

*Original Research*

# Spatial-Temporal Evolution of Green Development Efficiency of Urban Agglomeration in the Upper Reaches of the Yangtze River

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## Abstract

The green level of urban agglomeration in the upper reaches of the Yangtze River is directly related to the high-quality development of the Yangtze River Economic Belt. The understanding of green development efficiency law of urban agglomeration in the upper reaches of the Yangtze River is the basis of its choice of high-quality development path. Based on the relevant data from 2009 to 2018, DEA method and Malmquist index model are used to evaluate the static and dynamic performance of 23 cities in the three urban agglomerations of the upper reaches of the Yangtze River. The results show that: (1) From the temporal dimension, the green development efficiency of urban agglomerations in the upper reaches of the Yangtze River presents an obvious “down-up-decline” overall evolution characteristic. (2) From the spatial dimension, the green development efficiency of Chengdu-Chongqing, central Guizhou and central Yunnan urban agglomerations shows the hierarchical structure difference of “national urban agglomeration > regional urban agglomeration”. (3) The green development efficiency of central city does not match the level of its economic development. (4) The equilibrium degree within the urban agglomeration presents a certain difference. Strengthening technological innovation development, regional coordinated development and green transformation development of central cities are important ways to improve the green transformation development of urban agglomerations in the upper reaches of the Yangtze River.

**Keywords:** urban agglomeration in the upper reaches of Yangtze River, green efficiency, DEA, Malmquist index

## Introduction

The Yangtze River Economic Belt is an important economic development corridor in China and plays

an important supporting role in coordinating regional development, stimulating economic vitality, and building ecological civilization [1]. Promoting the high-quality development of the Yangtze River Economic Belt is related to the realization of the major strategic goal of national development, and is an important strategic measure to implement the five development concepts of “innovation, coordination, green, openness,

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and sharing". In September 2016, the "Outline of the Development Plan for the Yangtze River Economic Belt" clearly pointed out that the protection and restoration of the ecological environment of the Yangtze River should be placed in the first place, emphasizing that we should focus on large-scale protection and not large-scale development. In April 2018, General Secretary Xi Jinping presided over a symposium on in-depth promotion of the development of the Yangtze River Economic Belt in Wuhan, and emphasized that to promote the development of the Yangtze River Economic Belt, the premise is to adhere to the ecological priority, put the restoration of the ecological environment of the Yangtze River in an overwhelming position, and gradually solve the problem of ecological environment overdraft in the Yangtze River. It can be seen that green development is an inevitable choice for the high-quality development of the Yangtze River Economic Belt. As an important part of the Yangtze River Economic Belt, the urban agglomeration in the upper reaches of the Yangtze River is not only the ecological barrier protection area of the Yangtze River Economic Belt, but also shoulders the significant mission of leading the underdeveloped areas in the west to achieve coordinated development of economy, society and ecological environment. Nevertheless, in the process of green development, the urban agglomerations in the upper reaches of the Yangtze River are facing serious problems of soil erosion, pressure on the ecological environment, and high resource consumption intensity. How to apply the basic concepts of "ecological priority, green development" and "lucid waters and lush mountains are invaluable assets" throughout the entire process of the transformation and development of the urban agglomeration in the upper reaches of the Yangtze River, and to embark on a unique path of ecological civilization construction, which has become a key issue that needs to be solved urgently for the high-quality and coordinated development of the urban agglomeration in the upper reaches of the Yangtze River. It objectively requires a clear understanding of the current status of green development in the urban agglomeration in the upper reaches of the Yangtze River, and reveals the historical laws of green development to explore a scientific path suitable for the green development of urban agglomerations in the upper reaches of the Yangtze River.

In recent years, the majority of theoretical workers have conducted in-depth and comprehensive systematic research on green development. Green development is the highest state of harmonious coexistence between man and nature. Its essence is to achieve balanced development among economic growth, social progress, and ecological protection under the constraints of resource and environmental capacity, and to maximize comprehensive benefits [2-4]. The ultimate goal of green development is to enhance economic vitality, improve social welfare and increase resource wealth. It emphasizes the integrity and coordination of

economic system, social system and natural system [5]. The key to a regional green development lies in the improvement of green development efficiency, which can promote the transformation of a regional green development in the direction of sustainable development [6-8]. The green development efficiency is based on the essential principle of maximizing economic and social benefits or minimizing ecological damage, taking the coordinated development of economy, society and ecology as the fundamental requirement of resource input-output structural results, it improves the defects of traditional efficiency evaluation, which only considers the increase of material input, while ignoring the pursuit of scale expansion and total growth under the case of environment and energy constraints [9-11]. At present, the relevant green development efficiency measurement methods mainly include the comprehensive index method and the model evaluation method. The former is based on the multi-dimensional connotation of green development, determines the evaluation content, and uses the entropy method and the analytic hierarchy process to determine the weight and score of the indicators, so as to evaluate and analyze the green development level of the research object. In the process of practical application, different scholars have different understandings on the selection of evaluation dimensions and the quantification of indicators. Hence the constructed indicator systems are quite different [12]; the latter mostly use DEA (Data Envelopment Analysis) method, direction distance function method and other related models to measure green efficiency. Since DEA method does not need to set the production function in advance, nor does it need to manually set the weight, the measured efficiency value is the most favorable result for the decision-making unit under the objective environment, so it is widely recognized by the academic community and has long been applied to analyze the environmental efficiency of regional green development [13-16]. In recent years, the use of DEA-derived models such as the three-stage DEA model and the super-efficient SBM model has been increasing [17-19]. From the perspective of the measurement unit of green development efficiency, most of the relevant studies use cities as the measurement unit. Some studies directly analyze and compare the cities participating in the discussion, and some classify the research objects according to the levels of provinces, economic belts, and urban agglomerations to discuss the differences in green development between different regions [20-22].

Specific to the green development of the upper reaches of the Yangtze River Economic Belt, existing studies generally believe that the green efficiency of the upper reaches of the Yangtze River is relatively low [23, 24]. However, the comparative analysis among the urban agglomerations in the upper reaches of the Yangtze River and the dynamic evaluation of green development efficiency are relatively lacking. Not only is there a problem of insufficient understanding of the green development of urban agglomerations in the upper

reaches of the Yangtze River, but also it is difficult to classify and implement policies and is detrimental to green development at the regional level. Obviously, different cities have differences in geographical location, economic development level, resource endowment and other factors. Based on this objective reality, taking the green development efficiency among individual cities as the research unit, and using the results as the basis for strategy selection, it is easy to ignore the mutual influence between cities. Therefore, focusing on a larger spatial and regional level can better reflect the general law of the evolution of green development efficiency, and expanding the research objects can be conducive to the deepening of related research. The urban agglomeration takes a certain area as the spatial scale. It is a form of spatial development formed by urban agglomeration and diffusion development at the regional level, in which the cities are less constrained by the spatial distance, and are closely related with explicit division of labor, showing a relationship pattern of complementary advantages [25]. It can be seen that taking the green development efficiency of urban agglomerations as the research object can better show its changing laws at the spatial level.

Based on this, the purpose of this study is to evaluate the green efficiency of the urban agglomeration in the upper reaches of the Yangtze River. The main contributions lie in two aspects. Firstly, this paper combines DEA static and dynamic analysis methods to dynamically evaluate and compare the green development efficiency of urban agglomerations in the upper reaches of the Yangtze River, so as to gain a more comprehensive understanding of the green development level of urban agglomerations. Secondly, unlike the existing literature, this study enriches the research on urban agglomeration and clarifies the differences among the three urban agglomerations of Chengdu-Chongqing urban agglomeration, central Guizhou urban agglomeration, and central Yunnan urban agglomeration. To the best of our knowledge, no empirical studies have investigated the green development efficiency of urban agglomerations in the upper reaches of the Yangtze River, and thus this study fills a gap in the literature.

The remainder of the paper is organized as follows. Section 2 introduces research methods, indicator selection and data sources. Empirical results and discussions are reported in Section 3, and Section 4 concludes the study and proposes policy implications.

## Material and Methods

### DEA Method

DEA was first proposed by Charnes, Cooper and Rhodes (1978) based on Farrell's efficiency model, which is an evaluation method to present efficiency in the form of output/input ratio, and can effectively

evaluate the efficiency of decision-making units [26, 27]. DEA mainly has two modes: CCR and BCC. The former evaluates the efficiency of each decision-making unit based on constant returns to scale, while the latter removes the restriction of constant return to scale, and deconstructs the comprehensive technical efficiency in the CCR model into pure technical efficiency and scale efficiency, so as to achieve the purpose of more detailed description of efficiency [28]. Since the BCC model has excluded the influence of scale efficiency when measuring technical efficiency, it is more in line with the reality of urban green efficiency measurement. Therefore, this paper adopts the BCC model in DEA to measure the green efficiency of the urban agglomeration in the upper reaches of the Yangtze River. We regard the cities in the upper reaches of the Yangtze River as a decision-making unit (DMU). Suppose a DMU has  $s$  outputs and  $m$  inputs. The input vector of each decision-making unit is represented by  $X$ , and the output vector is represented by  $Y$ , representing a certain DMU. The efficiency index of a specific DMU, the mathematical programming formula constructed in CCR mode is:

$$\begin{aligned} \min Z_j &= \theta - \varepsilon \left( \sum_{i=1}^m s_i^- + \sum_{r=1}^s s_r^+ \right) \\ \text{s. t. } &\begin{cases} \sum_{j=1}^n \gamma_j X_{ij} - \theta X_{ij} + s_i^- = 0, i = 1, 2, \dots, m \\ \sum_{j=1}^n \gamma_j Y_{rj} - s_r^+ = Y_{rj}, r = 1, 2, \dots, s \\ \sum_{j=1}^n \gamma_j = 1 \\ \gamma_j, s_i^-, s_r^+ \geq 0, j = 1, 2, \dots, n; i = 1, 2, \dots, m; r = 1, 2, \dots, s \end{cases} \end{aligned} \tag{1}$$

In Equation (1),  $\theta$  represents the effective value,  $s_i^-$ ,  $s_r^+$  respectively represent the difference between the input and output items. When  $\theta = 1$ , and when  $s_i^- = 0$ ,  $s_r^+ = 0$ , then this DMU is effective relative to other DMUs, indicating that the DMU is at the frontier.

### Malmquist Exponential Model

In 1982, Caves et al. used the productivity index constructed by the Malmquist index when measuring the change of production efficiency [29]. In 1994, Fare integrated the DEA method with the Malmquist index to measure changes in inter-temporal total factor productivity, deconstructed the Malmquist index into changes in technical efficiency and technological progress, and further deconstructed development efficiency into changes in pure technical efficiency, scale Efficiency changes and technological progress [30]. The distance function formula for the Malmquist exponent is as follows:

$$\begin{aligned}
 ML &= \frac{d_i^t(x_t, y_t)}{d_i^s(x_s, y_s)} \sqrt{\left[ \frac{d_i^s(x_s, y_s)}{d_i^t(x_s, y_s)} \times \frac{d_i^s(x_t, y_t)}{d_i^t(x_t, y_t)} \right]} \\
 &= \sqrt{\left[ \frac{d_i^s(x_t, y_t)}{d_i^s(x_s, y_s)} \times \frac{d_i^t(x_t, y_t)}{d_i^t(x_s, y_s)} \right]} \quad (2)
 \end{aligned}$$

In Equation (2),  $d_i^s(x_s, y_s)$ ,  $d_i^t(x_t, y_t)$  measure the distance from the observations in the same period to the efficiency boundary;  $d_i^t(x_s, y_s)$ ,  $d_i^s(x_t, y_t)$  measure the inter-period efficiency index. When  $ML > 1$ , it means that the total factor productivity of the decision-making unit presents an upward trend; when  $ML = 1$ , it means that the total factor productivity of the decision-making unit remains unchanged; when  $ML < 1$ , it means that the total factor productivity of the decision-making unit presents a downward trend.

### Indicator Selection and Data Sources

From the perspective of development economics, labor and capital are the core elements that affect the economic growth of a country and a region. Similarly, urban green development is closely related to the two elements of resources and the environment, and in the context of the new economic normal, resources and the environment, as endogenous variables of economic development, have a more obvious impact on the scale and speed of economic development [31]. Therefore, resources and environmental factors should be taken into account when evaluating the green development efficiency of urban agglomerations, so as to ensure that the evaluation of urban green efficiency can fully reflect the balanced relationship between economy, society and ecology. Specifically, in the selection of input indicators, we use the number of employees at the end of the period, investment in fixed assets, and industrial electricity consumption to represent labor input, capital input, and resource input respectively. In the selection

of output indicators, the GDP can reflect the economic development level of the city, and the three indicators of industrial waste water discharge, industrial sulfur dioxide discharge, and industrial smoke and dust discharge can reflect the environmental pollution level of the city. We use the entropy weight method to obtain the weight of each environmental pollution index, and multiply it with the GDP to obtain the relative green GDP, which is used as the final output index. In order to eliminate the influence of inflation, the actual value after deflating the price index of each city in 2009 is used as the base period to represent the investment in fixed assets and the gross domestic product of each city. The specific indicators are selected in Table 1.

The urban agglomeration in the upper reaches of the Yangtze River consists of three major urban agglomerations, namely the Chengdu-Chongqing urban agglomeration, the central Yunnan urban agglomeration, and the central Guizhou urban agglomeration, covering 27 prefecture-level cities (and above) and autonomous prefectures including Chongqing, Chengdu, Zigong, Deyang, Mianyang, Guiyang, Zunyi, Kunming, Chuxiong Yi Autonomous Prefecture. Compared with prefecture-level cities, the data statistics of autonomous prefectures are more challenging and there are many missing data contents. Therefore, four autonomous prefectures, Chuxiong Yi Autonomous Prefecture, Honghe Hani and Yi Autonomous Prefecture, Qiandongnan Prefecture, and Qiannan Prefecture were excluded from the research scope, and the research objects were 23 prefecture-level cities in the three major urban agglomerations, as shown in Table 2. Taking 2009-2018 as the time period and the 2010-2019 “China Urban Statistical Yearbook” as the main data source, some missing data is filled in through the statistical yearbooks of various provinces and cities. For the data that is still missing, the “moving weighted average method” and “extension method” are used to make up according to the actual situation.

Table 1. Indicator selection.

Indicator	Secondary indicator	Third-level indicator
Input	Labor input	The number of employees at the end of the period (10000 people)
	Capital input	Investment in fixed assets (100 million yuan)
	Resource input	Industrial electricity consumption (100 million kilowatt-hour)
Output	Green output	Relative green GDP (100 million yuan)

Table 2. Major cities in the urban agglomeration in the upper reaches of the Yangtze River.

Urban agglomerations	Cities
Chengdu-Chongqing urban agglomeration	Chongqing, Chengdu, Zigong, Luzhou, Deyang, Mianyang, Suining, Neijiang, Leshan, Nanchong, Meishan, Yibin, Guang'an, Dazhou, Ya'an, Ziyang
Central Guizhou urban agglomeration	Guiyang, Zunyi, Anshun, Bijie
Central Yunnan urban agglomeration	Kunming, Qujing, Yuxi

## Results and Discussion

### Static Analysis of Green Development Efficiency of Urban Agglomerations

Using DEAP2.1 software to calculate the green input-output indicators of the above 23 cities, the comprehensive technical efficiency, pure technical efficiency and scale efficiency of each city are obtained, as shown in Table 3.

On the whole, in 2018, the average green efficiency of the Chengdu-Chongqing urban agglomeration was 0.762, that of the central Guizhou urban agglomeration was 0.698, and that of the central Yunnan urban agglomeration was 0.553. Although the green development level of the Chengdu-Chongqing urban agglomeration was better than that of the central Guizhou and central Yunnan urban agglomerations, the overall green efficiency was 0.762. The level is not high, which indicates that the coordinated development level of economy, society and ecology of the urban

agglomeration in the upper reaches of the Yangtze River is still low, which is consistent with Yan et al. (2021) as well as Cui et al. (2020) [32, 33].

In 2018, Chengdu, Ziyang, Chongqing, and Zigong were the only cities at the forefront, which achieved the optimal allocation of input and output and outperformed other cities in terms of resource utilization and environmental protection. It is worth pointing out that Chengdu, Chongqing, Kunming and Guiyang are the central cities of the urban agglomeration in the upper reaches of the Yangtze River. Only Chengdu and Chongqing are at the forefront, and the rest of the cities have not achieved DEA effectiveness, which is extremely disproportionate to their urban scale and economic development level. The basic fact that the green development of central cities in the upper reaches of the Yangtze River has a weak driving effect. From the perspective of pure technical efficiency (PTE), Chengdu, Ya'an, Ziyang, Chongqing, Zigong, Deyang, and Suining achieved pure technical efficiency and effectiveness, while Ya'an, Deyang, and Suining were

Table 3. The average green efficiency of the three major urban agglomerations in 2018.

Urban agglomerations	Cities	TE	PTE	SE
Chengdu-Chongqing urban agglomeration	Chengdu	1.000	1.000	1.000
	Nanchong	0.618	0.655	0.944
	Meishan	0.670	0.796	0.842
	Yibin	0.609	0.617	0.988
	Guang'an	0.651	0.738	0.881
	Dazhou	0.509	0.541	0.941
	Ya'an	0.542	1.000	0.542
	Ziyang	1.000	1.000	1.000
	Chongqing	1.000	1.000	1.000
	Zigong	1.000	1.000	1.000
	Luzhou	0.770	0.778	0.990
	Deyang	1.000	1.000	1.000
	Mianyang	0.748	0.786	0.952
	Neijiang	0.807	0.904	0.892
	Suining	0.809	1.000	0.809
	Leshan	0.766	0.885	0.866
average value		0.762	0.841	0.906
Central Guizhou urban agglomeration	Guiyang	0.758	0.891	0.851
	Zuiyi	0.630	0.647	0.974
	Anshun	0.897	1.000	0.897
	Bijie	0.554	0.641	0.865
	average value		0.698	0.780
Central Yunnan urban agglomeration	Kunming	0.619	0.698	0.887
	Qujing	0.360	0.397	0.908
	Yuxi	0.757	0.912	0.831
	average value		0.553	0.632

Note: The average value in the table is the geometric mean



not at the forefront, indicating that their low scale efficiency affects the improvement of comprehensive efficiency. From the perspective of scale efficiency (SE), the scale efficiency of urban agglomeration in central Guizhou in 2018 (0.875) was lower than that of Chengdu-Chongqing urban agglomeration (0.906) and central Yunnan urban agglomeration (0.896). Additionally increasing the input of green resources can effectively improve the comprehensive efficiency of the cities.

#### *Temporal Characteristics*

In order to further analyze the overall change trend of frontier cities and the change law of green development efficiency of the three major urban agglomerations, we collected statistics on cities with an annual comprehensive efficiency of 1 (as shown in Table 4), and plotted the trend of comprehensive efficiency, pure technical efficiency and scale efficiency of the three major urban agglomerations (as shown in Figs 1, 2, and 3), so as to reveal the temporal law of green development efficiency of urban agglomerations in the upper reaches of the Yangtze River from 2009 to 2018. From the perspective of the distribution of frontier cities, from 2009 to 2018, the frontier cities of the Chengdu-Chongqing urban agglomeration are mainly concentrated in the southern and western Sichuan regions, while the cities in the northern and eastern Sichuan regions have not achieved the effective DEA, which shows that the frontier cities of the Chengdu-Chongqing urban agglomeration are unevenly distributed; all the cities in the central Guizhou agglomeration have not achieved DEA effectiveness, indicating that the central Guizhou urban agglomeration has not yet achieved beneficial effect in green development construction; only Yuxi in the central Yunnan urban agglomeration has had DEA effectiveness, and the green efficiency has increased

from 2014 to 2018. The decrease shows that the green development of Yuxi has a downward trend.

From the changing trend of green development efficiency, the comprehensive efficiency of the urban agglomeration in the upper reaches of the Yangtze River has obvious three-stage evolution characteristics. In the first stage (2009-2011), the comprehensive efficiency continued to decline, from 0.796 in 2009 to 0.719 in 2011, a decrease of 9.67%. The possible explanation is: on the one hand, due to the impact of the 5.12 Wenchuan earthquake, the ecosystem in the upper reaches of the Yangtze River has been severely damaged, and geological disasters such as soil erosion, landslides, debris flows, and dammed lakes have occurred from time to time, resulting in rapid ecological carrying capacity. The decline has exacerbated the deterioration of the regional ecological environment and inhibited the improvement of its overall green development level. On the other hand, due to the impact of the 2008 world financial crisis and the pressure of "maintaining growth", the central and local governments have paid more attention to economic growth and not enough attention to environmental protection and ecological civilization construction, resulting in a decline in the efficiency of green development [34]. In the second stage (2011-2014), the comprehensive efficiency continued to rise, from 0.719 in 2011 to 0.787 in 2014, an increase of 9.46%. Thanks to the transformation of economic development mode, the promotion and strengthening of a series of policies such as "low-carbon life", "energy saving and emission reduction", the level of green development has been improved. What's more, the convening of the 2011 Ecological Civilization Guiyang Conference with the theme of "Green Transformation to Ecological Civilization – Opportunities and Challenges" aroused great attention from all walks of life, and played a huge role in promoting the transformation of the development mode of the urban agglomeration in the upper reaches of the Yangtze River. In the third stage

Table 4. Frontier cities of urban agglomeration in the upper reaches of the Yangtze River from 2009 to 2018.

Years	Chengdu-Chongqing urban agglomeration	Central Guizhou urban agglomeration	Central Yunnan urban agglomeration
2009	Chengdu, Ziyang, Chongqing, Neijiang	-	Yuxi
2010	Chengdu, Deyang, Neijiang	-	Yuxi
2011	Chengdu, Ya'an, Ziyang, Neijiang	-	Yuxi
2012	Chengdu, Ziyang, Neijiang	-	Yuxi
2013	Chengdu, Ziyang, Zigong, Neijiang	-	Yuxi
2014	Chengdu, Ziyang, Zigong, Deyang	-	-
2015	Chengdu, Ziyang, Zigong, Neijiang	-	-
2016	Chengdu, Ziyang, Chongqing, Zigong	-	-
2017	Chengdu, Ziyang, Chongqing, Zigong	-	-
2018	Chengdu, Ziyang, Chongqing, Zigong	-	-

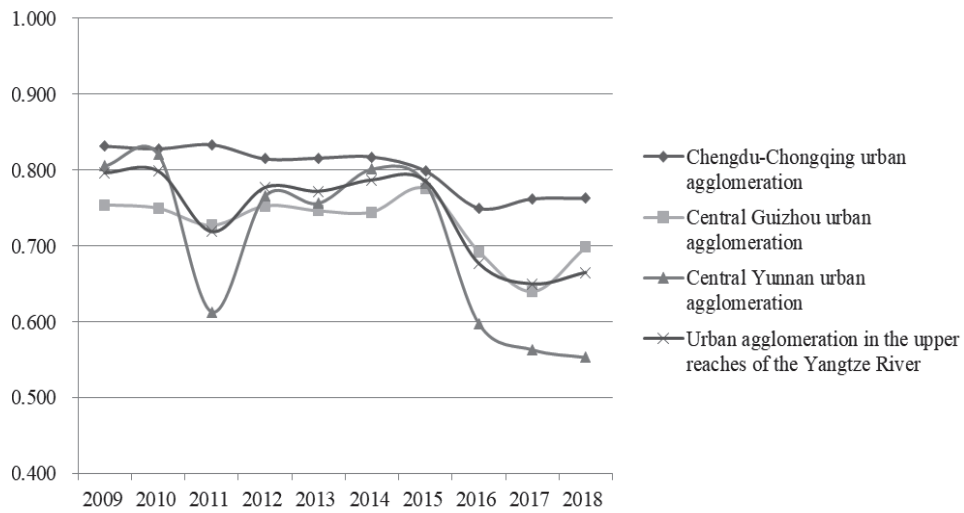


Fig. 1. Changes in the TE of the three major urban agglomerations from 2009 to 2018.

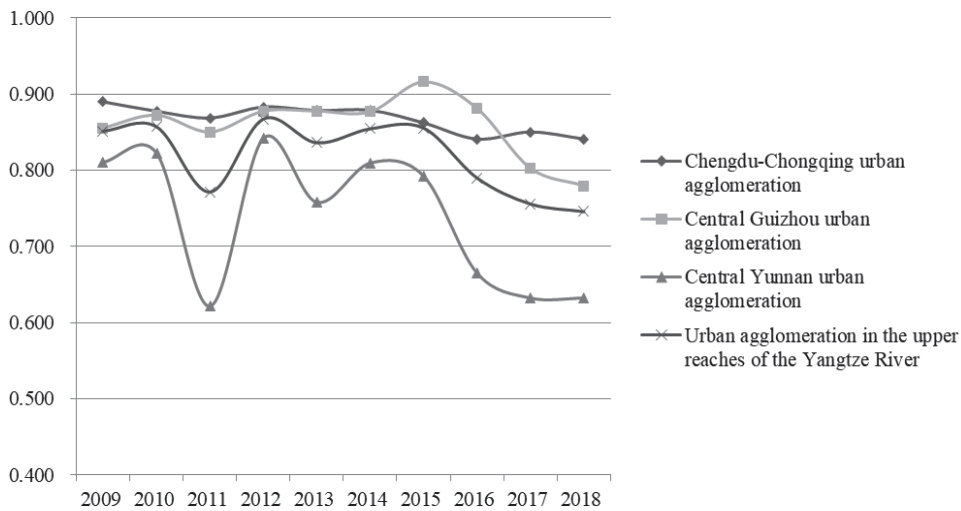


Fig. 2. Changes in the PTE of the three major urban agglomerations from 2009 to 2018.

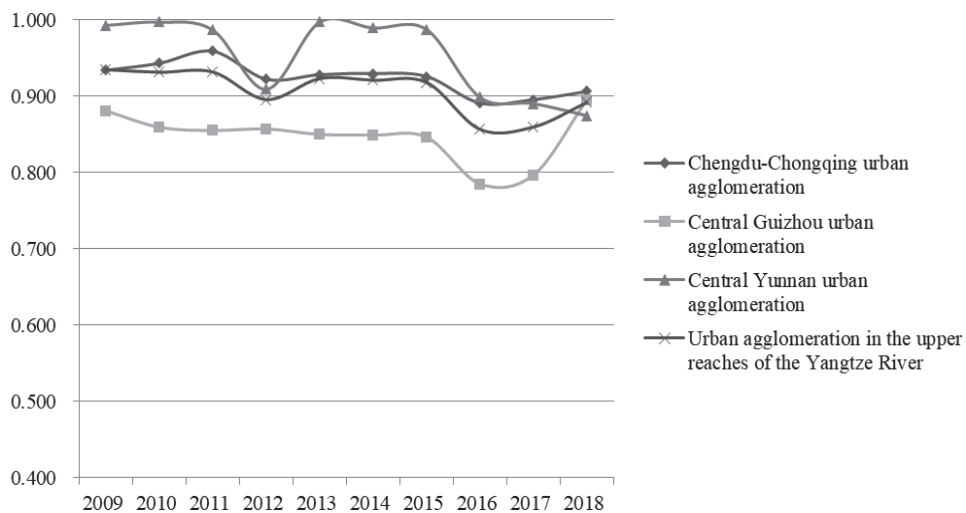


Fig. 3. Changes in the SE of the three major urban agglomerations from 2009 to 2018.

(2014-2018), the comprehensive efficiency showed a significant downward trend, from 0.787 in 2014 to 0.665 in 2018, a change of 15.5%. During this period, the pace of urbanization construction in the upper reaches of the Yangtze River has accelerated significantly. In order to promote economic development, the upper reaches of the Yangtze River have undertaken many high-pollution and high-emission energy development industries, which further aggravated regional environmental pollution and led to a decline in the efficiency of its green development.

It can be seen from the above analysis that 2011 is not the turning point of green development of the urban agglomeration in the upper reaches of the Yangtze River. The period of stable improvement of green development efficiency has not yet come, and there is a large room for improvement. In terms of urban agglomerations, the green development efficiency of the urban agglomerations in the upper reaches of the Yangtze River is distributed in a gradient. The Chengdu-Chongqing urban agglomeration is higher than that of the central Guizhou and central Yunnan urban agglomerations, and the comprehensive efficiency of the three major urban agglomerations has fluctuated to a certain extent from 2009 to 2018. Relatively speaking, the comprehensive efficiency of the Chengdu-Chongqing urban agglomeration is relatively stable,

while the comprehensive efficiency of the central Guizhou and central Yunnan urban agglomerations fluctuates more. After 2014, it showed a downward trend. From the perspective of comprehensive efficiency decomposition, the trend of pure technical efficiency and comprehensive efficiency of the three major urban agglomerations is basically the same, while the change trend of scale efficiency is relatively gentle, indicating that pure technical efficiency is the main factor causing the decline of comprehensive efficiency, which is consistent with Li et al. (2019) [35]. In the future, while maintaining high-scale efficiency, the important role of scientific management, technological progress should be actively played to improve the contribution level of pure technical efficiency.

### *Spatial Differentiation Characteristics*

According to the temporal characteristics of the green development efficiency of the urban agglomeration in the upper reaches of the Yangtze River, the comprehensive efficiency was the lowest in 2011, reached its peak in 2014, and then showed a clear downward trend. This paper selects 2009, 2011, 2014, and 2018 as four basic nodes to draw the distribution map of green development efficiency in each city (as shown in Fig. 4), and divides the green development

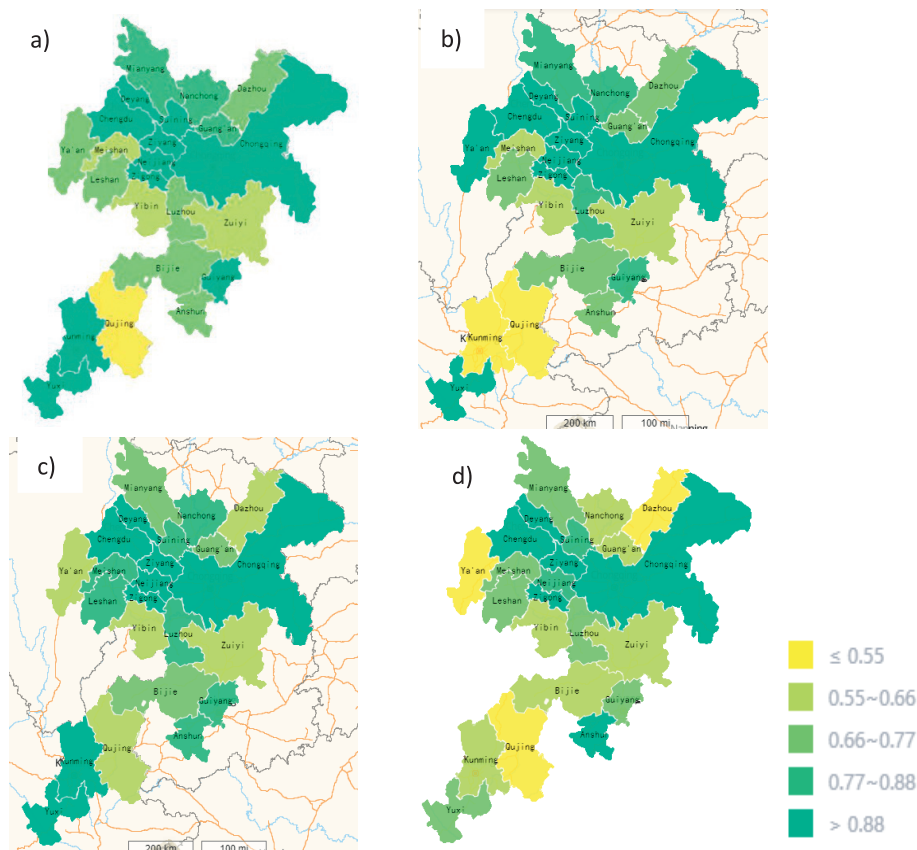


Fig. 4. The spatial distribution of TE in urban agglomeration in the upper reaches of the Yangtze River in years a) 2009, b) 2011, c) 2014, d) 2018.



efficiency into high level ( $>0.88$ ), medium-high level ( $0.77-0.88$ ), medium level ( $0.66-0.77$ ), medium-low level ( $0.55-0.66$ ), low level ( $\leq 0.55$ ), which can more intuitively show the spatial evolution characteristics of green development efficiency in different regions of the upper reaches of the Yangtze River urban agglomeration.

It can be seen from Fig. 4 that the spatial distribution of the green development level of the urban agglomeration in the upper reaches of the Yangtze River has typical unbalanced characteristics, and the unbalanced degree is gradually expanding. During the study period, the overall level of green development in the urban agglomeration in central Guizhou and central Yunnan was lower than that of the Chengdu-Chongqing urban agglomeration, and the level of green development changed significantly, which is accordant with Zhao et al. (2019) [36]. The possible explanation is that the urban agglomerations of central Guizhou and central Yunnan belong to regional urban agglomerations, and their development started relatively late. The green development plan is not enough, coupled with a single economic model, an unsound market mechanism, and prominent industrial structure contradictions, which lead to the bottleneck of economic development and a poor green development trend [37]. As a national-level urban agglomeration, the Chengdu-Chongqing urban agglomeration is a key national development area, with a better resource allocation method and a higher technical level, resulting in a promising green development trend. Specifically, in 2009, the overall development of the urban agglomeration in the upper reaches of the Yangtze River was relatively favorable. Except for Meishan, Yibin, Zunyi and Qijiang, the green development of all cities was above the medium level. In 2011, the urban agglomerations in central Guizhou and central Yunnan declined significantly, and Zunyi, Kunming and Qijiang were all at a medium-low level and a low level; in 2014, the overall level of green development has improved, and 14 cities have entered a medium-high level and a high level. In particular, the urban agglomeration in central Yunnan has improved the most, and all cities are out of the low level. In 2018, except for Chengdu, Ziyang, Chongqing and Zigong, the green development levels remained unchanged, and the rest of the cities have declined to varying degrees, especially all the cities in the central Yunnan urban agglomeration have dropped to the middle or lower level, indicating that the task of improving the level of green development is arduous.

#### Dynamic Analysis of Green Development Efficiency of Urban Agglomerations

In view of the fact that the use of the BCC model can only obtain the static efficiency of a single time point, and cannot process longitudinal and cross-sectional data for cross-period efficiency comparison. Therefore, the Malmquist index is introduced to calculate the inter-temporal changes in total factor productivity to further

compare and study the differences between urban agglomerations and within urban agglomerations.

#### *Difference Analysis between Urban Agglomerations*

From the previous analysis, it can be seen that the overall green development level of the urban agglomeration in the upper reaches of the Yangtze River is relatively low, and there is also a certain gap in green development among the urban agglomerations in Chengdu-Chongqing, central Guizhou, and central Yunnan. However, the dynamic trends and development laws of differences between urban agglomerations need to be further evaluated through the Malmquist index model. The MALMQUIST-DEA calculation was carried out on the green input-output indicators of 23 cities in the upper reaches of the Yangtze River for 10 years, and the technical efficiency changes, technological progress changes and TFP index (Total Factor Productivity) of each city were obtained.

It can be seen from Table 5 that, in general, the TFP index of the urban agglomeration in the upper reaches of the Yangtze River is 1.069, representing an upward trend in total factor productivity, but the increase in technological progress (1.084) has not made up for the decline in technical efficiency (0.986). Therefore, technical efficiency is the main factor affecting the green development efficiency of urban agglomerations in the upper reaches of the Yangtze River. In terms of urban agglomerations, the Chengdu-Chongqing, central Guizhou, and central Yunnan urban agglomerations have achieved TFP growth, and the total factor productivity has an obvious upward trend. And the average annual growth rate of the TFP index of the central Yunnan urban agglomeration is 3.5%, which is lower than that of the Chengdu-Chongqing urban agglomeration (7.5%) and the central Guizhou urban agglomeration (7.4%), and it is at the bottom of the urban agglomeration in the upper reaches of the Yangtze River.

#### *Analysis of Differences within Urban Agglomerations*

Urban agglomeration is a system structure in which large, medium and small cities with certain geographical relationships are guided and driven by core cities to form a system of cooperative cooperation and symbiotic evolution between cities [38, 39]. Due to differences in city scale, economic development level, resource allocation, etc., there must be differences in the green development of cities within the urban agglomeration, and the degree of internal differences reflects the balanced degree of green development in the urban agglomeration. By constructing the variation function of the TFP index to measure the differences within the urban agglomeration, the higher the coefficient of variation, the greater the differences within the urban agglomeration [40]. The coefficient of variation function is as follows:

Table 5. The Malmquist index average of the three major urban agglomerations from 2009 to 2018.

Urban agglomerations	Cities	effch	average	techch	average	tfpch	average
Chengdu-Chongqing urban agglomeration	Chengdu	1.000	0.990	1.081	1.085	1.081	1.075
	Nanchong	0.968		1.096		1.060	
	Meishan	1.002		1.077		1.079	
	Yibin	0.994		1.083		1.076	
	Guang'an	0.974		1.091		1.063	
	Dazhou	0.968		1.094		1.050	
	Ya'an	0.965		1.089		1.051	
	Ziyang	1.000		1.079		1.079	
	Chongqing	1.000		1.099		1.099	
	Zigong	1.007		1.085		1.093	
	Luzhou	1.009		1.078		1.088	
	Deyang	1.000		1.082		1.082	
	Mianyang	0.984		1.097		1.079	
	Neijiang	0.976		1.059		1.034	
	Suining	0.986		1.099		1.083	
Leshan	1.016	1.078	1.095				
Central Guizhou urban agglomeration	Guiyang	0.975	0.991	1.102	1.081	1.074	1.074
	Zuiyi	0.998		1.080		1.078	
	Anshun	1.020		1.077		1.099	
	Bijie	0.973		1.073		1.044	
Central Yunnan urban agglomeration	Kunming	0.950	0.959	1.084	1.079	1.030	1.035
	Qujing	0.958		1.082		1.036	
	Yuxi	0.970		1.072		1.039	
Mean			0.986		1.084		1.069

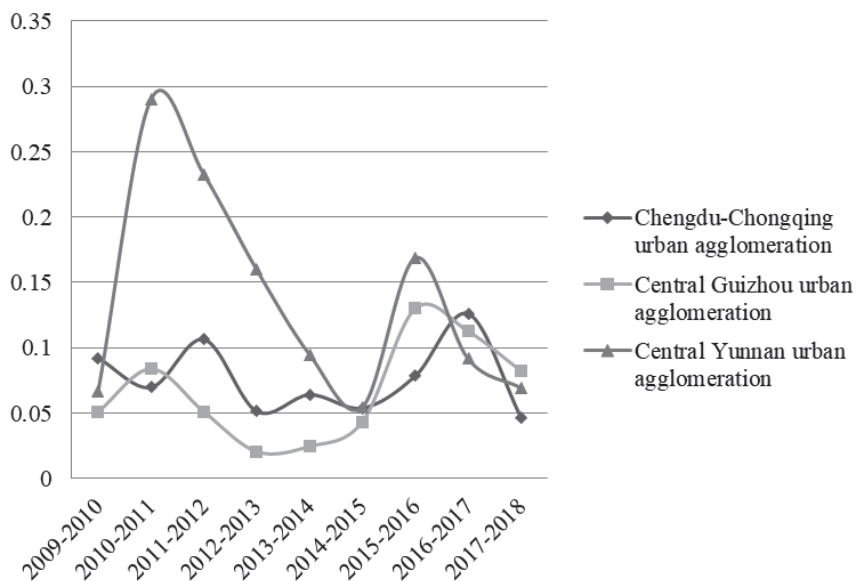


Fig. 5. The coefficient of variation of the Malmquist index of the three major urban agglomerations.

$$C_v = \frac{1}{\bar{y}} \sqrt{\frac{1}{n-1} \sum_{i=1}^n (y_i - \bar{y})^2} \quad (3)$$

In formula (3),  $C_v$  is the coefficient of variation,  $n$  is the number of studied cities,  $y_i$  is the TFP index value of the  $i$ -th studied city, and  $\bar{y}$  is the average TFP index of the studied city. The coefficient of variation of the TFP index of the three major urban agglomerations is calculated according to the coefficient of variation function, and a trend graph is generated, as shown in Fig. 5. It can be seen from Fig. 5 that the coefficient of variation of most time nodes in the central Yunnan urban agglomeration is higher than that of the Chengdu-Chongqing and the central Guizhou urban agglomeration, and even the coefficient of variation reached 0.3 between 2010 and 2011, indicating a huge difference within the urban agglomeration. Within the Chengdu-Chongqing and Central-Guizhou urban agglomerations, the coefficient of variation is basically maintained below 0.15, and the internal differences are small. Namely, the urban agglomerations of Chengdu, Chongqing and Central Guizhou have a higher degree of balance in their internal development, and there is not much difference in the level of green development among the cities, and an overall green development model has been basically formed. But at the same time, it also reflects the lack of regional green growth poles. It is necessary to cultivate a green leading area with a demonstration role; the urban agglomeration in central Yunnan, which has a relatively low degree of internal development balance, has not yet formed a better green development model.

## Conclusions

Based on the basic connotation of green development and comprehensively considering the core elements such as labor, capital, resources, and environment that affect urban green development, the DEA method and the Malmquist index model are used to analyze the main urban agglomerations in the upper reaches of the Yangtze River from static and dynamic aspects from 2009 to 2018. The following conclusions are drawn:

First, the overall development trend of the green development of the urban agglomeration in the upper reaches of the Yangtze River is not optimistic. From 0.796 in 2009 to 0.665 in 2018, it has an obvious three-stage evolution characteristic of "decline-up-down", and the recent decline is particularly obvious. How to curb the decline of green development has become a top priority.

Second, there are obvious gaps in the level of green development between the three major urban agglomerations of Chengdu-Chongqing, Central Guizhou, and Central Yunnan, as well as among the cities within the urban agglomeration. On the one hand,

the average green development efficiency of the three major urban agglomerations in the past ten years was 0.801, 0.727, and 0.698 respectively, showing obvious differences in the hierarchical structure of "national urban agglomeration>regional urban agglomeration". The TFP of the urban agglomerations of Chengdu-Chongqing, Central Guizhou, and Central Yunnan all showed an increasing trend, with an average annual growth rate of 7.5%, 7.4%, and 3.5%. On the other hand, the equilibrium degree within the urban agglomeration also presents a certain difference. According to the calculation of the coefficient of variation of the Malmquist index, it can be found that the urban agglomeration in Chengdu-Chongqing and central Guizhou has a relatively high degree of internal development balance, and the difference in green development between cities is small, while the degree of internal development balance in the urban agglomeration in central Yunnan is low, and the green development model has not yet formed. Based on this, further research can be employed to analyze regional coordinated development among the three major urban agglomerations in the future.

Third, the level of urban green development in central cities like Kunming and Guiyang does not match the level of economic development. In the past ten years, the frontier cities are mainly concentrated in Ziyang, Zigong, Neijiang, Yuxi and other cities with less developed economic strength. Kunming and Guiyang, the central cities of the urban agglomeration in the upper reaches of the Yangtze River, have strong economic strength, but they have not been able to achieve effective DEA, and the leading role of green development is not obvious, indicating that green transformation is urgently needed.

In response to the above conclusions, this paper proposes the following suggestions. First, we should vigorously improve pure technical efficiency. Specifically, we should increase investment in science and technology, encourage enterprises to carry out independent technological innovation, and provide them with a series of policy preferences such as tax incentives and financial support to create an excellent environment for technological innovation; then, we should replace traditional industrial technologies with high technology. On the one hand, increase the overall planning for industrial transformation, upgrading and development, and actively guide the development of high technology. On the other hand, carry out technological transformation and structural optimization on the existing high-pollution and high-emission industrial structure, and promote the green development of urban agglomerations through technological innovation and structural optimization.

Second, we should vigorously promote coordinated regional development. It is necessary to face up to the green development gap of urban agglomerations, strengthen regional coordinated development on the basis of respecting their respective comparative

advantages, and form a new pattern of overall promotion. The first is to increase investment in green resources in the Chengdu-Chongqing urban agglomeration to foster new growth poles for green development. The second is to attach importance to the urban planning and construction of urban agglomerations in central Guizhou and central Yunnan, including ecological construction planning at the government level and green development planning at the enterprise level, so as to avoid repeating the old development path of "pollution first and then treatment". The third is to identify the positioning of each city, and actively leverage its location and geographical advantages to develop green industries such as eco-tourism and green agriculture in the urban agglomeration of central Guizhou and central Yunnan, and build an industrial system with low environmental pollution and good comprehensive benefits. The fourth is to give full play to the core engine function of the Chengdu-Chongqing urban agglomeration, and guide the Chengdu-Chongqing urban agglomeration with high green efficiency to export advanced technology and management to the urban agglomerations in central Guizhou and central Yunnan, enhance its spillover effect, and strengthen exchanges and cooperation among cities, thus forming a new pattern of green development featuring mutual cooperation and win-win cooperation. The fifth is to improve the ecological coordinated protection mechanism, promote the construction of a joint prevention and control protection mechanism for urban agglomerations in the upper reaches of the Yangtze River, formulate a unified catalogue of restricted, prohibited and eliminated industries, and strengthen the coordinated control of industrial projects with high energy consumption.

Third, we should focus on promoting the green transformation and development of central cities. It is necessary to vigorously promote the green transformation of core cities to enhance their green radiation driving effect. The first is to accelerate the development of innovation platforms in core cities. Chengdu Tianfu New District, Chongqing Liangjiang New District, and Guizhou Gui'an New District are important platforms for innovation-driven development of urban agglomerations in the upper reaches of the Yangtze River. We should actively and steadily eliminate old production capacity, vigorously cultivate new technologies, new processes, and new industries as the starting point, and develop and expand green industrial clusters based on the development foundation and resource advantages. The second is to actively build eco-industrial parks, adhere to the principles of "green design, clean production, and pollution prevention", strive to curb pollution emissions from the source, develop a benign "recycling-reuse-design-production" green circular economy, and boost the green transformation of core cities in the upper reaches of the Yangtze River.

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## Conflict of Interest

The authors declare no conflict of interest.

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