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Research on the Coupling Coordination between New Urbanization and Land Green Use Efficiency in the Southwest China Urban Agglomeration

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ABSTRACT

Exploring the complex and dynamic relationship between new urbanization (NUR) and land green use efficiency (LGUE) contributes to optimizing the allocation of land resources and facilitating the process of NUR. This paper employed the linear weighted method to evaluate the NUR of urban agglomerations in Southwest China and utilized the Super-SBM model to calculate the LGUE. Utilizing the coupling coordination degree (CCD) model, the NUR, LGUE and spatial alterations of 33 cities in the urban agglomeration from 2008 to 2021 were analysed, and three key findings were obtained. (1) The NUR process in the study area is sluggish, and the NUR level is significantly lower than the LGUE level. (2) There are substantial spatial disparities in NUR and LGUE in the study area. The values of NUR and LGUE in provincial capital cities are relatively high. (3) The CCD of NUR and LGUE in the study area have slowly increased. The number of people engaged in scientific research and technical services and fiscal revenue are the key factors impacting the CCD. This work can serve as a reference for promoting the coordinated development of NUR and LGUE and coordinating the economic and social development and protection of the ecological environment.

KEYWORDS

New Urbanization; Land Green Use; Coupling Coordination; Driving Factors; Southwest China Urban Agglomeration.

1. INTRODUCTION

New urbanization (NUR) constitutes the key to attaining the Global Sustainable Development Goals (SDGs), with approximately 65% of the 17 SDGs requiring the participation of cities. Urbanization has propelled an annual infrastructure investment of up to \$2.3 trillion dollars globally, and it is anticipated that future investment will escalate further[35]. The urbanization level in China has improved remarkably since 1978, increasing from 17.9% in 1978 to 65.2% in 2022. NUR has augmented China's sustainable development capabilities in poverty reduction (SDGs 1, 2), safety and health (SDGs 3), and employment and economic growth (SDGs 8). Nevertheless, with the continuous progression of NUR, a substantial number of rural individuals have migrated to cities, the urban area has persistently expanded, and regional development disparities have continuously magnified, giving rise to increasingly prominent issues such as ecological damage, environmental pollution, and low land green use efficiency (LGUE), which threaten urban development and constructing an ecological civilization. Hence, the trade-off between NUR and LGUE has emerged as the focus of city planning and industrial layout. China's urbanization has entered the middle and late stages of development and is reaching a turning point of integrated urban–rural development. Adequately addressing these problems during the process of NUR is important for the high-quality development of new towns. Land resources serve as an essential material foundation for urbanization and constitute an important guarantee for economic and social development. Urbanization is closely intertwined with land utilization efficiency. Under limited land circumstances, pursuing the coupling coordination of urbanization and land use efficiency and investigating the corresponding driving factors are important for achieving the "Chinese characteristic NUR path", constructing "livable, smart and resilient cities", and achieving people-centred NUR.

Research has demonstrated that urbanization significantly affects land use efficiency. Although this impact is positive[2, 5], it also presents a multitude of challenges[11]. On the one hand, urbanization improves the LGUE by optimizing the industrial structure and increasing the employment rate, displaying significant heterogeneity in different regions[39]. On the other hand, an overly rapid urbanization process may lead to a reduction in land use efficiency since urban spatial expansion and agglomeration effects may become factors constraining the development of land use efficiency[31]. Land use efficiency also has a complex influence on urbanization. Enhancing land use efficiency benefits the sustainable growth of urbanization and is closely associated with the quality of urbanization and sustainable urban development[24]. This influence varies among different regions, and central and western China present more pronounced positive interactions than eastern China does[30].

Furthermore, many scholars have utilized diverse methods, such as the coupling coordination degree (CCD) model[34], the Super-DEA model[48], and the structural equation model, affirming a mutually influencing relationship between urbanization and land use efficiency; this relationship is not straightforwardly linear but rather complex and tends to become more intricate as the urbanization process accelerates. Rational urbanization and land use patterns facilitate further benign system coupling[34].

Urban agglomerations are the outcomes of the advanced stages of industrialization and urbanization. The Southwest China Urban Agglomeration is a new strategic pivot for western development and an economic belt of the Silk Road. Although existing studies on urbanization and land utilization efficiency are plentiful, few studies have focused on the urban agglomeration in Southwest China. The Southwest China Urban Agglomeration is an important ecological resource area and vulnerable region in China, and it is also the source and upstream area of many rivers, occupying a crucial position in implementing the strategy that "lucid waters and lush mountains are invaluable assets". The shortage of land resources caused by natural conditions restricts the economic development of the Southwest China Urban Agglomeration. The poverty alleviation population in this area is concentrated, the economic foundation is tenuous, and the urbanization level is low. Therefore, on the basis of the actual circumstances of the Southwest China Urban Agglomeration, conducting an in-depth exploration of NUR and LGUE is vital for the sustainable development of the Southwest China Urban Agglomeration.

2. STUDY AREA AND EVALUATION INDEX SYSTEM

2.1. Study Area

Southwest China encompasses Sichuan Province, Yunnan Province, Guizhou Province, Chongqing Municipality, Tibet Autonomous Region, etc. The total land area is approximately 2.25×106 km2, constituting approximately 24.5% of China's total land area. Southwest China comprises plateaus, mountains and hills, featuring relatively scarce plain areas. Karst landforms are extensively distributed, being the most concentrated area of karst landform distribution in China and one of the three major contiguous karst development areas worldwide. As an important ecological barrier, this region is China’s strategic reserve centre of water and forest resources. The region’s population constitutes approximately 20% of China's total population, yet the per capita GDP is merely twothirds of the national average. This region is situated in the Silk Road Economic Belt and is a hub and bearing area for China to connect with Europe and South Asia. It is strategically positioned in China's Western development and deepening economic cooperation on the Eurasian continent. The reconstruction of this region's urban agglomerations has brought new development opportunities.

Given the particularities of Tibet in terms of terrain and climate, local customs, ethnic culture, etc., the research area of this study is confined to an urban agglomeration composed of 33 prefecture-level cities in Sichuan Province, Yunnan Province, Guizhou Province and Chongqing Municipality. Fig 1 illustrates the specific regional scope. The data are from the "China Urban Statistical Yearbook", "China Urban Construction Statistical Yearbook" and the statistical yearbooks of various prefecture-level cities. A small amount of missing data are replenished by the linear interpolation method.

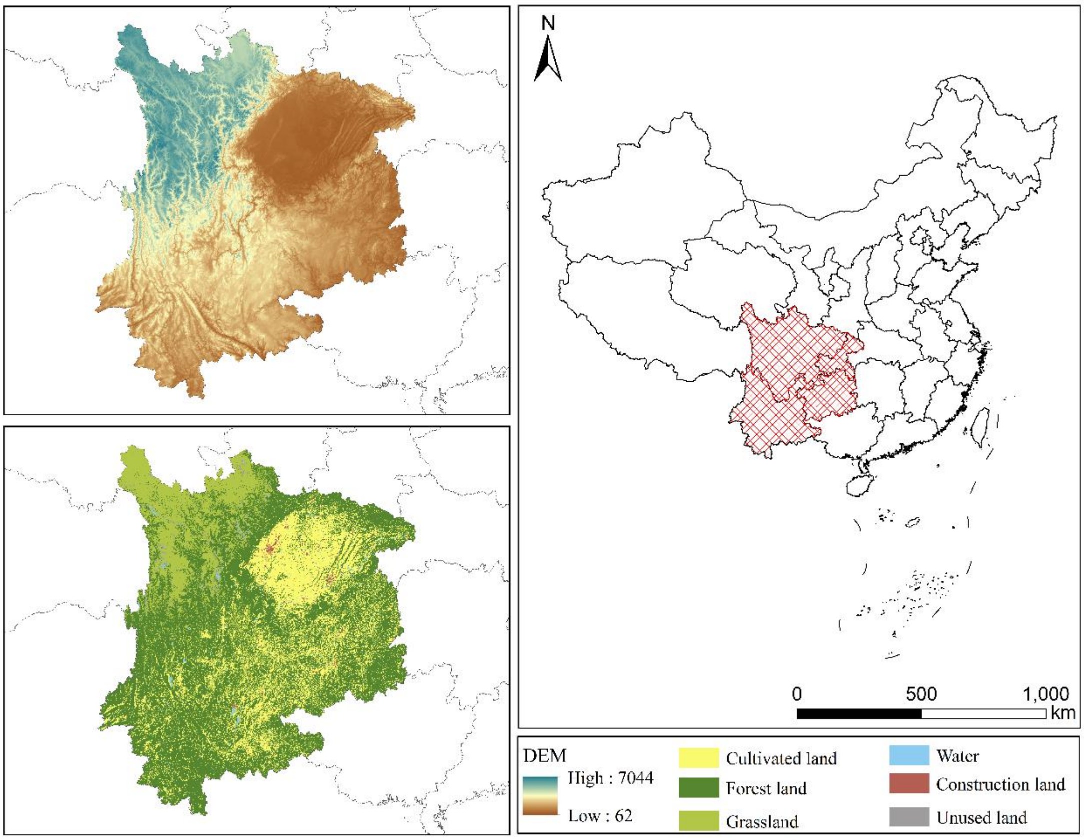

Fig 1 Study area.

2.2. Evaluation Index System

NUR is a process of agglomeration and expansion characterized by population concentration, urban construction land expansion, and economic growth[14]. It is typically comprehensively influenced by multiple factors, such as population[19], space[42], economy, society[23] and ecology[37]. By comprehensively evaluating the merits and demerits of various indicators for measuring NUR in the studies of[15,45,13], etc., this paper constructs an index system comprising four urbanization aspects: population, economic, social and spatial urbanization. Table 1 lists the detailed descriptions of each indicator.

Table 1 The evaluation index system of new urbanization.

Elements	Primary indicator	Indicators	Reference
New Urbanization	Population Urbanization (PU)	Urban population density	[26]
		Urbanization rate of permanent population	[12]
		Proportion of employees in the tertiary sector	[34]
	Economic Urbanization (EU)	Urban residents' Per capital disposable income	[44]
		Value added in the secondary and tertiary sectors	[7]
		Social consumer goods retail sales	[29]
	Spatial urbanization (SPU)	Number of registered unemployed in cities	[17]
		Number of doctors	[21]
		Collection of public library books	[4]
	Social urbanization (SOU)	Urban residential land area	[17]
		Urban construction land area as a proportion of Urban area	[25]
		Urban road area per capita	[43]

Measuring LGUE should comprehensively incorporate economic, social and ecological benefits. Simultaneously, it is necessary to reflect upon the traditional economic growth model of "high input and low output, high consumption and low efficiency, high speed and low quality" and avoid replicating the "extensive development model" [16]. On the basis of previous studies[8, 16, 49] and in conjunction with the specific circumstances and characteristics of the study area, this paper establishes an evaluation index system for the LGUE of urban agglomerations in Southwest China. Table 2 lists the specific descriptions of each LGUE indicator.

Table 2 Land green use efficiency measurement system.

Elements	Primary indicator	Indicators	Reference
Input indicators	Land	Urban construction land area	[46]
	Capital	Fixed assets investment amount	[34]
	Labour	Urban employed population	[38]
Expected output	Economy	GDP per capita	[34]
	Society	Average wage of employees	[38]
	Ecological	Green space coverage rate of built-up area	[41]
Undesired output	Environment pollution	Emissions of industrial wastewater	[18]
		Emissions of industrial SO2	[18]

3. METHODS

3.1. Linear weighted method

The entropy-weighted method, as an unbiased assignment approach, can eliminate any biases arising from subjective assignment and increase the precision of the evaluation results of each indicator[20]. It is widely utilized in numerous fields because of its objectivity and comprehensiveness, mainly for constructing urbanization systems[15]. In this paper, each indicator is standardized, the entropy-weighted method is employed to determine the indicator's weight, and ultimately, each city's NUR level is calculated via the linear weighted method. The calculation method is as follows:

$$U_{ij} = \sum_{j=1}^{n} W_{ij} \times Z_{ij} \tag{1}$$

where U is the evaluation result of the comprehensive level of NUR, W_{ij} refers to the weight matrix calculated via the entropy weight method, and Z_{ij} is the standardized matrix.

3.2. Super-SBM model

Data envelopment analysis, created by[3], has been extensively employed to gauge the relative effectiveness of decision-making units under multiple inputs and outputs. However, the traditional radial DEA model fails to fully consider the slack variables of inputs and outputs, and undesirable outputs are likewise excluded from the evaluation system. Thus, the applicability of this model is comparatively low. To measure efficiency more accurately, [27] used slack variables and proposed a measurement model (SBM-DEA) that considered undesirable outputs, which has the advantages of being nonradial and nonangular. To further compare the effective DMUs with an efficiency of 1, combined with the concept of superefficiency DEA and previous studies[16], the Super-SBM model was constructed to compute the LGUE. The calculation method can be found in the literature[22].

3.3. Coupling Coordination Degree Model

According to the calculation outcomes of the NUR and the LGUE, the coupling coordination relationship between the NUR and the LGUE is computed using the CCD model. The formula is as follows:

$$C = \sqrt{(U \times \rho) / \left(\frac{U+\rho}{2}\right)^2} \tag{2}$$

$$T = \alpha \times U + \beta \times \rho \tag{3}$$

$$D = \sqrt{C \times T} \tag{4}$$

where C is the coupling degree of the NUR and the LGUE, T represents the comprehensive evaluation value of the two subsystems, D denotes the CCD of the NUR and LGUE, and $D \in [0,1]$. U and ρ represent the comprehensive level of the NUR and the value of LGUE, respectively, and α and β represent the contributions of the NUR and the LGUE, respectively. Drawing upon the studies of relevant scholars, when it is undetermined which is more significant, it is supposed that both are of equal importance, thus, $\alpha = \beta = 0.5$ [32, 36].

On the basis of the current research outcomes and in conjunction with the literature[50], the coupling coordination results are further classified into Table 3.

Table 3 Grade classification of the coupling coordination degree.

Coupling coordination degree	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
Classification results	Moderate dissonance	Mild dissonance	Low coordination	Moderate coordination	High coordination

3.4. Geodetector

Geodetectors are valuable instruments for detecting spatially stratified heterogeneity and uncovering its driving factors[28]. The primary advantage of this approach lies in the absence of presuppositions and constraints and its universality, effectively surmounting the limitations of traditional statistical analysis methods when handling categorical variables. Hence, this paper employs factor detection and interaction detection within the geodetector to analyse the driving factors of coupling coordination.

Factor detection uses the q statistic to detect the extent to which a certain factor X accounts for the spatial differentiation of attribute Y. The formula is presented as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \tag{5}$$

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2, SST = N\sigma^2 \tag{6}$$

where $h = 1,...,L$ represents the stratification of X; N_h and N represent the number of subregions in the layer and the entire region, respectively; σ_h^2 and σ^2 represent the variances of stratum h and the entire region y; and SSW and SST represent the sum of squares within and the total sum of squares, respectively. The range of the value of q is $[0,1]$. A higher q value indicates a stronger explanatory power of X on Y, and vice versa. $q = 0$ indicates that there is no relationship between X and Y, whereas $q = 1$ indicates that X completely governs the spatial distribution of Y.

The interaction detection module quantifies the interaction between two explanatory factors X_1 and X_2 by comparing the q values of factors X_1 and X_2 with the interaction q value $(X_1 \cap X_2)$ to evaluate whether these factors undermine, enhance or are independent of each other. Generally, the results of the interaction detector can be categorized into five types, as presented in Table 4.

Table 4 Results of interaction detection.

Description	Interaction
$q(X_1 \cap X_2) < \min(q(X_1), q(X_2))$	Weakened, nonlinear
$\min(q(X_1), q(X_2)) < q(X_1 \cap X_2) < \max(q(X_1), q(X_2))$	Weakened, single factor nonlinear
$q(X_1 \cap X_2) > \max(q(X_1), q(X_2))$	Enhanced, nonlinear
$q(X_1 \cap X_2) = q(X_1) + q(X_2)$	Independent
$q(X_1 \cap X_2) > q(X_1) + q(X_2)$	Enhanced, nonlinear

4. RESULTS

4.1. Analysis of NUR

Overall, the level of NUR in the Southwest China Urban Agglomeration rose from 0.061 in 2008 to 0.126 in 2021, indicating a slow upwards trend. Fig 2 depicts the scores of the primary indicators of NUR from 2008 to 2021. During this period, the growth rate of economic urbanization reached 321.62%, indicating high volatility. Nevertheless, there was negative growth in 2020, and the growth rate decreased to -41.43%, which might be due to the epidemic's impact on the economy. Spatial urbanization and social urbanization also gradually increased from 2008 to 2021. Economic urbanization had the most significant impact on the level of NUR in the Southwest China Urban Agglomeration, whereas social urbanization made a relatively smaller contribution.

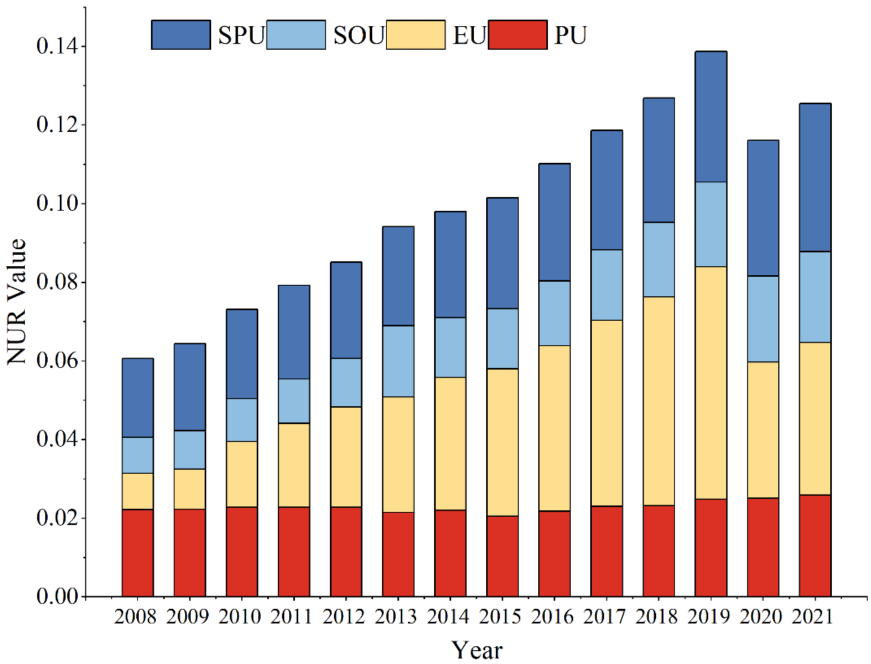

Fig 2 The scores of the primary indicators of NUR from 2008 to 2021.

From the provincial perspective (Fig 3), from 2008 to 2021, the levels of NUR in the four regions, ranked from the largest to the smallest, are Chongqing (0.4529), Yunnan (0.1151), Sichuan (0.0906), and Guizhou (0.0862). Among them, the level of NUR in Chongqing rose prominently, far surpassing those in the other three regions. In 2013, the level of NUR in Chongqing increased the most rapidly, with a growth rate as high as 56.45%. This might be due to the continuous advancement of Chongqing's "13th Five-Year" policy. The disparities in the levels of NUR among the three provinces of Sichuan, Guizhou, and Yunnan are relatively small. The level of NUR in Yunnan is marginally higher than that in Guizhou and Sichuan. The primary reason is the uneven population distribution and economic development levels in Guizhou and Sichuan Provinces.

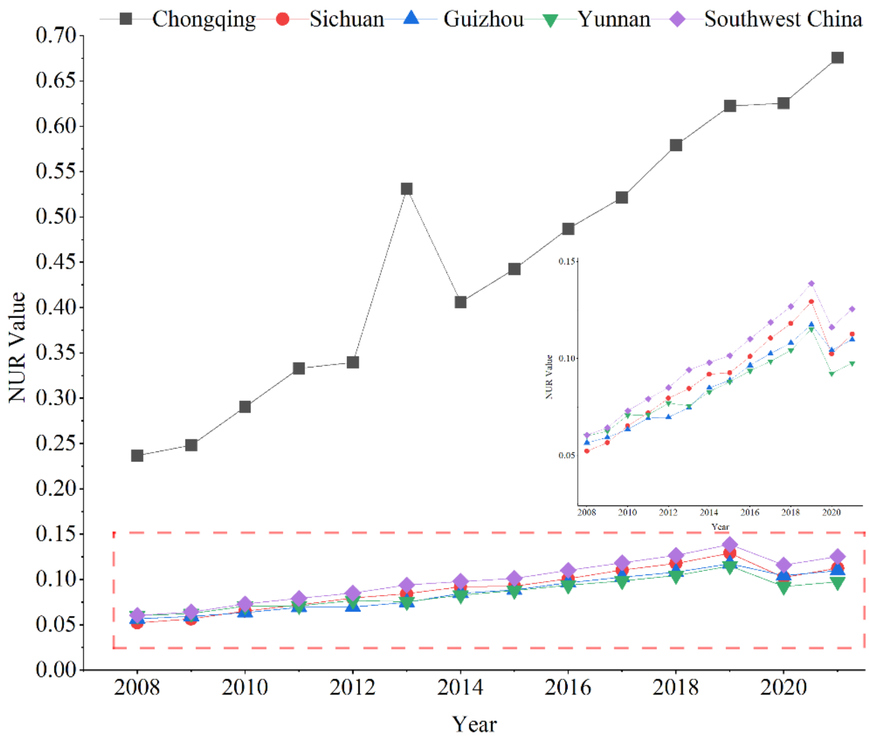

Fig 3 The comprehensive level of NUR from 2008 to 2021.

From the viewpoint of the average level of NUR of prefecture-level cities, Chongqing ranks first in the Southwest China Urban Agglomeration. Its level of NUR rose from 0.237 in 2008 to 0.675 in 2021, with a growth rate of 184.8%. Only two cities, namely, Chongqing (0.453) and Chengdu (0.413), had average NUR values above 0.40. As provincial capital cities, Chongqing and Chengdu are abundant in resources and possess outstanding comprehensive social and economic strength, which facilitates the rapid development of their NUR. The growth rates of 18 cities exceeded 100%, accounting for 54.56% of the total number of cities, including cities such as Mianyang (220.9%), Chengdu (153.4%), and Zunyi (153.6%). These data suggest that the NUR of multiple cities in the Southwest China Urban Agglomeration is undergoing a rapid development phase.

According to the spatiotemporal evolution outcomes of NUR (Fig 4错误!未找到引用源。), the levels of NUR in 33 cities of the Southwest China Urban Agglomeration are generally low. In 2008, with the exception of Chongqing, Chengdu, and Kunming, the levels of NUR in other cities were all less than 0.1. In 2013, the levels of NUR in Chongqing and Chengdu increased significantly. In 2018, the number of cities with an NUR ranging from 0.1 to 0.3 rose by 8 compared with 2013. In 2021, the levels of NUR in Zigong and Dazhou decreased (<0.1), mainly because the number of employed people in tertiary industry and the disposable income of urban residents in 2021 decreased markedly compared to 2018. The regions with relatively lower levels of NUR development are concentrated mainly in Tongren, Anshun, Meishan, and other areas. The common features of these regions include a lower level of economic development, a higher poverty rate, a weak industrial foundation, and extensive agricultural cultivation approaches. These factors jointly restrict the increase in NUR in these regions.

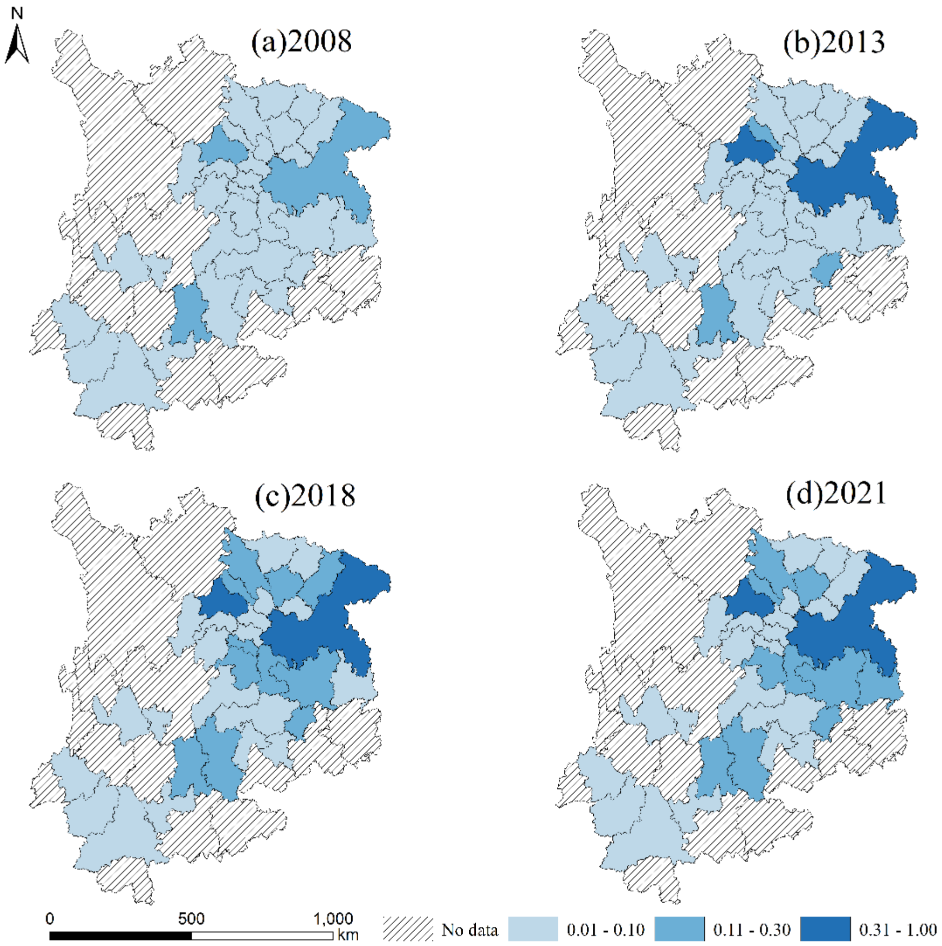

Fig 4 Spatial-temporal evolution of NUR in the study area in 2008, 2013, 2018 and 2021.

4.2. Analysis of LGUE

This study classifies LGUE into four grades: low (<0.4), medium (0.4–0.65), extremely high (0.65–1), and high (>1). As shown in Fig 5, during the research period, the LGUE in the Southwest China Urban Agglomeration underwent fluctuating alterations. From 2008 to 2012, the number of cities with low LGUE gradually decreased but increased in 2013. This might be because since 2012, ecological environment protection has been important to central and local governments, that have actively promoted the transformation of high-pollution and high-energy-consuming industries. However, in the initial stage of the transformation, it was difficult to strike a balance between the economy and environmental protection, resulting in a decline in the efficiency of land green use. After a period of exploration, each region followed a suitable development path, gradually resolving the contradiction between economic development and environmental protection. The LGUE gradually increased from 2014 to 2018. In 2017, the number of cities with high LGUE was the greatest, amounting to 21. However, the LGUE from 2019 to 2021 declined compared with that in the previous period, 27.27% of the cities experienced poor LGUE, and the average LGUE decreased by 11.62% in 2019.

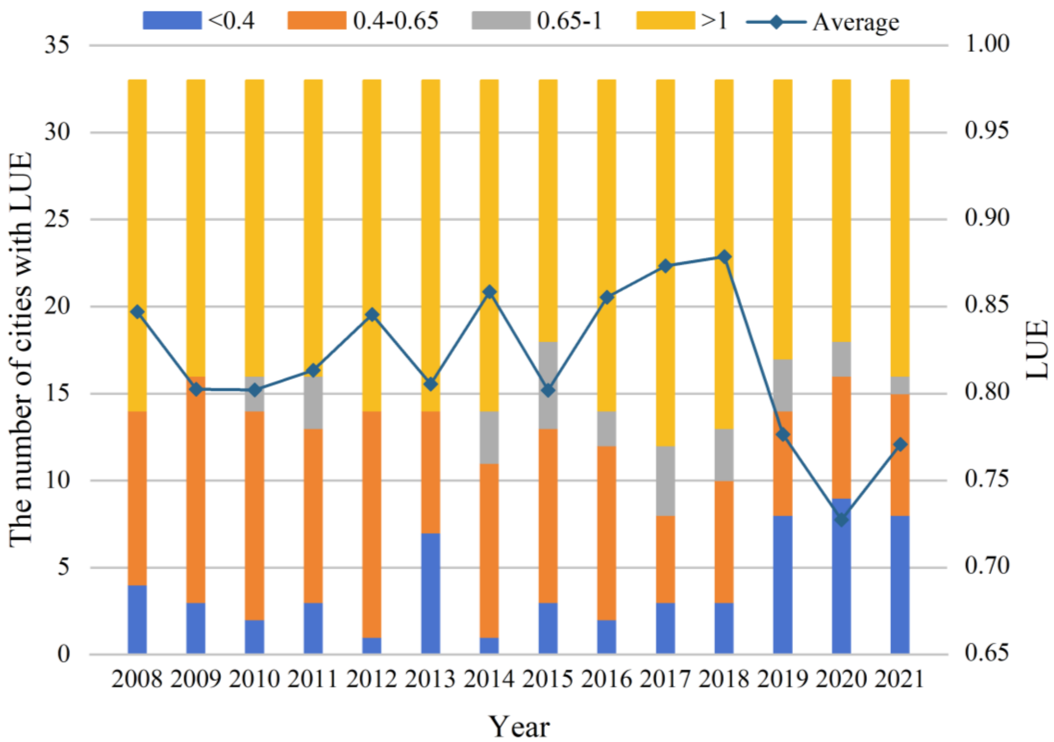

Fig 5 Classification and quantity of the LGUE grades of each city in the Southwest China Urban Agglomeration.

Table 5 presents the average values and rankings of the LGUE of each city in the Southwest China Urban Agglomeration from 2008 to 2021,which differ substantially. From 2008 to 2021, there were 7 cities in the Southwest China Urban Agglomeration whose average values of LGUE exceeded 1.0. The average values of Bazhong (1.2881), Lijiang (1.2217), and Chengdu (1.2014) were relatively high, whereas the average value of LGUE in Meishan (0.3973) was the lowest. Considering regional, natural, and economic conditions comprehensively, disparities in resources such as the urban climate, water, and minerals are the main reasons for this phenomenon. Moreover, with the continuous development of the urban economy and expansion of construction land, the LGUE of 20 cities in the Southwest China Urban Agglomeration has exhibited a downwards trend, accounting for 60.61% of the total number of cities. In the future, the Southwest China Urban Agglomeration should focus on the coordinated development of ecology and economy and increase land green use efficiency.

Table 5 Average LGUE values and rankings of cities.

City	No.	Score	City	No.	Score
Bazhong	1	1.2881	Ziyang	18	0.7996
Lijiang	2	1.2217	Yibin	19	0.7883
Chengdu	3	1.2014	Guangyuan	20	0.7860
Yuxi	4	1.1415	Liupanshui	21	0.7407
Yaan	5	1.1346	Mianyang	22	0.7365
Panzhihua	6	1.0550	Puer	23	0.7335
Anshun	7	1.0262	Dazhou	24	0.7063
Lincang	8	0.9940	Nanchong	25	0.6827
Zhaotong	9	0.9747	Bijie	26	0.5792
Deyang	10	0.9695	Zunyi	27	0.5414
Guiyang	11	0.9284	Neijiang	28	0.4906
Baoshan	12	0.9233	Leshan	29	0.4853
Zigong	13	0.8977	Qujing	30	0.4735
Tongren	14	0.8969	Luzhou	31	0.4724
Chongqing	15	0.8482	Guang’an	32	0.4235
Suining	16	0.8469	Meishan	33	0.3973
Kunming	17	0.8243			

According to the analysis of the spatiotemporal evolution outcomes of LGUE (Fig 6), cities with low LGUE are distributed rather dispersedly and are typically situated far from provincial capital cities, receiving less radiation-driven influence. Numerous low mountain and hilly landforms in these areas, such as Panzhihua, Guangyuan, Bijie, Baoshan, and Lincang, are not conducive to development and construction and have difficulty attracting investment. The number of cities with high LGUE decreased from 19 in 2008 to 17 in 2021. The LGUE of cities around Chengdu remained relatively high. This is attributed to Chengdu, the core area of Sichuan Province, which demonstrated strong development momentum during the research period and facilitated the circulation of resources among cities and the development of surrounding cities. However, the LGUE of some cities in the Southwest China Urban Agglomeration has significantly decreased.

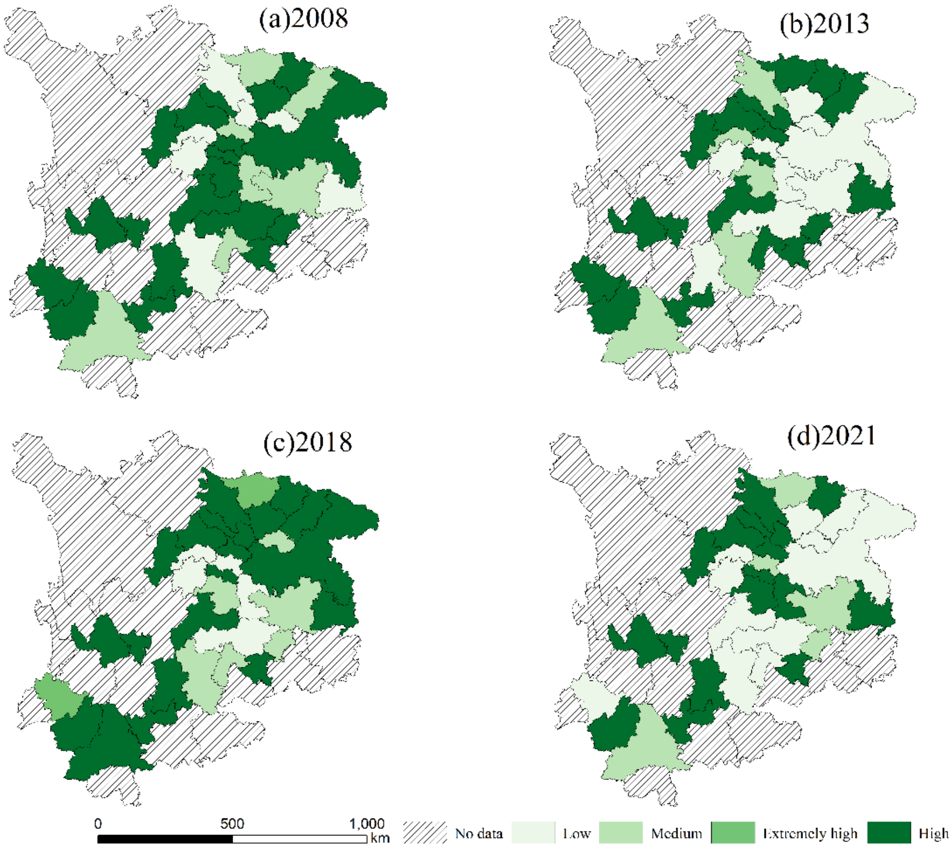

Fig 6 Spatial-temporal evolution of LGUE in the study area in 2008, 2013, 2018 and 2021.

4.3. Analysis of the CCD

According to the calculation results, from 2008 to 2021, the CCD between the NUR and the LGUE of the Southwest China Urban Agglomeration manifested a slow upwards tendency overall. Judging from the average value of the CCD, Chengdu boasted the highest CCD score, which increased from 0.4754 in 2008 to 0.8385 in 2021, with a growth rate of 76.37%. In addition, the growth rate of the CCD of 12 cities, such as Nanchong, Baoshan, Zhaotong, and Bijie, exceeded 100%, and Nanchong had the fastest growth rate, with a growth rate as high as 211.39%. Judging from the time evolution trend of the NUR, LGUE and CCD systems, the NUR of the Southwest China Urban Agglomeration lagged behind the LGUE. The evaluation score of the NUR fluctuated between 0.0606 and 0.1389, the LGUE fluctuated between 0.3627 and 1.2555, and the CCD score fluctuated between 0.1646 and 0.8465. These data suggest that although the CCD has improved, there is still an asynchronous phenomenon between NUR and LGUE, and further policy support and optimization and adjustment are needed.

According to the data displayed in Fig 7, from 2008 to 2021, only a few cities in the Southwest China Urban Agglomeration reached a coordinated state, while most cities were uncoordinated. The CCDs of Chengdu and Chongqing were relatively high. In 2021, the CCDs of Chengdu, Chongqing, Guiyang and Kunming all achieved coordination. On the whole, the construction of NUR in the Southwest China Urban Agglomeration still faces enormous challenges. Most areas have not achieved the coordinated development of NUR and LGUE, and there is still considerable room for improvement.

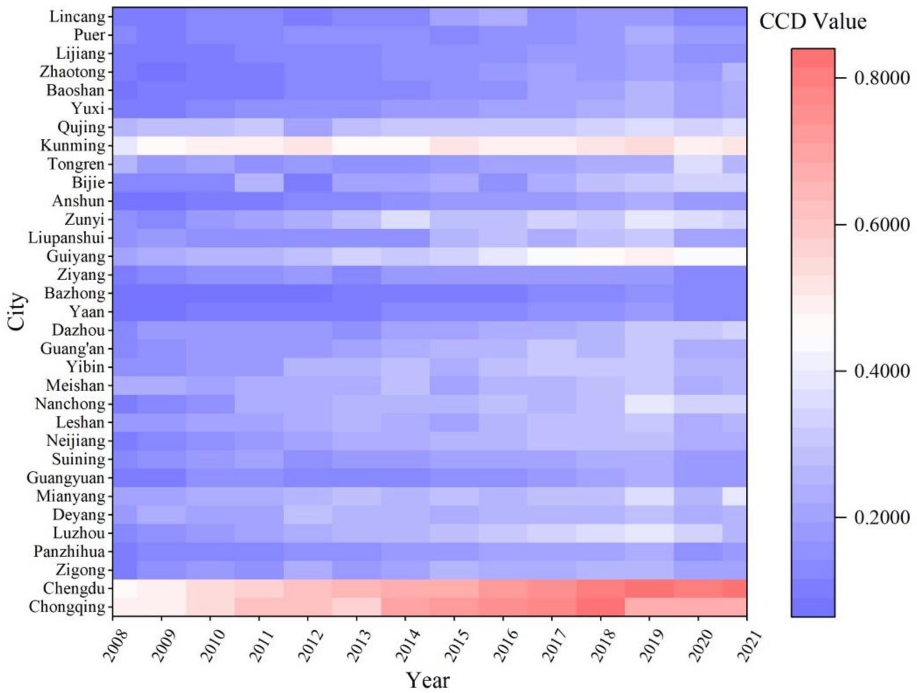

Fig 7 Coupling coordination values of 33 cities in the Southwest China Urban Agglomeration from 2008 to 2021.

This study plotted spatiotemporal distribution maps of the CCD in the Southwest China Urban Agglomeration in 2008, 2013, 2018 and 2021 (Fig 8) to clearly present each city's spatiotemporal evolution trend of the CCD. From the perspective of spatial distribution, the areas with imbalanced CCDs were concentrated mainly in the southern and middle parts of the study area, whereas the coordinated areas were concentrated mainly in the northeastern part of the study area. In 2008, the CCDs of Sichuan Province and Chongqing Municipality were relatively higher than those of Yunnan Province and Guizhou Province. Yunnan Province and Guizhou Province were significantly imbalanced, which might be attributed to the relatively backwards production and lifestyle in Yunnan and Guizhou Provinces. In 2013, Chengdu reached a moderate level of coordination, and Kunming and Chongqing also reached marginally coupled levels. Compared with 2013, the CCD clearly had improved in 2018. Liupanshui experienced a remarkable improvement, with a growth rate of 80.25%. In 2021, the CCD of Chongqing Municipality decreased. During these four years, the CCD of prefecture-level cities in Guizhou Province was generally low. The main reason might be that the economic development of Guizhou Province has relied mainly on heavy industries such as the chemical industry and mining, which have had adverse effects on urban land green use and the process of NUR production. Overall, only a few cities in the Southwest China Urban Agglomeration, such as Chengdu and Chongqing, had high and stable CCDs, while most of the other cities were at an imbalanced coupling coordination level.

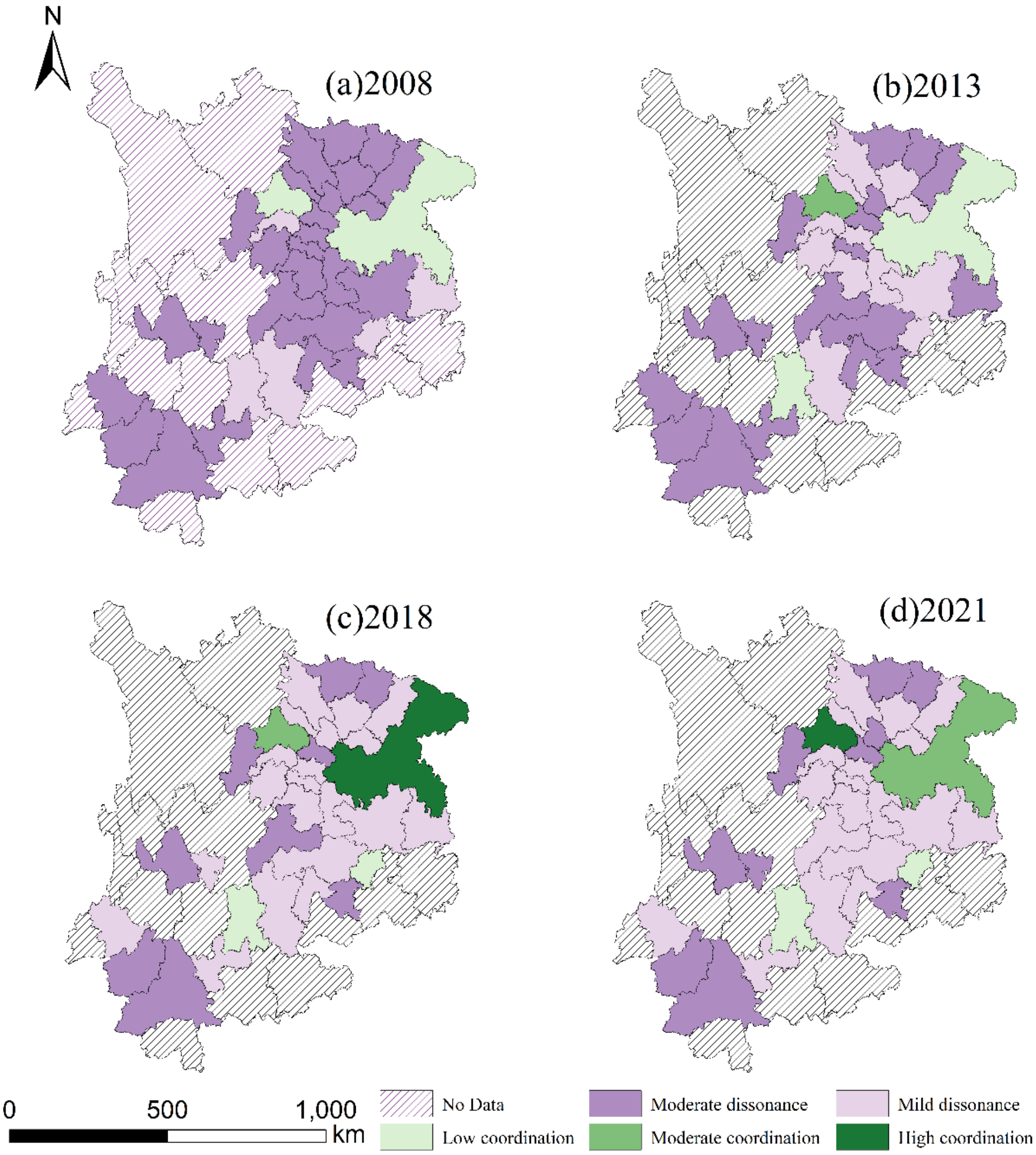

Fig 8 Spatial-temporal evolution of NUR in the study area in 2008, 2013, 2018 and 2021.

4.4. Analysis of Driving Factors

Studies have demonstrated that NUR and LGUE may be impacted by factors such as economic growth[32], government regulation[2], technological progress and the industrial structure[24]. To better comprehend the coupling coordination of NUR and LGUE, it is also necessary to measure its influencing factors. Therefore, on the basis of the feasibility of literature and data, this paper selects economic level, government support, industrial structure and scientific research investment as influencing factors. Table 6 sets out the specific information of each indicator.

Table 6 Geodetector of influencing factor indicators.

Variable	Indicator	Indicator description	Reference
Explanatory variable	level of economic development	Per capita GDP（X1)	[2]
		Fiscal revenue (X6)	[2]
	Government support	Financial expenditure/total population (X2)	[24]
	Industrial structure	Proportion of GDP from the secondary sector (X3)	[24]
	Research investment	Number of individuals engaged in scientific research, technical services, and geological surveys(X4)	[24]
		Expenditure on science and education per capita (X5)	[24]
Dependent variable	CCD	-	-

(1) Economic level: Per capita GDP (X1) and fiscal revenue (X6) somewhat reflect the economic development level of a city. The economic development level affects the input and output of land per unit area, influencing the CCD.

(2) Government support: Government public fiscal expenditures reflect the average level of public products and services obtained by residents. The ratio of public fiscal expenditure to total population (X6) reflects the impact of government factors on the CCDs of NUR and LGUE.

(3) Industrial structure: By eliminating backwards production capacity, transforming traditional technologies, and developing technology-intensive industries with high technological content and high added value, the industrial structure affects NUE and LGUE, which is represented by the proportion of the output value of the secondary industry in GDP (X3).

(4) Scientific research investment: Scientific and technological progress contributes to the transformation of production modes, which is represented by the number of people engaged in scientific research, technical services and geological surveys (X4) and the ratio of science and education expenditures to the total population (X5).

In analysing the six potential driving factors, the degrees of influence exerted by these factors on the CCD vary. Fig 9 presents the ranking of the intensities of the actions of each factor on the CCD. The number of people engaged in scientific research, technical services and geological surveys is the most significant, with a q value of 0.7326, indicating that the number of scientific researchers is the main driving force for the coupling and coordinated development of NUR and LGUE. In contrast, the driving effect of the proportion of secondary industry in GDP on the CCD is relatively weak, and the q value of this factor (0.0785) is the smallest. The value spillover effect of local fiscal revenue may promote land development, but this process may also lead to the expansion speed of land exceeding the actual demands of population growth and economic development, thereby affecting the sustainability of LGUE and NUR. Therefore, it is necessary to balance economic development and the rational utilization of land resources to ensure the sustainable development of NUR.

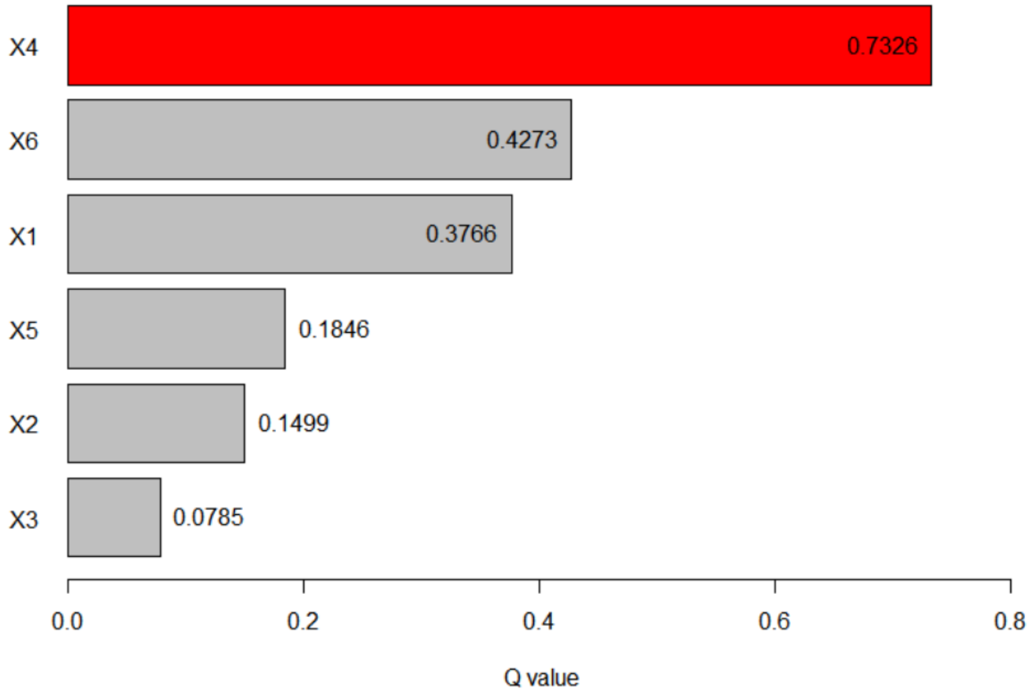

Fig 9 Results of single-factor interaction exploration.

The CCD is not determined by a single factor but is the comprehensive outcome of the interactions among numerous factors. Factor detection can assess only the influence of a single factor on the CCD. Hence, interaction detection should be further utilized to analyse the combined influence of two factors on the CCD, as illustrated in Fig 10:

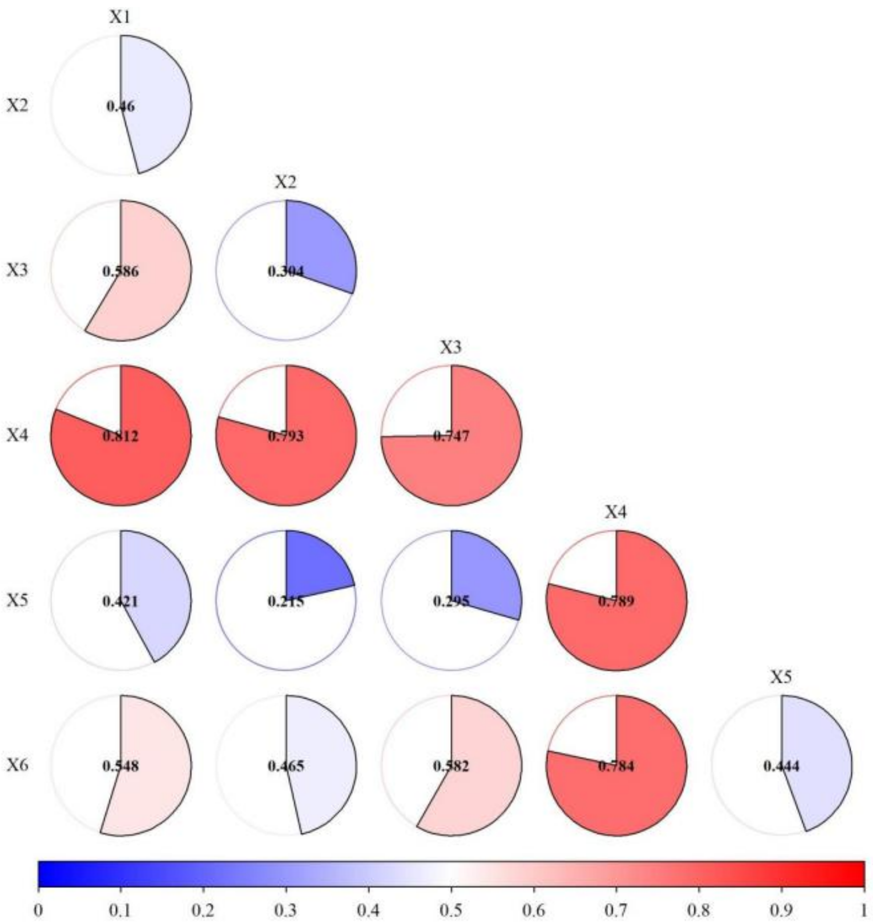

Fig 10 Driving factor interaction exploration results.

(1) The driving factors of the CCD are classified into two types: dual-factor and nonlinear enhancement. This study found that a single factor does not determine the CCD of NUR and LGUE in the Southwest China Urban Agglomeration but is the result of the joint driving effect of numerous factors.

(2) Among these factors, the interaction between per capita GDP (X1) and the number of people engaged in scientific research, technical services and geological surveys (X4) has the most substantial impact on the CCD, with a q value as high as 0.812. The combinations with interaction factor q values above 0.7 are the number of people engaged in scientific research, technical services and geological surveys (X4); the ratio of science and education expenditure to the total population (X5); the number of people engaged in scientific research, technical services and geological surveys (X4) and fiscal revenue (X6); the ratio of fiscal expenditure to the total population (X2); the number of people engaged in scientific research, technical services and geological surveys (X4); the proportion of the secondary industry in GDP (X3); and the number of people engaged in scientific research, technical services and geological surveys (X4). The interaction between fiscal expenditure and the total population (X2) and the ratio of science and education expenditure to the total population (X5) has a relatively weak influence on the coupling coordination, with a q value of 0.215.

The comprehensive results of the geodetector analysis reveal that for the CCDs of NUR and LGUE in the Southwest China Urban Agglomeration, the influence of scientific research investment and economic level surpasses that of government support. In particular, the influence of the number of people engaged in scientific research, technical services and geological surveys (X4) and fiscal revenue (X6) is the most prominent. Thus, policy-makers should pay particular attention to these factors when promoting the coupling and coordinated development of NUR and LGUE.

5. DISCUSSION

According to the results of the analysis of the coupling coordination and key factors of NUR and LGUE in the Southwest China Urban Agglomeration, this paper has reached the following conclusions.

Compared with other regions in China, the level of NUR in the Southwest China Urban Agglomeration is relatively low[38]. There are marked differences in the development conditions of various cities in China, prominent economic differences, and significant cross-regional population flows. The Southwest China Urban Agglomeration is generally an underdeveloped area. The supply of cities in underdeveloped areas is insufficient. Therefore, there is evident regional heterogeneity in the level of NUR[39]. In this paper, the level of NUR in Chongqing is significantly higher than that in other regions of the Southwest China Urban Agglomeration, which is consistent with the research results of Zhang Yue[47]. Zhang Yue noted that the communication of NUR among provinces in the Southwest China Urban Agglomeration is relatively sluggish and that there is an imbalance in NUR. However, Chongqing plays a dominant role in the development of NUR in the Southwest China Urban Agglomeration, which helps open channels for the integrated development of the western, central and eastern regions of China. The low level of NUR in cities such as Deyang and Panzhihua, with a sound industrial foundation, is attributed to the significantly different economic development paths of cities such as Deyang and Panzhihua from other cities. They rely mainly on state-owned enterprises and resource-based enterprises, which have not undergone the complete process of industrialization and thus lack the result of social capital accumulation against the backdrop of the market economy. It is difficult to derive the production service functions of modern cities, the space for further industrial upgrading and development is limited, and the transformation path is arduous. Currently, cities such as Panzhihua and Liupanshui are promoting health and tourism, but the employment absorption capacity of such industries is weak and is insufficient to support the further development of the city on the existing scale.

The LGUE of the Southwest China Urban Agglomeration fluctuated from 2008 to 2021, and its average value of LGUE was 0.8185. This outcome concurs with Li's research on the LGUE of resource-based cities in China, affirming the conclusion that the LGUE of western cities is relatively high[18]. In 2018, the average LGUE plummeted, mainly because the number of employees in secondary and tertiary industries, fixed asset investment, and urban construction areas in most cities began to decrease in 2019, impacting the LGUE that year.

The spatial distribution disparities in the coupling coordination between NUR and LGUE in the Southwest China Urban Agglomeration from 2008 to 2021 were notable. Provincial capital cities boasted a relatively elevated level of coordinated development, and these cities were more prone to engender significant radiation and diffusion effects[2,40]. Excluding provincial capital cities, the CCD results of other cities were relatively inferior, because provincial capital cities had evident comprehensive advantages and the areas with a sound industrialization foundation within the region were few. Simultaneously, they concentrated a considerable number of high-quality public service resources under political resources. They possessed significant advantages in terms of industrial agglomeration and life service agglomeration capabilities. Local governments have relatively ample funds for land governance and sustainable urban construction[6]. Nevertheless, other cities are confronted with numerous sustainability issues, such as unbalanced economic development, substantial differences in urban and rural infrastructure, the loss of a young labour force, and a single industrial structure, which would exert a direct negative influence on the NUR process and the pace of industrial upgrading[11]. The above research findings suggest that national and local governments should actively transcend administrative boundaries and promote regional cooperation in future land resource management to stimulate the spatial spillover effects of these regions and increase the degree of coordination between NUR and LGUE in adjacent areas.

The level of NUR in the Southwest China Urban Agglomeration lagged behind the level of LGUE. This was the direct reason for their discordance. According to existing research, the level of NUR in most underdeveloped and ecologically fragile areas has recently lagged behind the development of LGUE, presenting a linear fluctuation. In contrast, in developed areas, NUR and LGUE demonstrated a nonlinear change trend, and there was a highly coupled relationship between NUR and LGUE[34]. Compared with economically developed areas, the Southwest China Urban Agglomeration must confront more complex natural environments and socioeconomic transformation models, encompassing frequent natural disasters, ecological fragility, and a single industrial structure[9].

This study contributes to the literature by focusing on the Southwest City Cluster, an ecologically fragile region where the relationship between NUR and LGUE has been understudied. Previous research has focused predominantly on economically developed regions. Employing the CCD model, this study systematically analyses cities in the Southwest China Urban Agglomeration at the prefecture-level city level.

6. CONCLUSIONS

Studying the coupling coordination relationship between NUR and LGUE is important to optimize the land use structure and layout of the Southwest China Urban Agglomeration, advance the urbanization process, and facilitate the coordinated development among the economy, society and environment. On the basis of the data of 33 cities in the Southwest China Urban Agglomeration from 2008 to 2021, this paper constructs an evaluation index system for NUR and LGUE. The linear-weighting method is adopted to calculate the comprehensive evaluation score of NUR, and the Super-SBM model is employed to calculate the LGUE. the CCD model is applied to analyse the CCDs of NUR and LGUE in the Southwest China Urban Agglomeration and subsequently to analyse its temporal and spatial distribution characteristics. Finally, a geodetector is utilized to explore the driving factors of coupling coordination. The research conclusions are as follows:

(1) From 2008 to 2021, the level of NUR in the Southwest China Urban Agglomeration slowly increased, increasing from 0.061 in 2008 to 0.126 in 2021. Among them, the NUR levels in Chongqing and Chengdu increased significantly, whereas those in other cities lagged behind, potentially influenced by geographical location and natural conditions.

(2) Cities with high LGUE were concentrated in provincial capitals, such as Chongqing, Chengdu (Sichuan Province), Guiyang (Guizhou Province), and Kunming (Yunnan Province). Owing to the proximity peer effect, Chengdu and Chongqing radiated and drove the enhancement of LGUE in surrounding cities, whereas Anshun, Qujing, and Pu'er had low LGUE for reasons such as remote geographical locations and underdeveloped economies. From 2010 to 2019, influenced by factors such as Western development and technological progress, the LGUE value of the Southwest China Urban Agglomeration rose from 0.8022 to 0.8786.

(3) The coupling coordination between NUR and LGUE in the Southwest China Urban Agglomeration generally increasing. The coordinated regions were situated mainly in Chengdu, Chongqing, Guiyang, Kunming and their surrounding areas. The average coupling coordination value of Chengdu ranked the highest, reaching 0.6705, and Chongqing's average coupling coordination value was 0.6512.

(4) The geodetector model was utilized to disclose the dominant driving factors and their interaction types of coupling coordination in the Southwest China Urban Agglomeration. The CCD is jointly driven by factors such as economic, government, industrial, and scientific research input factors, among which the influence of scientific research and economic factors on coupling coordination exceeds that of government factors. The factor detector q value of X4 was the largest, at 0.7326, indicating that it played a crucial role in coupling coordination.

DATA AVAILABILITY STATEMENT

The new data created in this study are available on request.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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