et al., 2019). With the advancement of NU, population concentration, rapid economic development, and accelerated infrastructure construction have brought significant pressure on the ecological environment and deepened EV (Wen et al., 2023).

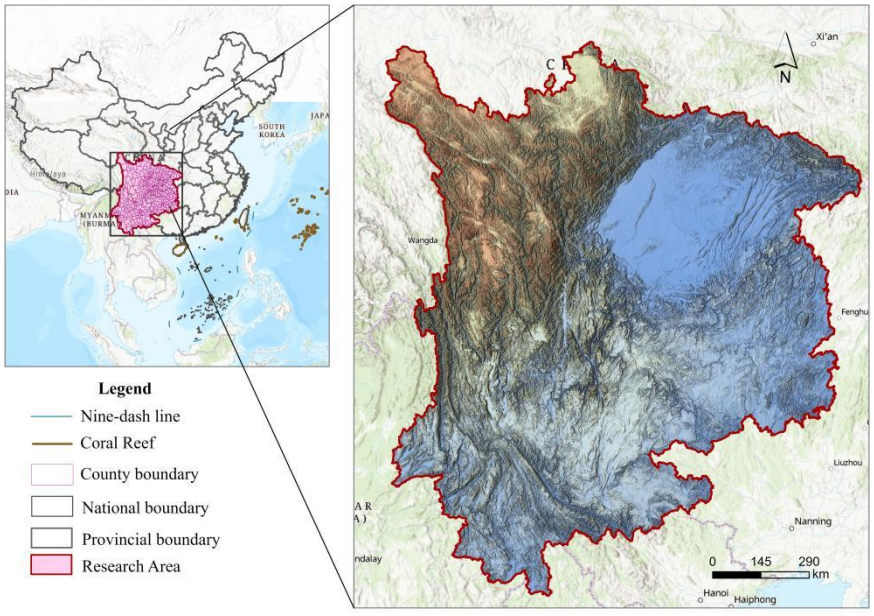


Figure 1 Location of the study area

As listed in Table 3, the data used in this study include remote sensing data and socio-economic statistical data at the county level from 2010 to 2020.

Table 3 Data sources

Data name	Data Source	Spatial Resolution /m
Elevation	Geospatial data cloud (http://www.gscloud.cn/)	30
Slope gradient, terrain undulation	The digital elevation model (SRTM 90m) data was resampled to 1km, and the model was used to calculate the kilometer grid dataset of landform undulation in China.	30
Annual average temperature and precipitation	Combined from monthly temperature and precipitation data, sourced from the national meteorological science Data sharing Service platform	1000
NDVI	By Landsat5 TM, Landsat8 OLI - TIRS data to calculate the normalized difference vegetation index, Landsat remote sensing image comes from the United States Geological Bureau	30
Land use type	Training samples were collected using 335,709 Landsat images from Google Earth Engine, combined with stable samples extracted from the China Land Use/Cover Dataset (CLUD) and visual interpretation samples from satellite time series data, Google Earth,	30

	and Google Maps	
Landscape diversity index, landscape aggregation index	The landscape indicators were calculated using FRAGSTATS 4.2 software	30
Social-economic data	County Statistical Yearbook 2010-2020	
Afforestation area	China Forestry and Grassland Statistical Yearbook 2010-2020	
Nighttime Light Index	National Earth System Science Data Center	500
$PM_{2.5}$	Calculate domestic PM2.5 data (in micrograms per cubic meter) based on Global/Regional Estimates	

4 Methods

To systematically investigate the coupling coordination relationship between NU and EV, this study employs a suite of quantitative models in a logical sequence, as illustrated in Figure 2. First, the entropy weight TOPSIS and the analytic hierarchy process (AHP) methods were used to measure the levels of NU and EV, respectively. Subsequently, the improved CCD model was applied to analyze the interaction and coordination between the two systems. Furthermore, the Dagum Gini coefficient decomposition method was utilized to explore the spatial heterogeneity and sources of regional disparities in the CCD. Finally, the autoregressive integrated moving average (ARIMA) model was adopted to predict future CCD trends under various scenarios.

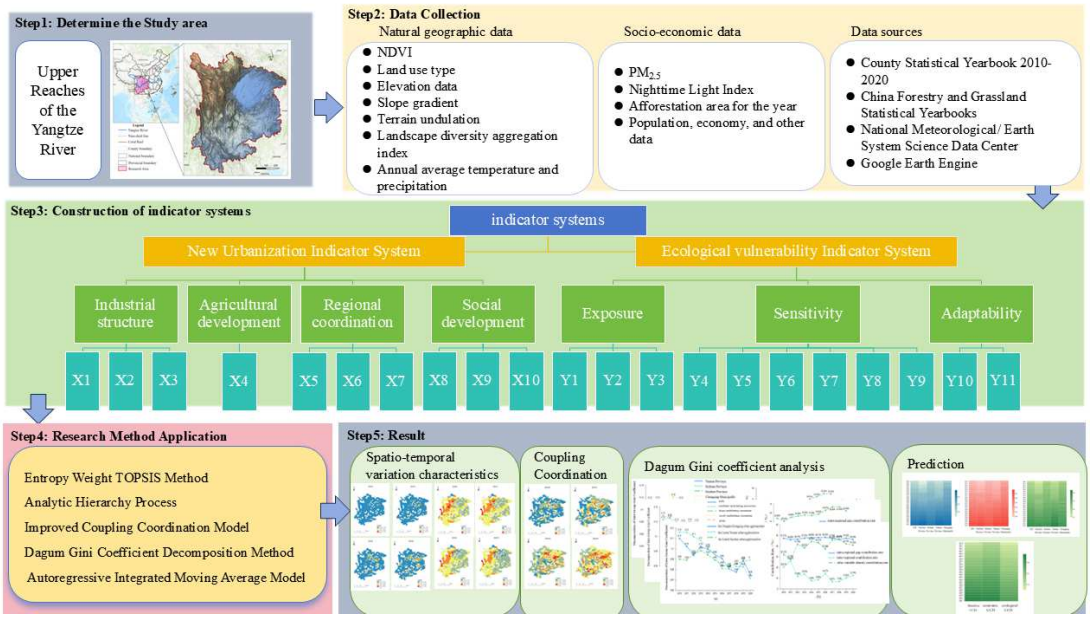


Figure 2 Methodology framework

4.1 Entropy weight TOPSIS method

The entropy weight TOPSIS method has obvious advantages in objective weighting and in multi-dimensional ranking. The entropy weight method makes full use of the information of each evaluation index to objectively determine the weights, while TOPSIS can evaluate the relative advantages and disadvantages among a limited number of objects. Referring to existing studies (Lei et al., 2024), the steps for measuring the level of NU are as follows.

(1) Assuming there are m evaluation objects and n evaluation indicators, the initial matrix X is constructed: $X = (X_{ij})_{m\times n}$, where x_{ij} represents the original value of the j-th indicator for the i-th county. The formula is:

$$X = \begin{bmatrix} X_{11} & \cdots & X_{1n} \\ \vdots & \ddots & \vdots \\ X_{m1} & \cdots & X_{mn} \end{bmatrix} \quad (1)$$

(2) Data standardization processing:

$$Z_{ij}^{+} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} + 0.00001 \tag{2}$$

$$Z_{ij}^{-} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} + 0.0001 \tag{3}$$

Since evaluation indicators can be divided into positive and negative, data must be normalized to eliminate the effects of dimensions. All indicator values are uniformly mapped to the interval [0,1], resulting in comparable dimensionless values Z_{ij}. And $\max(X_{ij})$ and $\min(X_{ij})$ represent the maximum and minimum values in the jth column, respectively.

(3) Calculate information entropy E_j and information entropy redundancy g_j:

$$P_{ij} = \frac{Z_{ij}}{\sum_{i=1}^{m} Z_{ij}} \tag{4}$$

$$g_j = 1 - E_j \tag{5}$$

$$E_j = -\frac{1}{\ln m} \sum_{i=1}^{m} p_{ij} \ln(p_{ij}), \quad 1 \le i \le \mathrm{m}, 1 \le j \le \mathrm{n} \tag{6}$$

P_{ij} represents the characteristic proportion of the *i*-th county on the *j*-th indicator, g_j denotes the redundancy of information entropy or the coefficient of variation for the *j*-th indicator, and E_j signifies the information entropy of the *j*-th indicator.

(4) Determine the weight of each indicator w_j :

$$w_j = \frac{g_j}{\sum_{j=1}^{n} g_j} \tag{7}$$

(5) Calculate the matrix of weights

$$R = (r_{ij})_{m\times n} \tag{8}$$

$$r_{ij} = w_j \times Z_{ij} \tag{9}$$

R is the weighted standardized decision matrix, and r_{ij} forms the basis for subsequent distance calculations, as it integrates the standardized values of the indicators with their objective weights.

(6) Determine the optimal and the worst solutions:

$$V^+ = \{maxv_{ij}|j = 1,2,\cdots,n\} = \{v_1^+, v_2^+, \cdots v_n^+\} \tag{10}$$

$$V^- = \{minv_{ij}|j = 1,2,\cdots,n\} = \{v_1^-, v_2^-, \cdots v_n^-\} \tag{11}$$

V^+ and V^- represent the positive ideal solution and the negative ideal solution, respectively. V^+ is formed by the maximum value of each indicator in the weighted standardized matrix, representing the theoretically optimal scenario, while V^- is formed by the minimum value of each indicator, representing the theoretically worst-case scenario.

(7) Euclidean distance between each scheme and the optimal and worst solution is calculated:

$$D_i^+ = \sqrt{\sum_{i=1}^{n}(r_{ij} - V^+)^2} \tag{12}$$

$$D_i^- = \sqrt{\sum_{i=1}^{n}(r_{ij} - V^-)^2} \tag{13}$$

D_i^+ and D_i^- denote the Euclidean distances from the *i*-th county to the positive ideal solution and the negative ideal solution, respectively. A smaller D_i^+ indicates that

the county's development level is closer to the optimal state; a larger D_i^- indicates that it is farther from the worst-case scenario.

(8) Calculate the comprehensive rating index:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, 0 \le C_i \le 1 \quad (14)$$

C_i represents the comprehensive evaluation index of the *i*-th county and the final score for its new urbanization level. The closer C_i is to 1, the higher the county's new urbanization level and the closer it is to the optimal scenario; conversely, the closer it is to 0, the lower the level.

4.2 AHP method

AHP is a systematic, flexible, and widely applied multi-criteria weighted decision-making method (Hu et al., 2021; Qiu et al., 2008), which subjectively ranks and allocates the importance of index data to form a multi-level structure of objectives, criteria, and schemes, and then obtains the weight of each index data (Chen et al., 2023). This study uses AHP to determine the weights of the EV indexes, and the calculation steps are as follows:

$$CI = \frac{\lambda_{max} - m}{m - 1} \quad (15)$$

$$CR = \mathrm{CI}/\mathrm{RI} \quad (16)$$

Where CI represents the consistency index of the judgment matrix, $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix, m is the order of the judgment matrix, and RI is the average random consistency index of the judgment matrix.

4.3 Improved CCD Model

This study uses the improved CCD model to determine the corresponding contribution coefficients of NU and EV based on their performance (Dong et al., 2023). The formula is as follows:

$$\mathrm{T}' = \alpha'\mathrm{U} + \beta'\mathrm{A} \tag{17}$$

$$\alpha' = \frac{\mathrm{A}}{\mathrm{U} + \mathrm{A}} \tag{18}$$

$$\beta' = \frac{\mathrm{U}}{\mathrm{U} + \mathrm{A}} \tag{19}$$

$$\mathrm{D}' = \sqrt{\mathrm{C} * \mathrm{T}'} \tag{20}$$

Where α' and β' are the contribution coefficients for the improvement of the NU level and EV level respectively. *U* represents the NU level, *A* represents the EV level, D' indicates is the CCD, and *T* is the comprehensive development index.

If the comprehensive score of the NU level is relatively low, the α' is relatively large, indicating that more attention should be paid to the development of NU in the future. If the overall score of the EV level is low, the β' will be relatively large, indicating that more attention should be paid to improving ecological conditions in the future. CCDs between NU and EV can be classified into eight types based on CCD scores (Lei et al., 2024), as shown in Table 4.

Table 4 Stage division of CCD between NU and EV

CCD	CCD Level
(0.00, 0.20)	Extreme imbalance
[0.20, 0.30)	Serious imbalance
[0.30, 0.40)	Mild imbalance
[0.40, 0.50)	Near imbalance
[0.50, 0.60)	Reluctant coordination
[0.60, 0.70)	Primary coordination
[0.70, 0.80)	Good coordination
[0.80, 1.00]	High-quality coordination

4.4 Dagum Gini Coefficient Decomposition method

Compared with the Thiel index and the traditional Gini coefficient, the Dagum Gini coefficient effectively addresses the problem of cross-overlap of sample data (Lv et al., 2021; Wen et al., 2023). It breaks down the overall differences of the sample into three parts: intra-regional Gini coefficient (G_w), inter-regional Gini coefficient (G_{nb}), and the intensity of transvariation (G_t). The formula is as follows:

$$\mathrm{G} = \frac{\sum_{\mathrm{j}=1}^{\mathrm{k}} \sum_{\mathrm{h}=1}^{\mathrm{k}} \sum_{\mathrm{i}=1}^{\mathrm{n_j}} \sum_{\mathrm{r}=1}^{\mathrm{n_h}} \left|\mathrm{y_{ji}} - \mathrm{y_{hr}}\right|}{2\mathrm{n}^2\mu} \tag{21}$$

$$G_{jj} = \frac{1}{2\mu_j n_j^2} \sum_{i=1}^{n_j} \sum_{r=1}^{n_j} \left|y_{ji} - y_{hr}\right| \tag{23}$$

$$G_{jh} = \frac{\sum_{i=1}^{n_j} \sum_{r=1}^{n_h} \left|y_{ji} - y_{hr}\right|}{n_j n_h \left(\mu_j + \mu_h\right)} \tag{24}$$

$$G_w = \sum_{j=1}^{k} G_{jj} p_j s_j \tag{25}$$

$$G_{nb} = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh}\left(p_j s_h + p_h s_j\right) D_{jh} \tag{26}$$

$$G_t = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh}\left(p_j s_h + p_h s_j\right)\left(1 - D_{jh}\right) \tag{27}$$

Where G_{jj} is the Gini coefficient of region *j*, G_{jh} is the Gini coefficient between region *j* and region *h*. G_w denotes the intra-regional Gini coefficient, G_{nb} is the inter-regional Gini coefficient, and G_t is the intensity of transvariation. y_{ji} is the CCD level of the *i* counties within the j region, y_{hr} is the CCD level of the r counties within the *h* region. μ is the mean CCD level of all counties, *n* is the number of counties, *k* is the number of divided regions, $n_j(n_h)$ is the number of counties included in the *j(h)* region, $p_j = n_j/n, s_j = n_j\mu_j/(n\mu)$, D_{jh} is the relative influence of the CCD level between the *j* and *h* regions.

4.5 ARIMA Model

Based on previous studies (Luo et al., 2019; Wu et al., 2023), ARIMA model can effectively handle univariate time series data with a relatively simple structure that only requires setting three parameters: autoregression order p, number of differences d, and moving average order q, which can be intuitively selected through the autocorrelation function and partial autocorrelation function graphs. The formula is as follows.

$$Y_t = c + \varphi_1 Y_{t-1} + \varphi_2 Y_{t-2} + \cdots + \varphi_p Y_{t-p} + \theta_1 \varepsilon_{t-1} + \theta_2 \varepsilon_{t-2} + \cdots + \theta_q \varepsilon_{t-q} + \varepsilon_t \quad (28)$$

Y_t is the time series data, φ_1 to φ_p describe the relationship between the current value and the values at p past time points, θ_1 to θ_q describe the relationship between the current value and the error at *q* past time points, ε_t is the error term at t time point,

and c is the constant term.

5 Result

5.1 Spatio-temporal variation characteristics of NU and EV

As shown in Figure 3, from 2010 to 2019, NU development in the study area gradually advanced from central cities to the outside, and the level of NU presents a distinct “core-periphery” differentiation pattern. In 2010, the levels of NU in most counties were relatively low, and from 2013 to 2016, urbanization accelerated with increasing investment from the state and local governments for the development strategy of the Yangtze River Economic Belt. From 2016 to 2019, the NU growth rate was more significant, and the number of high-incidence urban areas increased markedly around urban agglomerations, such as Chengdu, Chongqing, and Kunming, while the urbanization process in the peripheral areas was relatively slow.

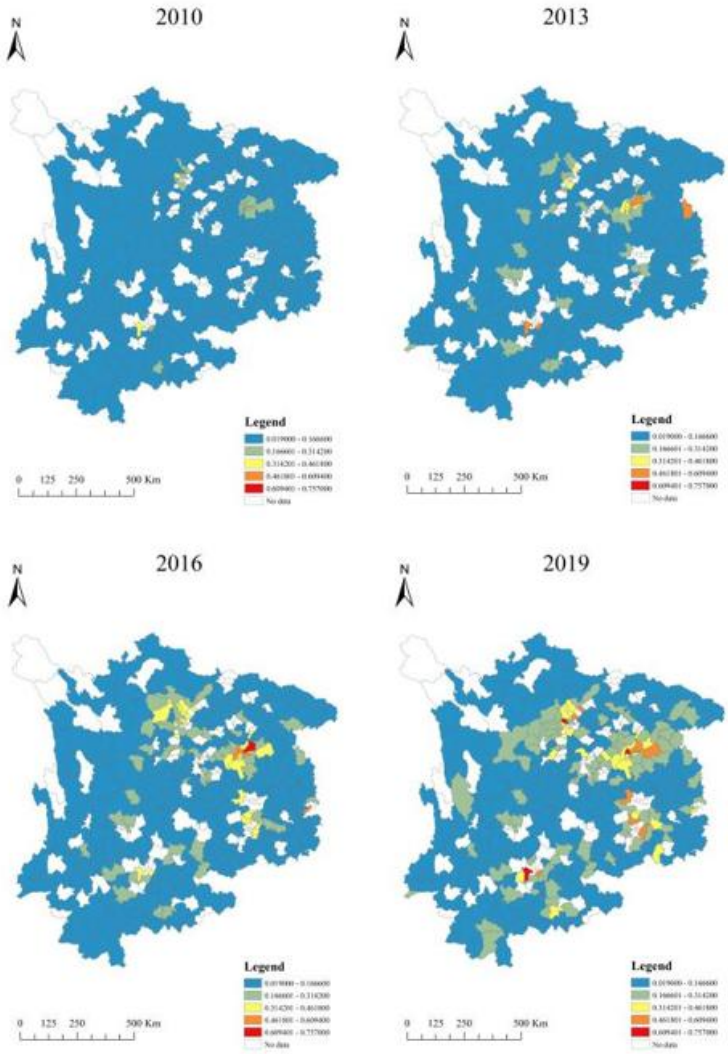


Figure 3 Spatio-temporal evolution trend of the level of NU

As shown in Figure 4, the spatial distribution of EV in the study area from 2010 to 2019 shows a slow and uneven improvement trend with significant spatial characteristics. The areas with higher EV were concentrated in the middle and upper parts of the study area and some mountainous regions with complex terrain, forming a distinct band distribution feature along the main stream of the Yangtze River and its major tributaries. From 2010 to 2013, the changes in EV were not obvious, and from 2016 to 2019, counties with high EV decreased, indicating that ecological protection

and restoration measures were better implemented during this period.

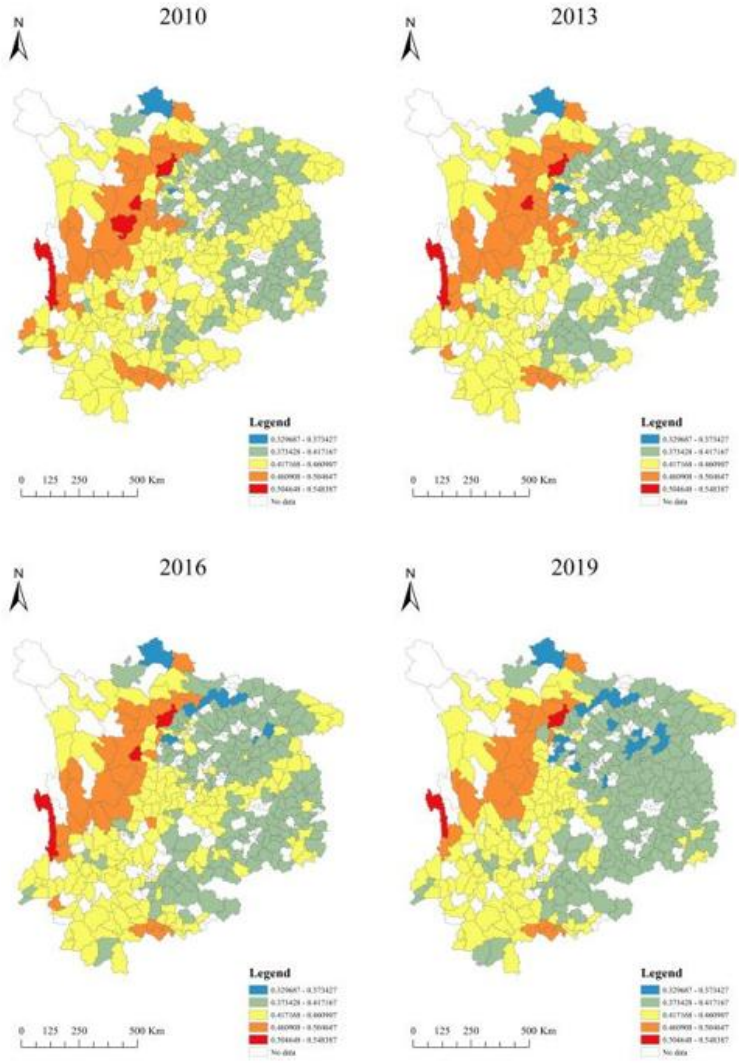


Figure 4 Spatio-temporal evolution trend of the level of EV

5.2 CCD between NU and EV

As shown in Figure 5, from 2010 to 2019, the CCD between NU and EV in the study area improved gradually, with the southwest region showing the most significant trend. The average level of CCD improved from serious imbalance to near imbalance, and the proportion of primary coordination rose from 4.06% to 28.41%. However, the overall CCD remained low, with near imbalance being predominant, good coordination

type accounting for only 0.29%, and no area in a state of high-quality coordination. Initiating from low CCD levels in 2010, many counties experienced a significant increase in CCD from 2013, due to enhanced ecological protection measures (Li et al., 2022). By 2019, the level of CCD had significantly improved, with an increase in good coordination types, particularly concentrated along the main stream of the Yangtze River and around some core cities, indicating urbanization and ecological protection had achieved a relative balance. It should be noted that the improvement of CCD in mountainous and ecologically fragile areas was slow due to differences in terrain and resource distribution.

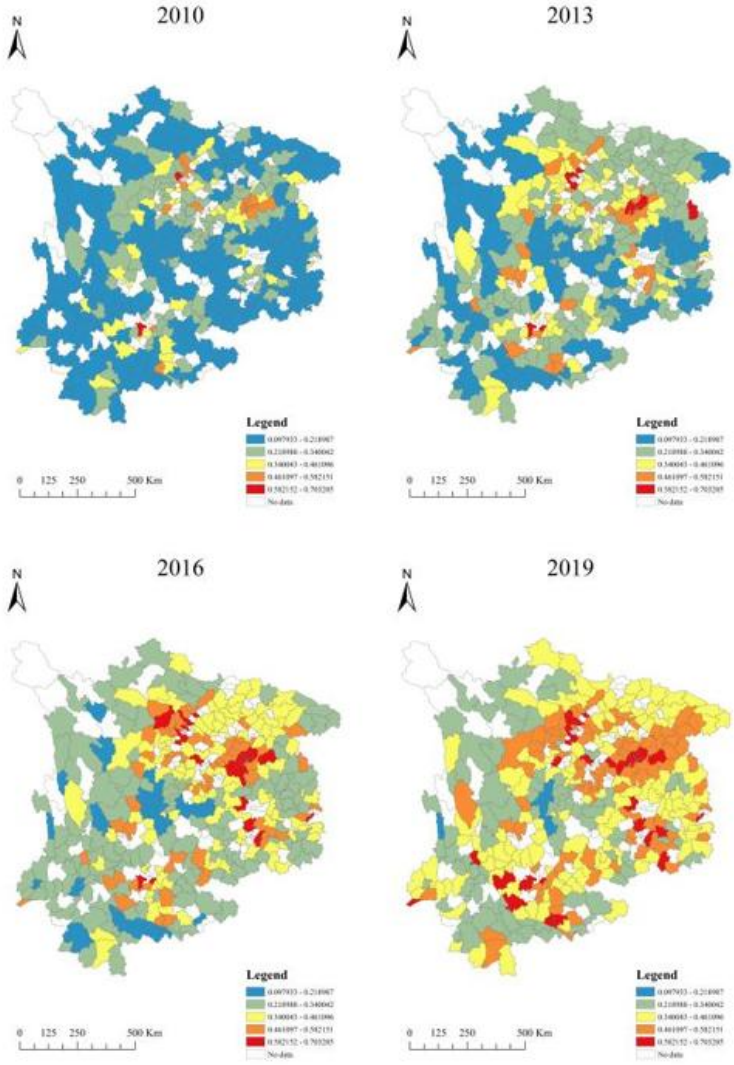


Figure 5 Spatio-temporal evolution trend of the level of CCD

5.3 Dagum Gini coefficient analysis

First, this study divided the study area into four administrative sub-regions, namely Yunnan Province (107 counties), Sichuan Province (131 counties), Guizhou Province (70 counties), and Chongqing Municipality (37 counties), to explore the spatial differences and the causes of various CCD levels among administrative areas. Figure 6(a) shows the trend of the intra-regional Gini coefficient. From 2010 to 2020, the overall Gini coefficient declined from 0.114 to 0.076, indicating a reduction in CCD

within the region. The Gini coefficient in Guizhou Province remained at relatively low levels and showed a slight upward trend, indicating a smaller gap within the region. The Gini coefficient in Chongqing Municipality showed a gradual decline, especially after 2016. Figure 6(b) shows the changes in intra-regional Gini coefficient contribution rate, inter-regional Gini coefficient contribution rate, and intensity of transvariation. From 2010 to 2020, the inter-regional Gini coefficient contribution rate declined, while the intra-regional Gini coefficient contribution rate showed a slight upward trend. The intensity of transvariation shows an upward trend and contributed the most to the overall Gini coefficient exceeding 50% since 2017, indicating that the influence of cross-overlap of CCD between regions is gradually increasing.

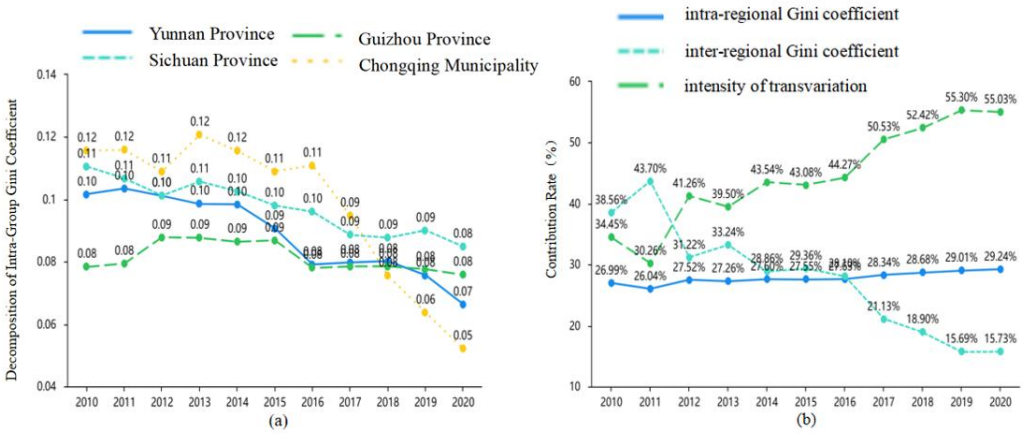


Figure 6 Dagum Gini coefficient in administrative areas

Second, the study area is divided into five sub-regions based on the differences in geomorphic types, namely plain (90 counties, hilly (104 counties), small undulating mountain (82 counties), medium undulating mountain (32 counties), and large undulating mountain (37 counties) to explore the spatial differences and the causes of various CCD levels among different terrains. As shown in Figure 7(a), from 2010 to

2020, there is a downward trend of the intra-regional Gini coefficient of different geomorphic types, with the lowest value in the hilly area, indicating the smallest gap. Although the CCD gap in all geomorphic types has narrowed, the speeds and extents were different, indicating that topographic factors have an impact on CCD. Figure 7(b) shows the changes in intra-regional Gini coefficient contribution rate, inter-regional Gini coefficient contribution rate, and intensity of transvariation from 2010 to 2020. The intra-regional Gini coefficient contribution rate fluctuated slightly and stabilized at around 22%, while the inter-regional Gini coefficient contribution rate presents a "U-shaped" curve from 2016 to 2020. Furthermore, the intensity of transvariation contributed the most to the overall Gini coefficient, and the gap in the level of CCD among regions narrowed.

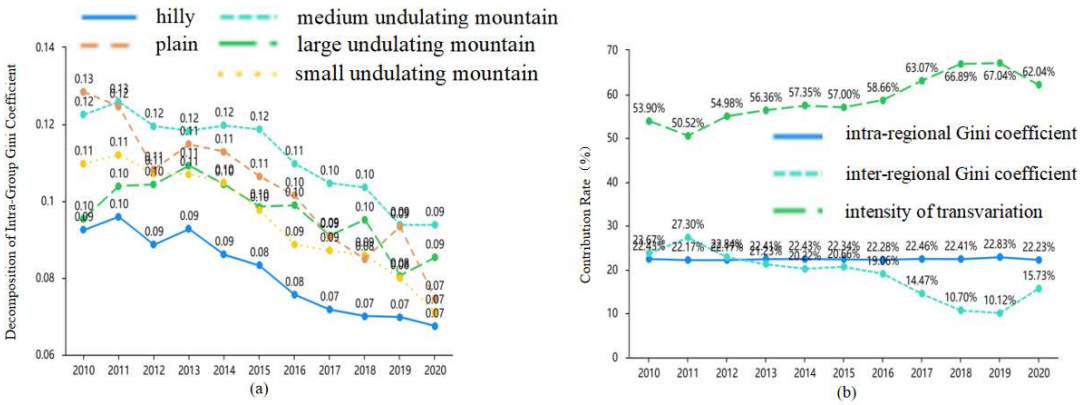


Figure 7 Dagum Gini coefficient in geomorphic type areas

Third, the study area is divided into three sub-regions based on urban agglomeration differences, namely the Chengdu-Chongqing urban agglomeration (168 counties), the central Yunnan urban agglomeration (107 counties), and the central Guizhou urban agglomeration (70 counties) to explore the spatial differences and the

causes of various CCD levels. Figure 8(a) shows an overall declining trend of the intra-regional Gini coefficient in urban agglomerations from 2010 to 2020. The central Yunnan urban agglomeration had the highest intra-regional Gini coefficient in 2010 and the lowest in 2020, indicating that the CCD gap narrowed significantly during the study period. Similar trend shows in the Chengdu-Chongqing urban agglomeration, while the intra-regional Gini coefficient in the central Guizhou urban agglomeration remained stable at 0.09 with no significant change. Figure 8(b) shows the changes in intra-regional Gini coefficient contribution rate, inter-regional Gini coefficient contribution rate, and intensity of transvariation from 2010 to 2020. The intra-regional Gini coefficient contribution rate gradually decreased from 47.37% to 46.24%, making the greatest contribution to the overall Gini coefficient. The inter-regional Gini coefficient contribution rate shows a fluctuating downward trend, while the intensity of transvariation changed in the opposite direction.

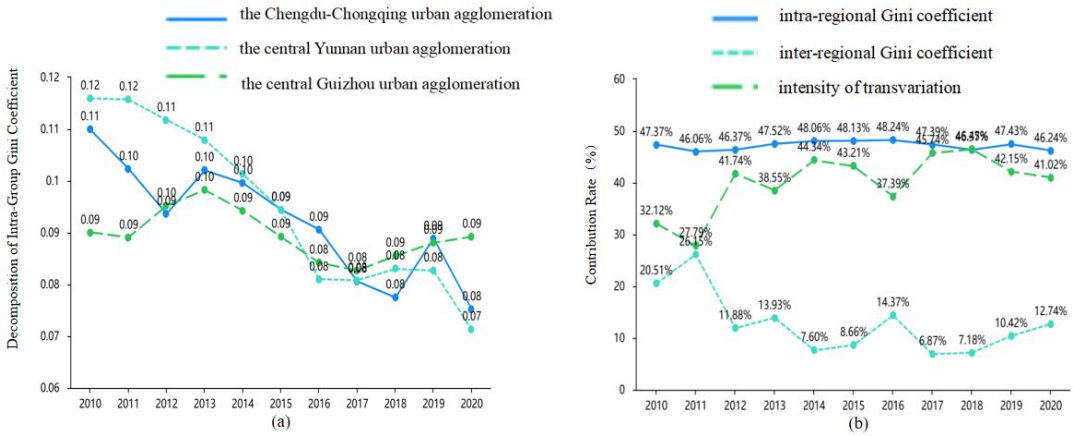


Figure 8 Dagum Gini coefficient in urban agglomerations

5.4 Prediction of future trends of CCD between NU and EV levels

Based on previous research (Fan, 2024), this study constructs three scenarios to

simulate the dynamic changes of NU and EV in the study area from 2021 to 2032, and predicts future CCD trends, as illustrated in Figure 9(a), (b), and (c). The baseline scenario is based on historical data from 2000 to 2020, and the parameters of each indicator are maintained according to the current development model. In this context, county-level CCD gradually raise above 0.6 after 2020, with Yunnan and Guizhou Province showing relatively rapid increases and Sichuan Province and Chongqing Municipality showing relatively slower increases in CCD. The economic priority scenario is to achieve rapid economic development in line with the status quo. In this context, county-level CCD in the study area shows a gradually strengthening trend, and the coupling relationship between economic development and environmental carrying capacity is constantly improving. The ecological priority scenario aims to achieve the goal of ecological conservation through the reduction of PM2.5 and the optimal regulation of climate indicators, including temperature and precipitation. In this context, the trend of county-level CCD in the study area shows a steady upward trend, with Yunnan Province having the highest CCD. As shown in Figure 9(d), the trends of county-level CCD in the study area from 2021 to 2032 under three scenarios show a gradually increasing trend with different growth rates. The CCD growth rate and final CCD level under the economic priority scenario are significantly higher than those under other scenarios.

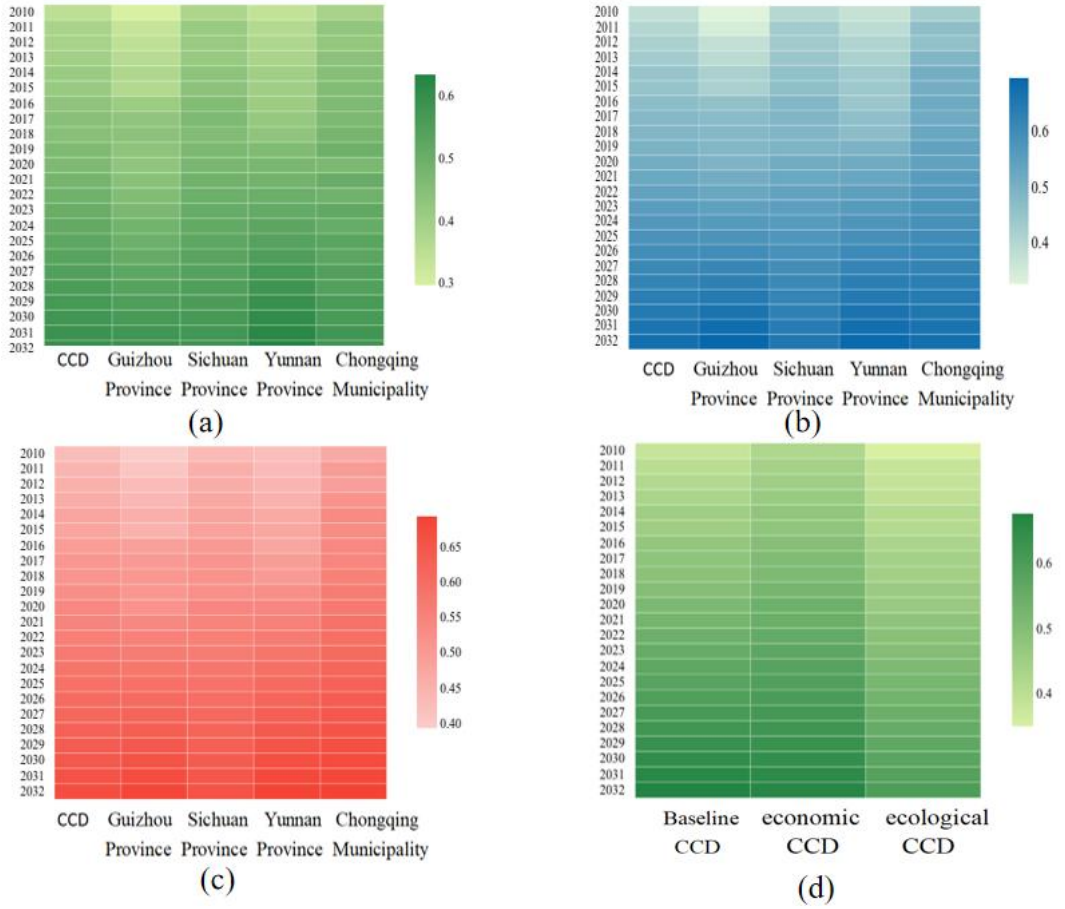


Figure 9 ARIMA prediction results

6 Discussions

6.1 The spatio-temporal evolution trend of CCD between NU and EV

In terms of temporal changes, the regional CCD has achieved a leap from serious imbalance to mainly near imbalance, and the proportion of primary coordination areas has significantly increased. This demonstrates that the series of national strategies, such as NU and ecological civilization construction, have produced positive synergy effects (Chen et al., 2019). However, it is also necessary to note that the overall CCD of the entire region remains at a relatively low level (Zhang et al., 2023), and no county has reached the state of high-quality coordination, indicating that the contradiction between

urbanization and ecological protection remains the core bottleneck, restricting the high-quality regional development.

In terms of spatial patterns, the CCD shows a significant “core-periphery” differentiation feature, indicating that in economically developed core areas, resources can be integrated more effectively, and the fruits of economic growth can be fed back to ecological construction, thereby achieving reluctant coordination between the two. Conversely, remote mountainous areas with high EV have fallen into the predicament of reluctant coordination (Yang et al., 2024). These regions often have fragile natural conditions and insufficient development momentum. Their urbanization processes struggle to exert a positive impact on the ecological environment. Remote mountainous regions under the extensive development mode will aggravate ecological degradation, resulting in a lag in both development and ecological protection (Liu et al., 2021).

6.2 Regional heterogeneity of CCD between NU and EV

Among different provinces, the CCDs have narrowed during the study period. The observed convergence stems from the positive spillover effects of central cities, as shown by faster CCD growth in their adjacent counties compared to remote mountainous regions. This indicates that central cities play a positive role in promoting CCD in their surrounding areas. (Li et al., 2022; Zhang and Zhou, 2023). The slower improvement of CCD in mountainous and ecologically fragile areas can be attributed to their high ecological vulnerability, which is often exacerbated by economic activities such as resource-intensive industries and tourism development (Yang et al., 2022;

Ghosh et al., 2023). Among different geomorphic types, the intra-regional Gini coefficient is the lowest in the hilly area, and relatively high in the medium undulating and large undulating mountains, indicating that terrain complexity imposes constraints on CCD development. High altitude and complex terrain can limit human activity and increase social and economic vulnerability in a region (Lin et al., 2021; Liu et al., 2021; Lin et al., 2019), making it difficult to coordinate ecological and economic development in these regions. Among urban agglomerations, the Chengdu-Chongqing urban agglomeration and the central Yunnan urban agglomeration have improved CCD, mainly due to stronger economic foundation, policy support, and infrastructure construction (Zhang and Zhou, 2023; Li et al., 2022; Yang et al., 2024). The coordinated development process in the central Guizhou urban agglomeration is slower due to the relatively lagging economic development, uneven resource distribution, and weak government impetus (Li et al., 2022; Wu and Ren, 2024).

6.3 The contradiction and synergy between NU and ecological conservation

The current study has shown that the most important factor restricting county-level urbanization is the poor natural endowment, especially in the marginal areas far from the central cities, high altitudes, and less educated population clusters (Zhang et al., 2022). This study found that in areas with high EV, the level of NU is generally low, and with the acceleration of economic growth, these fragile ecological areas are at risk of being overdeveloped. These areas are mainly concentrated in the mountainous areas with complex terrain, where the ecological environment carrying capacity is limited, and they are vulnerable to both natural and human factors. Although ecological

conditions have been improved in some regions, there are still areas facing higher ecological risks as urbanization and economic development pressures continue to increase (Chen et al., 2020; Chen et al., 2024).

Therefore, balancing the demands of ecological conservation and economic development and preventing irreversible damage to ecosystems caused by overdevelopment have become key challenges for the study area in the future. The economic priority scenario can boost regional economic growth in the short term and thereby rapidly enhance the CCD. However, in the long term, this may lead to an accumulation of ecosystem stress, an increased risk of excessive resource consumption and environmental degradation. In contrast, the ecological priority scenario, although effectively improving the environment through ecological policies, may restrict regional economic growth and result in slow growth in CCD (Cheng et al., 2024). Sustainable development should be characterized by coordination, greenness, differentiation and long-term mechanisms, and achieve the organic combination and coordination of NU and ecological protection.

6.4 Policy Implications

To enhance the level of regional coordinated development, policies must focus on key problem areas. In medium and large undulating mountainous areas, a strategy of conservation priority and moderate development should be implemented. This involves alleviating environmental pressure and ensuring livelihoods through ecological migration, developing characteristic eco-industries, and improving ecological

compensation mechanisms. To address the core-periphery development gap, it is essential to promote the gradient transfer of green industries and production factors from core cities to surrounding counties, driving the development of peripheral areas through the establishment of cooperative industrial parks and the development of green supply chains. Simultaneously, the strictest spatial regulation and ecological restoration should be enforced on urban-rural transitional zones and ecologically vulnerable areas. Furthermore, given that the transvariation is the primary source of regional disparity, it is recommended to establish cross-provincial coordination platforms and horizontal ecological compensation mechanisms, and promote the interoperability of eco-tourism routes to reduce redundant construction and enhance the overall efficiency.

7 Conclusions

This study systematically evaluated the coupling coordination relationship between NU and EV in counties located in the upper reaches of the Yangtze River from 2010 to 2020. The findings revealed a core-periphery differentiation pattern in NU development, and the overall EV has been reduced with significant regional differences. Although the CCD gradually improved, it remained predominantly near imbalance, due to transvariation effects. Predictions indicated the ecological priority approach would be more sustainable compared to the economic priority approach. Limitations of this study include incomplete county-level data, and insufficient exploration of human-environment interaction mechanisms. Future research should expand dynamic data, strengthen mechanism analysis, and conduct multi-scenario simulations to support precise decision-making for high-quality coordinated regional development.

Declarations

Abbreviations

CCD, coupling and coordinated development; EV, ecological vulnerability; NU, new urbanization; AHP, Analytic Hierarchy Process; ARIMA, Autoregressive Integrated Moving Averag; TOPSIS, Technique for Order Preference by Similarity to an Ideal Solution; URYR, upper reaches of the Yangtze River; GDP, Gross Domestic Product; NDVI, Normalized Difference Vegetation Index

Ethics approval and consent to participate

Not applicable. This study is based on county-level statistical data and does not involve human participants, human tissue, or animal experiments.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data in any form.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, Jue Wang, upon reasonable request. No new materials were generated.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this

paper.

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Authors' contributions

Hongjin Yu: Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft. Yanping Wang: Visualization, Methodology, Formal analysis, Writing – original draft. Xugong Jia: Data curation, Software, Visualization. Jue Wang: Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. Ming Chang: Funding acquisition, Data curation.

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