



# What were the spatiotemporal evolution characteristics and the influencing factors of urban land green use efficiency? A case study of the Yangtze River Economic Belt

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**Abstract** China's rapid urbanization has had a tremendous impact on the country's limited land resources, and one of the major issues of green development is how to utilize the limited land resources to maximize social, economic, and environmental advantages. From 2005 to 2019, the super epsilon-based measure model (EBM) was employed to assess the green land use efficiency of 108 prefecture-level and above cities in the Yangtze River Economic Belt (YREB), as well as investigate its spatial and temporal evolution and influential factors. The findings demonstrate that overall, urban land green use efficiency (ULGUE) in the YREB has been ineffective; in terms of city scale, megacities have the highest efficiency, followed by large cities and small and medium-sized cities; and at the regional level, downstream efficiency does have the greatest average value, followed by upstream efficiency and middle efficiency. The results of temporal and spatial evolution reveal that the number of cities with a high ULGUE is increasing in general but that their spatial characteristics are

relatively dispersed. Population density, environmental regulation, industrial structure, technology input, and the intensity of urban land investment all have major beneficial effects on ULGUE, whereas urban economic development level and urban land use scale clearly have inhibitory effects. In light of the previous conclusions, some recommendations are made to continuously improve ULGUE.

**Keywords** Yangtze River Economic Belt · Urban land green use · Super-EBM · Tobit model · Spatial and temporal evolution · Influencing factor

## Introduction

Urban land resources serve as both the fundamental living space for city dwellers and the spatial conduit for urban social and commercial activities (Fu et al., 2021; Xue et al., 2022). In the past few decades, China has witnessed rapid urbanization, with urban populations rising from 201 million in 1981 to 884 million in 2019, and the area of urban construction land expanding from 6720 square kilometers in 1981 to 58,308 square kilometers in 2019 (NBSC, 2021). China has the reality that there are more people than land, and the continuous expansion of urban construction land will inevitably intrude on agricultural and forest land (Lambin & Meyfroidt, 2010), which makes the conflict between urban development, the protection

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of cultivated land, and ecological construction increasingly prominent (P. Liu & Ravenscroft, 2017; Y. Liu, 2018). Moreover, the rapid growth of urban construction land will cause issues like excessive land use and energy consumption (C. Zhang & Luo, 2022), and these problems are detrimental to the green development of cities.

Green development aims to improve natural resource utilization efficiency and promote a sustainable lifestyle (Tan et al., 2021). In current history, the Chinese government has increasingly prioritized green development and comprehensively improved resource utilization efficiency (C. Liu & Zhao, 2022). According to the 2019 China Municipal Government Work Report, it is critical to promote land protection and intensive utilization, as well as to enhance the potential usage of existing construction land and the green benefits of all types of land use. The “14th Five-Year Plan” emphasizes green development even more, fosters human-nature coexistence, and makes significant provisions for comprehensively improving the green utilization efficiency of land, energy, and other resources. The 2022 China Municipal Government Work Report emphasizes continuous environmental improvement as well as the promotion of green and low-carbon development. As a result, studying the spatio-temporal evolution of urban land green use efficiency (ULGUE) and its influential factors not only promotes green development but also serves as a reference for the Chinese government when developing land green use policy ideas.

The Yangtze River Economic Belt (YREB) is one of China’s regions with the greatest comprehensive strength and strategic support. By 2019, the YREB’s average urbanization rate was 61.7%, which was higher than the national rate (Yang et al., 2022a, 2022b). However, the YREB’s rapid economic growth and high urbanization rate require it to overcome numerous challenges (Ye et al., 2022), such as the conflict between urban development and land scarcity, resource waste, environmental pollution caused by inefficient land use, and so on. Accordingly, 108 cities in the YREB are chosen as research areas, and efficiency thinking is implemented to build a thorough evaluation indicator system for the cities’ sustainable development. This essay assesses the YREB’s ULGUE level, examines the characteristics of its spatial and temporal evolution, and offers some advice for the city’s green and sustainable growth.

The following is how this paper is structured: “Literature review” section reviews the literature on ULGUE, and “Methodology and data” section describes the data and methodologies employed in this study. “Results and analysis” section provides an empirical investigation of ULGUE in the YREB from 2005 to 2019, discussing its time–space evolution as well as the factors that influence it. “Discussion” section contains a discussion of the research findings. “Conclusions” section gives the conclusions.

## Literature review

The academic community is interested in land because it is a crucial component of production, resulting in a relatively rich theoretical and research output. Traditional urban land use efficiency is a crucial metric for assessing the connection between inputs on the land and outputs in the economy (Du et al., 2016). However, complex land use systems encompass economic, social, and natural environments (Zhong et al., 2022). Traditional urban land use efficiency emphasizes economic and social scope (Xie & Wang, 2015), ignoring the connection between input from the land and output in terms of the environment. As a result, academics expanded their study of ULGUE based on urban land use efficiency. ULGUE is a key measure that accounts for both the resources wasted by environmentally unfriendly approaches and their unexpected outcomes as well as the resources consumed by the green approach and its ideal urban land use output (Tan et al., 2021).

As for the research object of ULGUE, it mainly focuses on the green use efficiency of different types of land, including agricultural land (Xie et al., 2018), construction land (Gao et al., 2022), and industrial land (Chen et al., 2020). In regards to the size of the research, the dimensions are diverse, involving different spatial ranges in the country (Jiao et al., 2020), province (Zhang et al., 2020), river basin (Wu et al., 2022), and urban agglomeration (Zhang et al., 2022a, 2022b). Regarding research techniques, they mainly fall into three categories: the index evaluation method, the parametric method, and the non-parametric method. Prior researchers measured land use efficiency using just one indicator; for instance, they used economic productivity per square kilometer (Kuo & Tsou, 2015). However, the joint action of land

input, labor input, and economic and social output, as well as other factors, leads to efficient use of land. One index evaluation technique cannot adequately capture the intricate process of land use. Therefore, Li and Zhang (2015) consider using the multi-index evaluation method to assess land use efficiency. The Stochastic Frontier Approach (SFA), which symbolizes the parametric approach, incorporates randomness terms into its approach to improve the accuracy of efficiency measurement, but systematic errors may occur when such an approach sets particular work functions (C. Zhang & Chen, 2022). The non-parametric approach is represented by data envelopment analysis (DEA). Input and output data are all that is required for the DEA method; no parameter estimates of the function's parameters are required. The SFA raises the risk of efficiency measurements when establishing equations, leading to a greater DEA (Z. Liu et al., 2021). For instance, Zhu et al. (2019) measured the scale, technical, and overall efficiency of land use in 35 Chinese megacities from 2008 to 2015 by using the super-SBM model; Yang and Wu (2019) used the mixed directional distance function to determine the land use ecological efficiency from 2003 to 2015; and Han and Zhang (2020) employed the strong efficient frontier minimum distance model (MinDS) and the Malmquist index.

Numerous studies have recently concentrated on the ULGUE-affecting variables. One of the crucial elements influencing the effectiveness of green land usage is economic and social indicators. The main economic and social factors considered include GDP per capita, industrial structure, and population density (Xie et al., 2019; Yu et al., 2019). Among them, environmental factors have been given more and more attention by scholars. Three urban metropolitan areas in China were evaluated for their effectiveness in terms of land usage against the backdrop of carbon emissions by Lu et al. (2022). Luo et al. (2020) investigated land use efficiency in light of carbon emission constraints, and researchers also investigated the efficiency of land use in the context of environmental constraints (Lu et al., 2018; Luo et al., 2020; Yang et al., 2022a, 2022b). Government intervention and land marketization will affect land use efficiency. Du et al. (2016) discovered through research that land pricing systems can promote investing and enterprise administration, hence supporting the improvement of land-use efficiency; Zhong et al. (2022) revealed

that urban land finance and land green use efficiency in the YREB are “inverted U-shaped”; Jiang et al. (2021) used data from 285 Chinese cities to examine the effects of marketization of transferring property on urban land use efficiency. The shape and size of cities will also influence land-use efficiency. He et al. (2020) discovered that city shape influences urban land use efficiency, and this effect is sensitive to city size. Wu et al. (2022) discovered that irregular urban forms have a bad impact on property use efficiency, whereas compact and clustered urban forms improve land efficiency under low carbon constraints. Furthermore, in the research methods for the influencing factors of ULGUE, a spatial econometric model, a geographical probe model, a scenario simulation model, machine learning, and other methods were used (Zhou et al., 2022a; Zhou et al., 2022b).

According to a review of the literature, scholars in the field of YREB land use are primarily concerned with the land use efficiency of urban agglomerations and provincial levels, with relatively few studies on YREB regional levels. What's more, ULGUE observation is a long-term process. Most of the existing studies span about 10 years, and there are few ULGUE studies with longer time scales. Therefore, in this study, we innovatively studied ULGUE in YREB from 2005 to 2019. To begin, this research constructs a thorough index system and applies the super-EBM model to analyze ULGUE. Next, we examined ULGUE's temporal and spatial characteristics from 2005 to 2019. Finally, we will discuss the factors that influence ULGUE using the Tobit model. The following issues are addressed in this paper: (1) What is the overall growth tendency and temporal and spatial features of YREB's ULGUE from 2005 to 2019? (2) What factors have an impact on ULGUE? (3) What policy insights can we glean to assist policymakers in making better use of scarce urban land?

## Methodology and data

### Approach of investigation

#### *Super-EBM model*

The traditional DEA model is a typical approach to measure efficiency, which generally includes two categories: the radial CCR model and BBC model and

the non-radial model represented by SBM (Zhao et al., 2020a, 2020b). Existing literature studies have confirmed that the above models are all inadequate. Radial models measure efficiency by reducing input factors in the same proportion (Tone, 2001). This strict assumption often leads to inconsistencies in the actual situation. The non-radial model improves on the former’s problem of equal scaling down (K.-L. Wang et al., 2019), but it ignores the problem of undesirable outcomes, which are the result of economic outputs and should not be overlooked when assessing related efficiency (K. Wang et al., 2012). Tone and Tsutsui (2010) developed an EBM model that can have both radial and non-radial properties to overcome the limitations of the preceding model. The unexpected output is taken into account in this paper, and the effectiveness is calculated based on the output orientation. EBM-O-C is written as:

$$1/r^* = \max \varphi + \varepsilon^+ \left( \sum_{r=1}^s \frac{w_r^+ s_r^+}{y_{r0}} + \sum_{p=1}^q \frac{w_p^{u-} s_p^{u-}}{u_{p0}} \right) \quad (1)$$

$$\begin{aligned} \text{s.t. } & \sum_{i=1}^m \sum_{j=1}^n x_{ij} \lambda_j \leq x_{i0} \\ & \sum_{j=1}^n y_{rj} \lambda_j - s_r^+ = \phi_{y_{r0}} \\ & \sum_{j=1}^n u_{pj} \lambda_j + s_p^- = \phi_{u_{p0}} \end{aligned} \quad (2)$$

$r^*$  represents the optimal value of efficiency, DMU  $j$  ( $j = 1, \dots, n$ ) represents decision-making unit,  $x_{ij}$  ( $i = 1, \dots, m$ ),  $y_{rj}$  ( $r = 1, \dots, s$ ), and  $u_{pj}$  ( $p = 1, \dots, q$ ) are the input parameters, the preferred outcome, and the undesirable outcome, respectively.  $s_r^+$  and  $s_p^-$  represent intended output and unfavorable output slack variables.  $w_r^+$  and  $w_p^{u-}$  indicate the importance of desired output and undesired output.  $\varphi$  is a variable, indicating the non-radial weight. The value spectrum of  $\varepsilon$  is  $[0, 1]$ , indicating the value of the non-radial component.  $\lambda_j$  is the linear combination coefficient.

However, the limitation of the EBM model is that it cannot compare the DMU with an efficiency of 1. On this basis, combined with the super-efficient DEA model suggested by Andersen and Petersen (1993), this model can compare the effective DMU. The super-efficiency model excludes itself when measuring the first DMU and expresses it by the linear combination of input and output of other DMUs, which can further

compare the DMU on the frontier, making the measurement results more accurate and true. Its specific expression is as follows:

$$\text{s.t. } \left\{ \begin{aligned} & \sum_{j=1}^n x_{ij} \lambda_j, \theta x_{ik} \\ & j \neq k \\ & \sum_{j=1}^n y_{ij} \lambda_j \dots y_{jk} \\ & j \neq k \\ & \sum_{j=1}^n u_{pj} \lambda_j, u_{pk} u \\ & j \neq k \\ & \lambda_j \dots 0, j = 1, 2, \dots, n \end{aligned} \right. \quad (3)$$

Some variables have the same meanings as formula (1) and formula (2).  $x_{ik}$ ,  $y_{rk}$ , and  $u_{pk}$  represent the input, desired output, and undesired output of the DMU  $k$ .  $\theta$  is a variable and a non-radial weight. In this paper, the EBM model and the super-efficient DEA model are linked and expressed as the super-EBM model.

### Spatial autocorrelation model

The analysis of spatial autocorrelation, which is segmented into global spatial autocorrelation and local spatial autocorrelation, is a crucial tool for determining if the observed value of one element has a substantial association with the observed value of its surrounding region (Wu et al., 2022). Global spatial autocorrelation is applied to analyze whether the observed values have aggregation characteristics in the global space, but it cannot accurately locate the spatial location of aggregation. Therefore, local spatial autocorrelation analysis is required to further determine the aggregation area (Xue et al., 2022). The approaches mentioned above are used in this paper to examine the spatial correlation.

The following is the expression for the global spatial autocorrelation:

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^n W_{ij} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (4)$$

$I$  is the global Moran index,  $n$  is the quantity of research items,  $x_i$  and  $x_j$  represent the ULGUE values

of cities  $i$  and  $j$  respectively.  $\bar{x}$  is the average value of ULGUE in the study area.  $W_{ij}$  is a measure of whether cities  $i$  and  $j$  are adjacent. A Moran index greater than 0 means that the spatial correlation is positive; when it is less than 0, the spatial correlation is negative. Additionally, if it is indefinitely near to 0, it indicates that there has been no agglomeration.

The local spatial autocorrelation expression is as follows:

$$I_i = \frac{n(x_i - \bar{x}) \sum_{j=1}^n W_{ij}(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \tag{5}$$

$I_i$  is the local Moran index,  $n$ ,  $x_i$ ,  $x_j$ ,  $\bar{x}$ , and  $W_{ij}$  have the same meanings as the above equation.

*Tobit model*

Traditional estimating techniques (such as the conventional least squares method) may produce erroneous results since ULGUE is a finite dependent variable (Song et al., 2020). Therefore, this study chooses the Tobit model to do regression analysis on the relationship between various influencing factors and ULGUE. Then, it finds out how each factor affects ULGUE. Its general expression is (Xue et al., 2022):

$$y = \begin{cases} y_i = \beta_0 + \sum_{i=1}^n \beta_i X_i + \varepsilon, y_i > 0 \\ 0, y_i \leq 0 \end{cases} \tag{6}$$

$y_i$  is the efficiency value of the DMU $_i$ .  $X_i$  represents influencing factors; there are  $n$  influencing factors.  $\beta_0$  is intercept, and  $\beta_i$  is the coefficient of influencing factors.  $\varepsilon$  is the random error vector, which accords with the normal distribution.

Indicator choice

*Indicators for input and output*

This report chooses seven characteristics to build the ULGUE detailed evaluation system based on prior research (Table 1).

Input includes land, capital, and labor.

**Land input** Urban growth depends on land, and how much land is invested has a big impact on how effectively it is used for environmental purposes. This paper selects the area of construction land in municipal areas to look at the YREB cities' land investments. Construction land is defined as land that is suitable for urban construction in government planning and is the basic element of human production and life. It carries out multiple composite functions such as economy, society, population, and nature (M. Wang et al., 2022) and covers eight types of land, including residential and industrial land. It is one of the important input elements of the ULGUE.

**Capital input** The capital investment in the green land use process will have an impact on the city's benefits economically and socially. This paper selects

**Table 1** Indexing of input and output

Index type	Category	Specific indicators	Unit	References
Input	Land	Area of construction land in municipal area	km <sup>2</sup>	(Yu et al., 2019)
	Capital	Investment in fixed assets in municipal area	10,000 yuan	(Tan et al., 2021)
	Labor	Employees of secondary and tertiary industries in municipal area	10,000 persons	(Song et al., 2022)
Desirable output	Economic	Output value of urban secondary and tertiary industries	10,000 yuan	(Gao et al., 2020)
	Social	Municipal population	10,000 persons	(Ding et al., 2021)
	Environmental	Green coverage area of built-up area	Hectare	(Lu et al., 2022)
Undesirable output	Environmental pollution	Industrial wastewater discharge	10,000 tons	(Xue et al., 2022)
		Industrial smoke and dust emission	Ton	
		Industrial sulfur dioxide emission	Ton	

the purchase of property and equipment in municipal areas as the capital investment index. The investment amount of fixed assets refers to the sum of the workload and related expenses incurred by the whole society in building or investing in capital expenditures over a specific time period, and it is expressed in monetary form. In the process of green land use, it works together with land and labor input to promote expected and unexpected output.

**Labor input** The labor force drives urban economic development by acting as a medium between the input elements, effectively transforming land and capital input into output. Workers in the secondary and tertiary sectors are chosen as input elements of the labor force due to the city's emphasis on developing these sectors.

In terms of output, the choice is primarily based on three factors: economic, social, and environmental advantages.

**Economic benefits** Economic benefits will be generated after the input factors take effect. In this study, the financial benefits of using green land are represented by the observed value of the secondary and tertiary sectors. Due to its unique functions, the city's main economic activities are secondary and tertiary industries, so its output value can more accurately reflect the financial advantages of using green land in the city.

**Social benefits** Social benefits are also called external indirect economic benefits. The population of municipal districts is used as the index of social benefits in this paper because it can reflect both the amount of urban development and the populace's

attraction to the city, as well as the expected output formed by side input elements.

**Environmental benefits** Relevant symposiums guiding the development of the YREB and relevant documents issued clearly indicate that we should take the road of green development and ecological priority. Therefore, this paper chooses environmental benefit as one of the important outputs of urban land green utilization and takes the built-up area's green coverage area as the specific index. The amount of green space per capita increases with the size of the green area. It can directly reflect the urban ecological environment.

**Undesirable output** Environmental pollution will inevitably occur in the process of greening urban land. Considering that the main source of urban pollution is industry and adhering to the principle of data availability, industrial wastewater outflow, industrial smoke emission, and industrial sulfur dioxide emission are selected to represent environmental pollution.

#### *Choosing the influential elements*

Numerous elements affect ULGUE. According to the existing research literature, considering the input–output index system as well as data comparability and scientificity fundamentals, we should choose the corresponding main factors that affect the ULGUE (Table 2).

**Economic factors** The degree of urban economic growth is measured by per capita GDP. Generally speaking, the input and output of unit land can be reflected by the level of urban economic progress,

**Table 2** Influencing factors of ULGUE

Influencing factor	Index	Abbreviation	Unit
Economic factor	Urban economic development level	EDL	Yuan/person
Demographic factor	Population density	PD	Person/km <sup>2</sup>
Capital factor	Urban land investment intensity	LII	10,000 yuan/km <sup>2</sup>
Environmental factor	Environmental regulation	ER	-
Scientific and technological factors	Technology input	TE	10,000 yuan
Industrial structure factors	Industry structure	IS	-
Land use scale factor	Urban land use scale	ULS	-
Dependent factor	Urban land green use efficiency	ULGUE	-



which will affect ULGUE. On the one hand, constant growth in the degree of economic growth accelerates the speed of land circulation, which promotes the improvement of land-use efficiency; on the other hand, once the degree of economic growth reaches a certain level, there is going to be a logical inconsistency for both supply and demand for land, which will hinder the improvement of green land efficiency (Zhao et al., 2020a, 2020b). Therefore, the influence of the urban economic development level on ULGUE in the YREB needs further examination.

**Demographic factor** Population density is a measure of the concentration of urban populations. When the population density is low, increasing population density can exert the effect of population agglomeration, drive all kinds of resources into cities, promote cities to gradually form economies of scale, and optimize land use to a certain extent. However, resource supply and demand imbalances, as well as environmental pollution caused by overpopulation, are not helpful for improving the effectiveness of using green land (Zhang et al., 2019). Because of this, it is essential to further verify the influence of population density on land efficiency.

**Capital factor** The investment intensity of urban land is represented by urban construction land investment per unit of fixed assets, and how it affects ULGUE is analyzed from the perspective of capital investment (Li, 2018). When the intensity of urban land investment is low, there may be extensive land use patterns, which will impede the development of more efficient land use. With the development of the economy and urbanization, the intensity of land investment is constantly improving, thus promoting intensive land use, optimizing land use mode and layout in limited urban space, and encouraging the enhancement of efficient green land use. However, when the intensity of land investment reaches a high level, the limitation of land resources may lead to resource waste and unnecessary investment. Therefore, the impact of urban land investment intensity on ULGUE needs to be verified.

**Environmental factors** In the operation of greening urban land, unwanted liquid waste, waste gas, and waste products will be produced. In this paper, the comprehensive usage rate of industrial solid

waste is chosen to represent environmental regulation. Through the reuse of solid waste, the land users can recover certain income, thus forming the internal motivation to continually increase utilization efficiency (Zhu & Ning, 2021), which will help increase the effectiveness of land usage. Moreover, the comprehensive utilization of solid waste is favorable to raising public consciousness about pollution prevention. In terms of output, enterprises will produce products with lower carbon footprints and improved environmental protection. From the perspective of consumption, consumers will prefer green and low-carbon products. It can form a beneficial loop that helps to increase the effectiveness of using green land.

**Scientific and technological factors** This paper chooses fiscal investment in science and technology to symbolize scientific and technological factors. On the one hand, financial investment in science and technology usually reduces the cost of technological innovation for enterprises and stimulates their enthusiasm for technological innovation by means of direct subsidies or interest subsidies; on the other hand, it organically combines with enterprise policies, attracts private capital, and makes joint efforts in the field of innovation to advance the degree of technical innovation for enterprises (Che et al., 2020). Therefore, technological advancement encourages the use of urban space in a sustainable manner.

**Industrial structure factors** The share of tertiary sector output in GDP represents the industrial structure. Urban land use patterns will alter as a result of the advanced development of industrial structures, which will also aid in the logical use of land resources. However, the impacts of land use structures in different regions and at different urban development levels are different (Zhao et al., 2020a, 2020b). As a result, the impact of industrial structures on ULGUE must be investigated further.

**Land use scale factor** In this essay, the scale of land use is represented by the ratio of urban building land area to urban area. The amount of urban construction land already in use will have an impact on how closely the government monitors construction sites and how readily available future development land will be (Zhu & Ning, 2021). It is more likely to

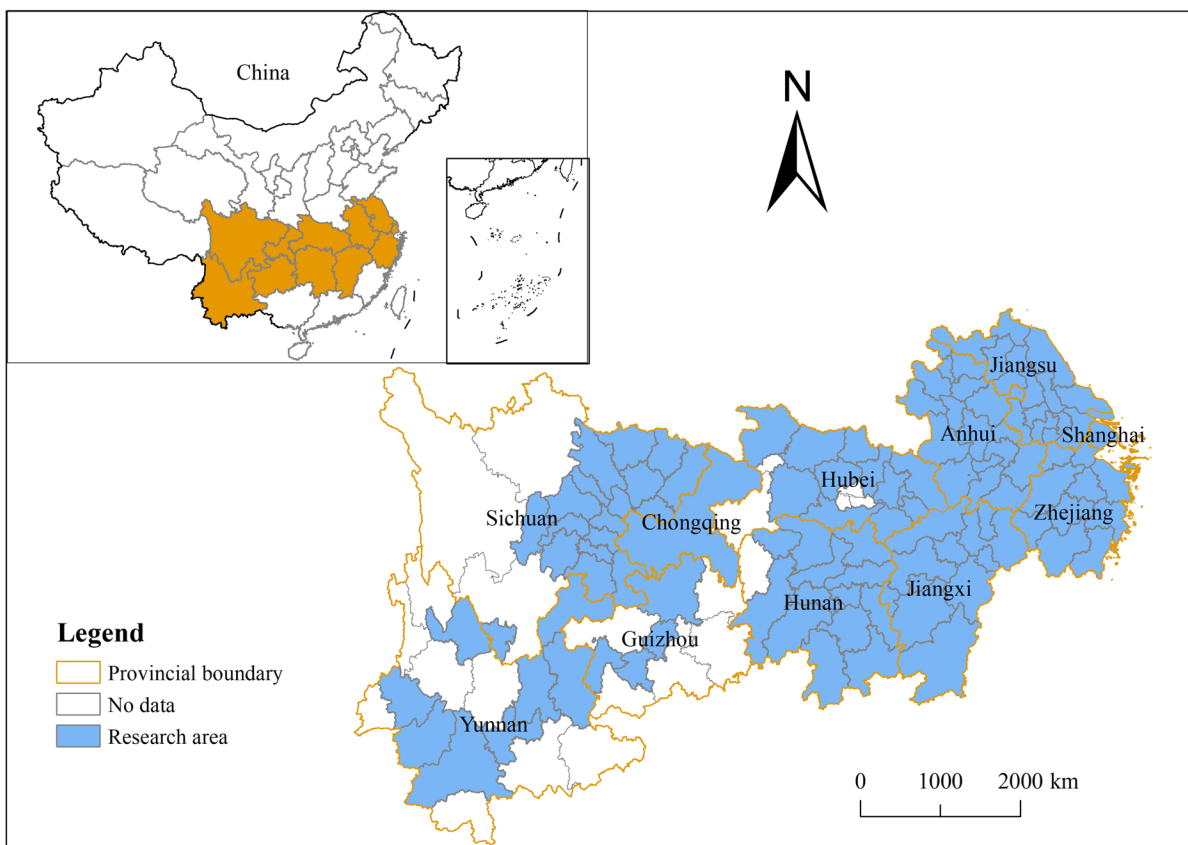
acquire new construction property when the area of existing land for development is modest. The expansion of construction land will result in unexpected output and economic growth, which will hinder efforts to boost the effectiveness of green land use. When the area of construction land is vast, the likelihood of finding new construction land is low, the government is more motivated to improve the planning of construction land, and the efficiency of land usage is increased. Therefore, it is still required to verify how land use scale affects ULGUE.

### Study area and data origin

This paper investigates the YREB's ULGUE. It includes 130 cities along the YREB, according to the Yangtze River Economic Belt Development Plan Outline and 2019 Chinese administrative division data. Because the data from 17 autonomous states in Sichuan, Yunnan, Guizhou, Hubei, and

Hunan provinces were insufficient, they were not included in this study. Furthermore, the cities of Xiantao, Qianjiang, and Tianmen in Hubei province, as well as Bijie and Tongren in Guizhou province, were excluded from this study because the data were insufficient as a result of administrative level changes (Fig. 1). As it turns out, the 108 cities in YREB are the subject of this paper, and the study spans the years 2005–2019.

The China Urban Statistical Yearbook (2006–2020) and the China Urban Construction Statistical Yearbook (2006–2020) serve as the primary data sources for this study. The statistics yearbooks of each city are employed to augment some of the data, and linear interpolation is applied to supplement the missing data. In order to enhance the comparability effect, regional GDP and fixed asset investment are adjusted using the GDP deflator and the fixed asset investment price index set in 2005.



**Fig. 1** Study area



## Results and analysis

In this paper, the ULGUE of YREB from 2005 to 2019 is calculated by applying the Super-EBM program in DEA software. The time-change characteristics are investigated from three perspectives: the whole, the city scale, and the region. Its geographic correlation properties are examined using spatial autocorrelation, and its temporal and spatial evolution is examined using ArcGIS software.

Time evolution characteristics of ULGUE

### *Comprehensive examination of evolution*

The average level of ULGUE in YREB fluctuates and changes as a whole. Where the first time change node is 2008, the average ULGUE prior to 2008 shows a declining trend. After 2008, there is a clear rising trend in efficiency that lasts until 2010. It decreases in 2011, rises year by year from 2012 to 2014, and reaches its highest efficiency in 2014. The efficiency declined slightly after 2014 and then showed an upward trend again in 2018–2019 (Fig. 2a).

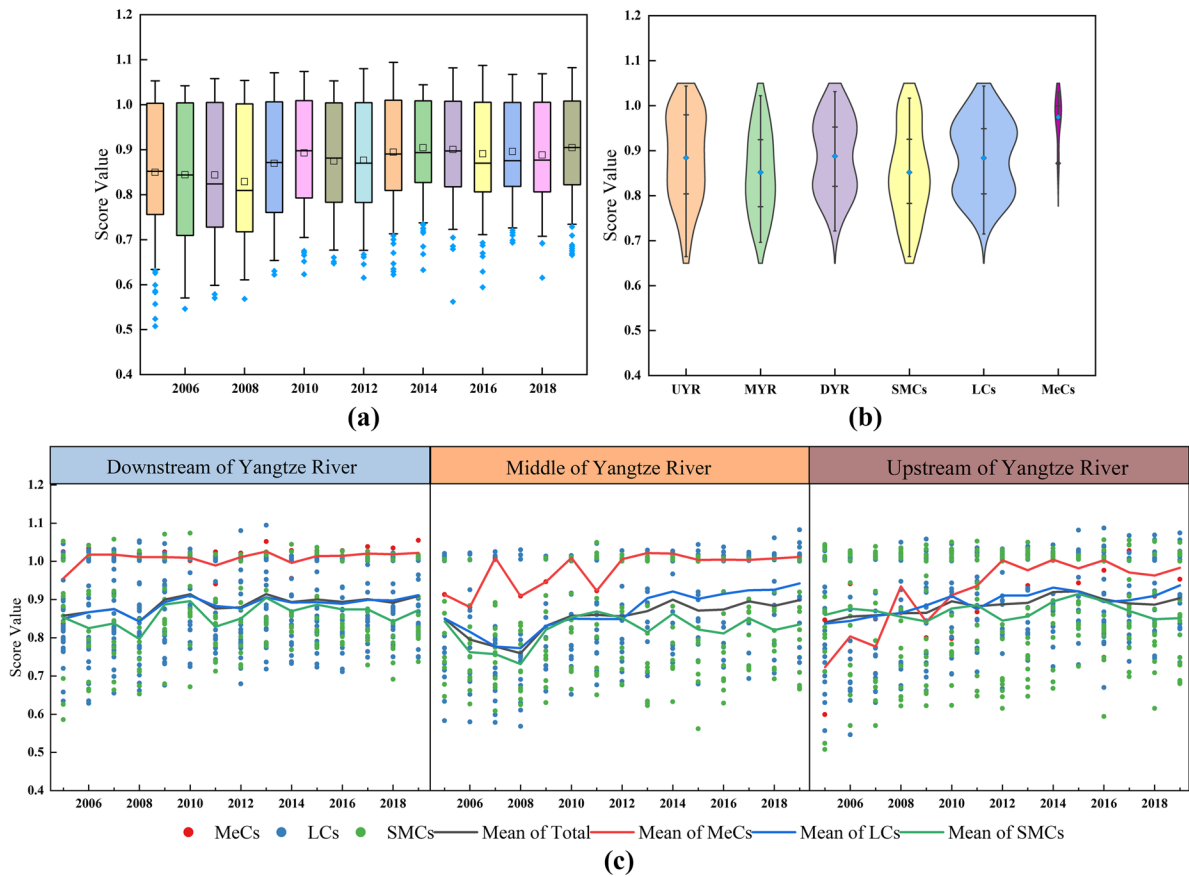
The changes in the average ULGUE of YREB are related to the introduction of policies related to environmental protection and land. The Ministry of Environmental Protection was formed in 2008, and local governments at all levels have strictly implemented the instructions of the central government, deeply adhered to the application of the scientific theory of development, strengthened the work of pollution reduction, and continued to promote the environmental treatment and ecological protection of key watershed areas, etc., gradually achieving results, and the efficiency from 2008 to 2010 has been year by year increasing. In 2011, the Land and Resources Ministry conducted a pilot land bidding and auction listing reform and issued the “Opinions of the Ministry of Land and Resources on Advancing the Rule of Law in Land and Resources Management and Further Promoting the Administration of the Law” to further improve the construction land use right bidding and auction listing system, a system that can maximize land development and increase the level of land marketization. Since 2012, the application of the Standard for Urban Land Classification and Construction Land Planning has effectively encouraged the scientific and reasonable use of land resources. During

the same year, the 18th Party Congress incorporated the development of environmental protection into the policy of the overall layout of the five elements, effectively promoting the cause of environmental protection. In 2014, the Land and Resources Ministry considered and adopted the Regulations on the Economical and Intensive Use of Land, regulating and guiding it for the first time, so that the average ULGUE in 2014 reached the highest level in history. In 2018, the Natural Resources Ministry promulgated the Circular on Improving the Mechanism of “Linking Increases and Savings” of Construction Land to strengthen the effectiveness of land use planning for vacant and new building land. The average ULGUE in 2019 is higher than the 2005 level, and the relevant land policies introduced in recent years have contributed to the increasing effectiveness of urban land use while environmental protection policies have contributed to the reduction of undesirable output, resulting in an increase in the average ULGUE.

### *Analysis of time progression at various city scales*

Due to different developments in economic, environmental, and other factors, there are certain differences in ULGUE levels at different city scales (Zhang et al., 2022a, 2022b). Therefore, cities in the YREB are divided into three categories according to the State Council’s announcement regarding the modification of the standards for classifying cities’ sizes, specifically, small and medium-sized cities (SMCs) have a population of less than one million, while large cities (LCs) have a population of one to five million, and megacities (MeCs) have a population of more than five million. Based on the number of urban residents as of the end of 2019, the YREB is classified into three groups of cities of various sizes, covering 39 small and medium-sized cities, 63 large cities, and 6 megacities.

Small and medium-sized cities, large cities, and megacities all have mean ULGUEs of 0.852, 0.884, and 0.986, respectively (Fig. 2b). It is clear that the average LUGUE level for different city sizes is not achieved effectively and is concentrated around 1. The average level of ULGUE for megacities is the highest, followed by large cities and small and medium-sized cities. The megacities are mainly provincial capitals and local governments that are governed by the federal government, which have



**Fig. 2** Variations in ULGUE levels in the YREB include the following: **a** range of ULGUE score values in the YREB from 2005 to 2019; **b** intensity of ULGUE scores at various scales

across different areas; and **c** trends in ULGUE levels across various regions and cities in the YREB

a more advanced economy and are more attractive to population and resources, creating more desired output on limited urban land; in the same way, megacities have a better industrial structure, focus on technological innovation, and have relatively less undesired output; thus, ULGUE is closer to the effective state. The average ULGUE level in small and medium-sized cities is comparatively the lowest, in part because these cities' industrial structures, population sizes, and levels of economic prosperity lag behind those of big cities and megacities. Therefore, we should mainly focus on the improvement of ULGUE in small and medium-sized cities.

*Analysis of time evolution in various places*

To better evaluate ULGUE levels in different areas of the YREB, this process divides the cities in the YREB into upstream, midstream, and downstream based on the Yangtze River's upper, middle, and lower reaches, with 38 cities in the upper portion, 28 cities in the middle reaches, and 42 cities in the lower regions.

According to a regional viewpoint (Fig. 2b), the mean ULGUE levels in the upstream, midstream, and downstream of the YREB are 0.884, 0.852, and 0.888, respectively, with the highest ULGUE level in the downstream, the second

highest in the upstream, and the relatively lowest in the midstream. A crucial reason contributing to the greater ULGUE in the YREB's downstream cities is that the downstream cities have superior location conditions and an earlier start of economic development, and various resources such as labor and capital converge on the downstream cities, boosting the effectiveness of land usage and hastening land transfer. At the same time, the downstream cities carry out the green transformation of industry earlier, which brings about the continuous reduction of industrial "three wastes" output and the improvement of the total amount of solid trash utilized, which effectively improves the ULGUE. The ULGUE in midstream and upstream cities is relatively unsatisfactory, indicating that they still need to further improve their green land use systems.

Cities on the upper, medium, and lower reaches of the YREB's ULGUE levels fluctuate over time but generally show an upward development trend (Fig. 2c). Among them, the average ULGUE level in the downstream of the YREB increased slightly from 0.858 in 2005 to 0.909 in 2019, a rise of 0.051; the midstream increased fluctuatingly from 0.850 in 2005 to 0.899 in 2019, an increment of 0.049; and the upstream increased slowly from 0.841 in 2005 to 0.904 in 2019, a boost of 0.063. This demonstrates that the most significant increase is in the upstream region, followed by the downstream and midstream regions, all of which have relatively small increases. The reason for the largest increase in the upstream region may be due to the fact that cities in the upstream are located inland and lag behind other cities in terms of economic development. Besides, with a relatively small ULGUE base, there is more room for efficiency improvement.

In addition, a comparative analysis of ULGUE in different regions and different city scales (Fig. 2c) shows that megacities and large cities have a higher ULGUE than their average in different regions, while the ULGUE of small and medium-sized cities is slightly below the average, which requires more adjustment of green land use in those cities to reduce the gap in ULGUE between different city scales.

## Spatial relevance characteristics of ULGUE

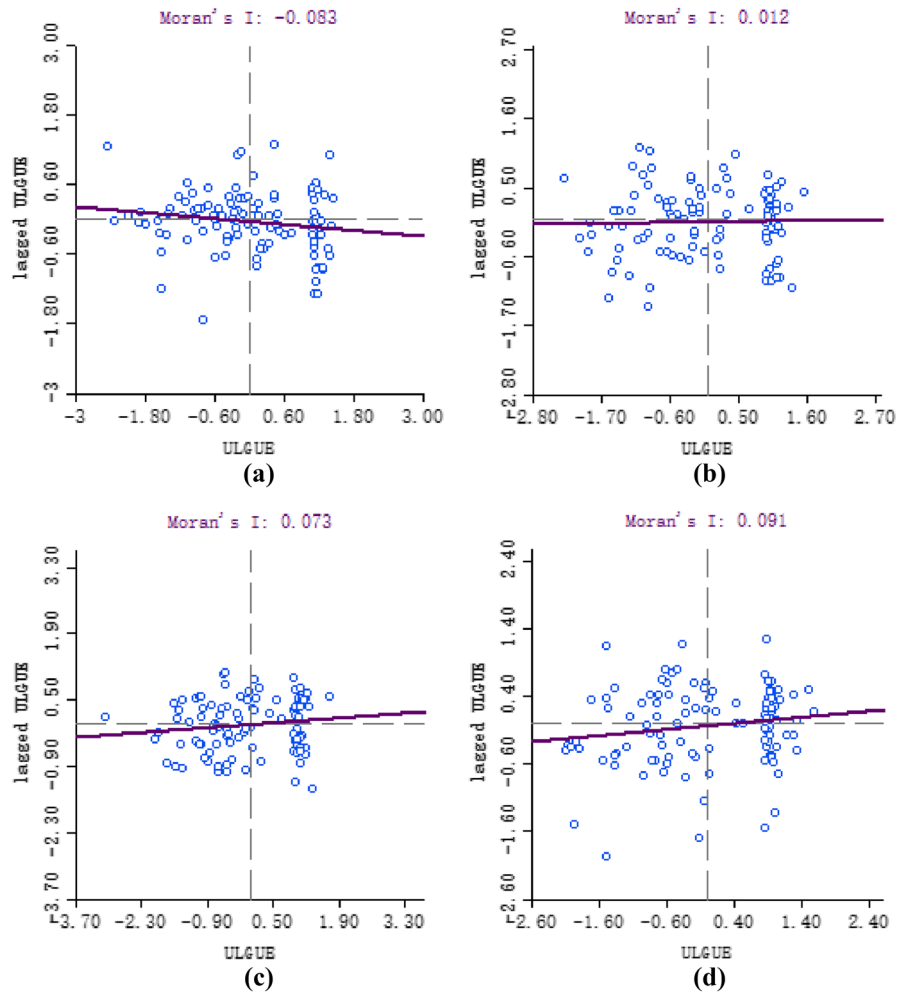
### *Global spatial autocorrelation analysis*

To identify the spatial attributes between ULGUE and its neighboring municipalities, GeoDa software was used in a spatial correlation study to further investigate the spatially divergent characteristics of ULGUE. The data of 2005, 2010, 2015, and 2019 were selected for analysis, and the global Moran index of ULGUE of YREB in typical years was measured using the global autocorrelation formula (Fig. 3). The global Moran score of ULGUE for YREB ranges from  $-0.083$  to  $0.091$ , as can be shown, and the Moran index shows an overall increasing trend, with most Moran index values greater than 0 and tending to 0, indicating that its global spatial correlation mainly presents a positive correlation, but the spatial correlation among cities is weak and the clustering trend is not obvious. The global Moran index scatter plot is divided into four quadrants: quadrants I and III indicate high-high (H-H) and low-low (L-L) clustering, respectively, while quadrants II and IV reflect high-low (H-L) and low-high (L-H) outliers, respectively. Many points in Fig. 3 fall in quadrants II and III, indicating that ULGUE shows H-L outlier and L-L clustering characteristics. There are neighboring municipal lands where the green utilization efficiency of the neighboring municipalities is poor and the green utilization efficiency of the central city is high, and the low-efficiency municipalities have a clustering effect with the neighboring low-value cities. The number of points falling into quadrant I and quadrant IV is relatively small, which indicates that the H-H clustering characteristics of ULGUE in YREB are not obvious, and there are few cases in which the efficiency values of neighboring municipalities differ greatly from their own.

### *Local spatial autocorrelation analysis*

The global Moran score merely measures the average degree of spatial correlation between cities and the cities that encompass them. It assesses spatial correlation globally. This paper employs LISA spatial morphology (Fig. 4) at the 0.05 significance level to

**Fig. 3** ULGUE global Moran scatter plot for YREB

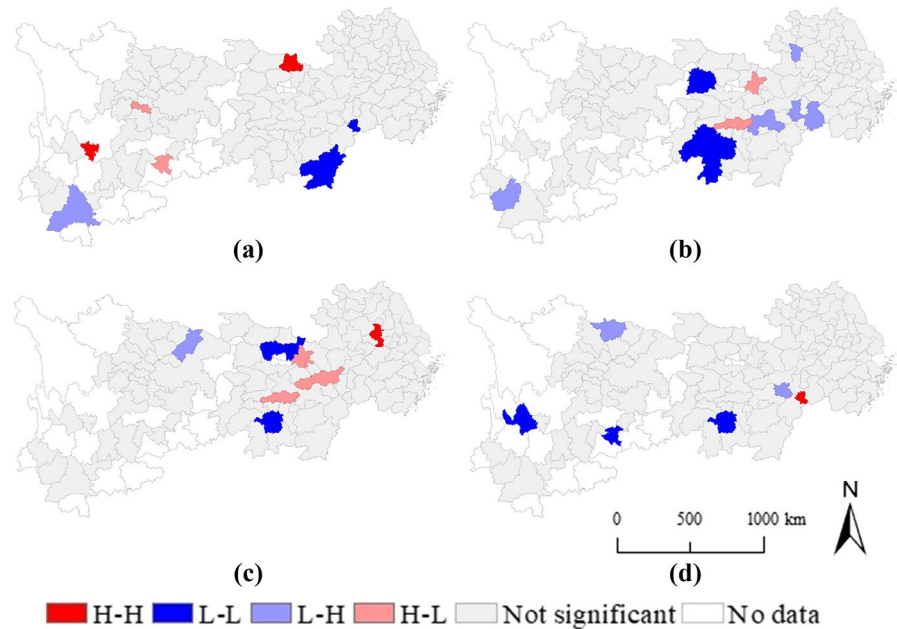


further determine the spatial location of local spatial aggregation or abnormal features in ULGUE.

The figure shows that the H–H concentration range changed by first decreasing and then increasing, and the distribution changed significantly during the sample research. Among them, in 2005, H–H clusters were distributed in Suizhou and Panzhihua in the Yangtze River's middle and upper sections. Suizhou, located in the north of Hubei Province, is an important city in the center of the Yangtze River, with a lot of room for economic development. It allocates its workforce, land, finances, and other resources sensibly. Suizhou City has a moderately surprising output when compared to the secondary and tertiary sectors and has won the title of "National Deep Forest City." With a high level of ecological construction,

the ULGUE is close to the forefront, forming an H–H agglomeration area. In this experiment, the nearby spatial weight served as the spatial weight, while the surrounding areas of Panzhihua City are mostly uncovered by samples and have a high ULGUE, forming an H–H agglomeration area. The results need to be further verified in the follow-up study by increasing the scope of sample research. No H–H gathering area was formed in 2010. In 2015, H–H clusters were distributed in Nanjing. Nanjing is an important city in the lower reaches of the Yangtze River, and its geographical position is dominant. Nanjing attaches great importance to scientific research and education and has strong scientific and technological innovation abilities. The secondary and tertiary sectors developed earlier, the development system was

**Fig. 4** ULGUR's local spatial autocorrelation in the YREB



perfect, and the industrial structure was reasonable. It attaches great importance to environmental protection and has won the honors of related cities many times, making its ULGUE effective, and its surroundings are mostly high-efficiency areas, forming H–H agglomeration areas. In 2019, it was distributed in Yingtian City. The surrounding cities of Yingtian City are Nanchang City, Shangrao City, and Fuzhou City. These cities have high ULGUE, and Yingtian City's own efficiency is close to the effective state, forming an H–H cluster area.

The spatial change of the H–H cluster mainly occurs between the middle reaches and the lower reaches, and the reasons for the change are inseparable from the implementation of relevant policies. In September 2013, Premier Li Keqiang instructed in a document: “It is an important law of regional economic development to develop coastal and riverside areas first and then advance to inland areas gradually.” Therefore, the downstream cities developed rapidly under the promotion of location advantages and policies, exerted the agglomeration effect, improved ULGUE, and formed the H–H agglomeration area in 2015. In 2016, the “Thirteenth Five-Year Plan” proposed for YREB that it should take “joint efforts to protect and not develop” as a means and adhere to ecological priority and green development as a strategy. YREB's high-energy consumption

and high-pollution industries need to be upgraded urgently to reduce the generation of unexpected output. According to the comparison of the original data, this has the greatest impact on the downstream, which may lead to the decline of ULGUE in some downstream cities, resulting in no H–H agglomeration area in the downstream. In the Outline of National Land Planning issued in 2017, it is mentioned that key development areas such as the middle reaches of the Yangtze River and Chengdu-Chongqing areas should be supported to accelerate industrial development and population agglomeration, promote economic and social development, appropriately increase the intensity of land development, and stabilize the supply of construction land. The downstream radiation and policy promotion are conducive to the improvement of ULGUE in the middle reaches of the city, thus forming an H–H agglomeration area.

The L-L agglomeration area has continuously migrated from Jiangxi, Hunan, and Hubei provinces to Yunnan and Guizhou provinces, from the center region to the western region, and its scope has gradually narrowed. These cities' geographic conditions are often poor; the economic development lags behind the lower region of the Yangtze River; innovation in science and technology is insufficient; and both these cities' and the nearby cities' efficiency ratings are low, showing a positive correlation with the space

of low efficiency. In addition, the downstream has a stronger radiation effect on the middle reaches than on the upstream, which is the reason why the L-L agglomeration moves to the western region.

In general, the L-H outliers showed a development pattern of initially rising and then declining, and the spatial distribution was scattered. In 2005, it was distributed in Pu'er City, Yunnan Province. It is located on the border, with mountainous terrain, mostly ethnic minorities in the city, slow economic development, and low ULGUE. However, in 2005, the efficiency value of surrounding cities in Pu'er City was high, resulting in the formation of an L-H outlier. In 2010, the scope of L-H outliers expanded, mainly in Jiangxi and Anhui provinces. The efficiency values of these cities are low, while the surrounding areas are high-value cities, and the efficiency values of neighboring cities are quite different. It was distributed in Dazhou City in 2015, and its geographical position is unique. It is located in the Yangtze River's upper reaches, at the crossroads of four provinces and the Chengdu-Chongqing metropolitan agglomeration. In 2015, the ULGUE of surrounding cities was high, but its own efficiency was relatively low, forming an L-H outlier. The L-H outlier area was relocated to Nanchang and Guangyuan cities in 2019. Compared with previous years, in 2019, Nanchang reduced the greening of a large area while slightly increasing the construction land, and the amount spent on science and technology fell, which lowered the ULGUE in Nanchang. The surrounding cities are areas with high efficiency values, which are quite different from those of Nanchang, forming L-H outliers. The surrounding cities of Guangyuan City are Bazhong, Nanchong, and Mianyang City, and the ULGUE of the surrounding cities has reached an effective state, while the ULGUE of Guangyuan City is 0.860, which is far behind the surrounding cities and forms an L-H outlier.

During the study period, the H-L outlier range fluctuates slightly, showing a decreasing trend, and its spatial distribution gradually moves from the west to the center. These cities are located in the major urban agglomerations in the central and western regions, and their own economic and social conditions are better than those of the surrounding cities, and their own ULGUE is higher than that of the adjacent cities, thus forming an H-L outlier zone. The main reason for the formation and spatial change of L-H and

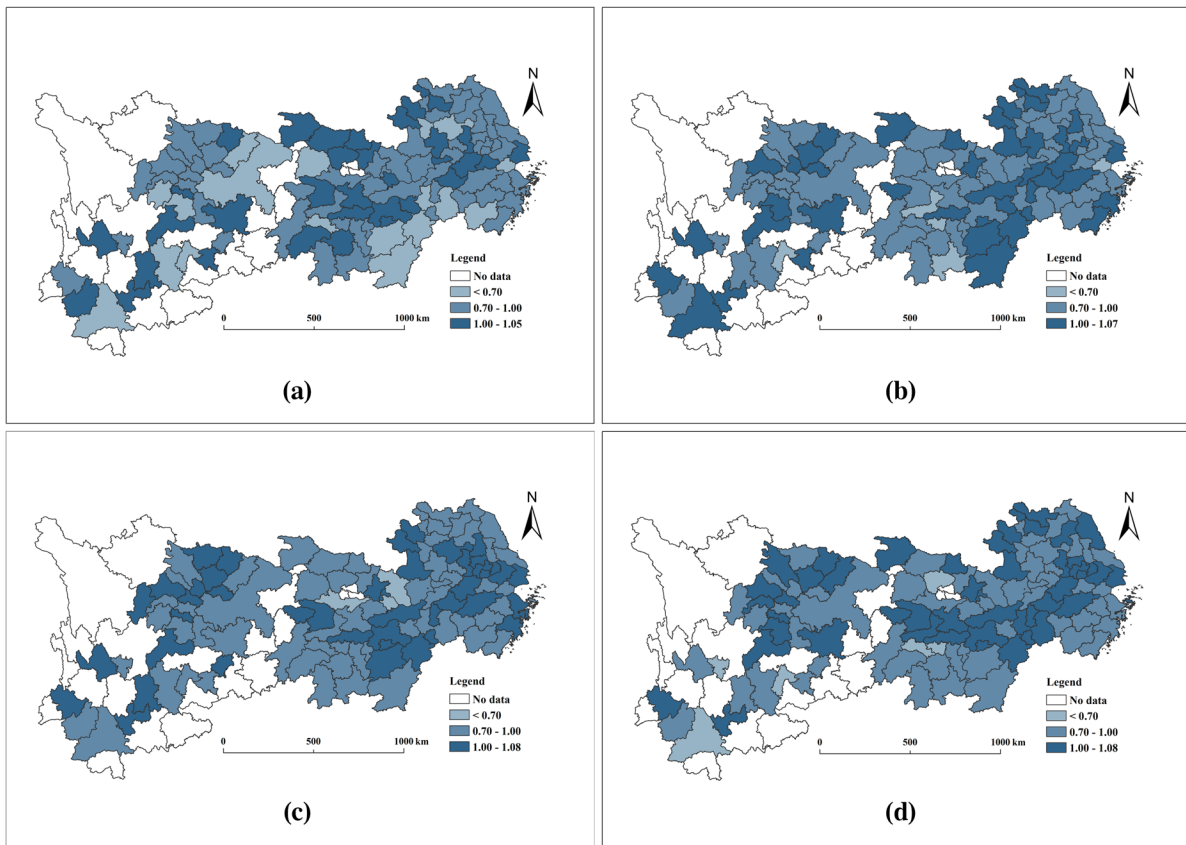
H-L outliers is that the coordinated development of YREB has not reached the ideal state. The provincial capital cities and the core cities of urban agglomerations have more advantages in resources and population, and the ULGUE is relatively higher, but it does not give full play to the radiation role and promote the development of surrounding cities. Therefore, L-H and H-L outliers form and move around the core cities.

In general, ULGUE's local spatial association in YREB is characterized by "small aggregation and large dispersion," and the integrated progress of the city's upper, middle, and lower portions needs to be strengthened. Therefore, the amount of newly added construction land should be within YREB city's authority, and it should actively innovate its utilization mode in the future, explore the path of urban industrial optimization and upgrading, strengthen the linkage development among cities, and exert the synergistic effect to support YREB city's unified growth.

#### ULGUE's time and space evolution features

Regarding the progression of time and space, the ULGUE of 108 cities in YREB is graphically represented by ArcGIS 10.8.1 (Fig. 5). The darker the color in the picture, the higher the efficiency. This paper selects four typical years—2005, 2010, 2015, and 2019—for comparative analysis. In 2005, there were 33 cities with effective ULGUE, 58 cities with high ULGUE (efficiency values of 0.70 to 1), and 17 cities with an efficiency value of less than 0.70. Among them, the cities with effective ULGUE and low ULGUE were evenly distributed in the YREB, and the high-efficiency cities were primarily located upstream and downstream. In 2010, the number of cities with effective ULGUE increased to 42, the number of cities with 0.70–1.00 ULGUE increased to 61, and the number of cities with less than 0.70 ULGUE decreased to 5. The situation of ULGUE has improved, and the areas with effective efficiency are concentrated upstream and downstream. The distribution of cities without effective efficiency is even in YREB. The number of cities with various efficiency ranges varied somewhat in 2015, with the number of cities being 43, 62, and 3, respectively, and the spatial distribution being similar to that of 2010. In 2019, the number of cities in the three different efficiency bands is 46, 56, and 6, respectively. In 2019, the number of





**Fig. 5** Temporal and spatial distribution of YREB’s ULGUE

cities in the three efficiency bands is 46, 56, and 6, indicating that some cities have effectively promoted ULGUE while others have declined ULGUE.

Overall, from 2005 to 2019, the number of cities with higher ULGUE in the YREB exhibited a trend toward growth, while the number of cities with lower efficiency gradually decreased. Their spatial distribution was relatively scattered, and the ULGUE of each city fluctuated in different years. Furthermore, there were still many cities in the YREB whose ULGUE had not been effective during the sample period, so it is vital to concentrate on underdeveloped cities and promote the coordinated development of the YREB.

**Analysis of influencing factors**

Input–output index is one aspect that affects YREB’s ULGUE, but there are other influences as well. Based on the existing literature and the reality of green utilization of urban land, this paper selects urban economic progress and density of the population, urban land

investment intensity, etc. as explanatory variables. See Table 2 for details, and it takes a logarithm for some variables. Build the Tobit regression model as follows:

$$y = \begin{cases} y_i = \beta_0 + \beta_1 \ln(EDL) + \beta_2 \ln(PD) + \beta_3 \ln(LII) + \beta_4 ER + \beta_5 \ln(TE) + \beta_6 IS + \beta_7 ULS + \varepsilon, & y_i > 0 \\ 0, & y_i \leq 0 \end{cases} \quad (7)$$

$y_i$  represents ULGUE,  $\beta_0$  represents intercept,  $\beta_i$  ( $i=1,2,\dots,7$ ) is each affecting factor’s regression coefficient.  $\varepsilon$  is a measure of deviation. In this paper, Stata 12.0 is applied to test the significance of various influential elements of ULGUE, and the estimation results of specific independent variable coefficients are shown in Table 3 below.

The coefficient of EDL is  $-0.0165$ , which indicates that EDL has a negative influence on ULGUE in YREB. With other conditions unchanged, EDL will increase by 1%, ULGUE will decrease by 0.0165%, and EDL will significantly affect efficiency at 5%. This paper’s 2005–2019 research period is

**Table 3** Consequences of the Tobit model's regression

Variables	Coefficient	T value	P value
EDL	-0.0165**	-2.25	0.024
PD	0.0153**	2.21	0.027
LII	0.0099*	1.66	0.098
ER	0.0454***	2.80	0.005
TE	0.0134***	5.59	0.000
IS	0.2126***	6.60	0.000
ULS	-0.2431***	-3.54	0.000
L-likelihood	1137.3917		

\*, \*\*, and \*\*\*, respectively, indicate the significance levels of 10%, 5%, and 1%

covered. At this stage, the emphasis is typically on rapid economic progress. According to the principle of excessively pursuing the speed and scale of economic development, YREB's cities have the problem of extensive economic development while ignoring high-quality economic development, which shows that only increasing per capita GDP cannot improve ULGUE.

PD has a 5% significant positive influence on ULGUE, meaning that the increase in PD is beneficial to green land use, which agrees with the research's finding, according to Zhang et al. (2019). With the development of urbanization, the transfer of rurally registered populations to cities is speeding up, which leads to a gradual increase in the population per unit area of cities. The agglomeration advantage and population pressure caused by the increase in PD will enable the effective use of scarce land resources, thus helping to improve ULGUE.

At a 10% level of significance, LII has a positive effect on ULGUE, showing that raising LII will help ULGUE improve (Li, 2018). The improvement of LII will promote technological progress, optimize land use structure and layout on limited urban land, and improve ULGUE.

The aforementioned hypothesis is supported by the regression line of ER, which is 0.0454, and the 1% significance level test, which implies that ER has a meaningfully beneficial impact on ULGUE. On the one hand, the stronger the strength of ER, the more the development of enterprises tends to be green and environmentally friendly, which, to some extent, helps to prevent unwanted output in the manufacturing process and increases solid waste reuse;

on the other hand, ER contributes to the cultivation and development of environmental awareness in the whole society, and it can be applied to encourage the sustainable usage of land, thus helping to promote ULGUE.

The coefficient of TE is 0.0134 and passes the 1% significance level test, demonstrating that it significantly promotes YREB's ULGUE. Under normal circumstances, a 1% rise in TE will result in an increase in ULGUE of 0.0134%. This is consistent with the previous hypothesis. A TE increase can stimulate the technological innovation enthusiasm of enterprises and other subjects, promote the progress and change of science and technology, and accelerate the development of high-technology industries, which will support industrial modernization and transformation, the optimization of industrial structure, and, to some extent, the use of green space.

The growth in the proportion of tertiary industrial output in GDP is helpful for enhancing ULGUE, as evidenced by the coefficient of IS, which is 0.2126 and passed the examination at a 1% significant level (Zhang et al., 2019). The rise in IS level suggests a gradual decline in the proportion of primary and secondary industries; the proportion of tertiary industries increases; and the industrial structure is continuously optimized. Accordingly, the land use structure also changes, and the elimination of low-end enterprises that consume a lot of energy and pollute the environment has helped to solve the problem of land pollution. The tertiary industry's rapid growth can not only help the city's economy, but it can also help to a greater extent solve the employment issue and act as a catalyst for technological innovation. Therefore, the improvement of the IS will contribute to the improvement of ULGUE.

ULS has a negative impact on ULGUE at a level of 1%, which indicates that the expansion of urban construction land area will reduce ULGUE. To some extent, the urbanization process drives the increase in urban construction land. Cities become farther apart as urbanization develops quickly. This expansion is often accompanied by the uncontrolled development of urban land, which only expands the area of urban construction land but does not improve ULGUE (Hu et al., 2018). Hence, in order to minimize negative effects, we should emphasize high-quality economic growth and gradually increase the scale of urban building land.

## Discussion

### Comparison with previous studies

From a time evolution perspective, the ULGUE is overall positive, with the downstream ULGUE being the highest on average, followed by the upstream and midstream, which is partially inconsistent with the findings of Jin et al. (2018). This paper includes non-desired output in the study and the upstream has better natural endowment conditions, so the result of this study is that the ULGUE is higher in the upstream than in the midstream. This paper also analyzes ULGUE from the perspective of different city sizes, and mega-cities have the highest average ULGUE, followed by large cities and small and medium cities, which enriches the perspective of ULGUE analysis and makes the results of the study relatively more comprehensive. From the perspective of spatial evolution, this paper is consistent with the results of previous studies, and the spatial association is characterized by “small aggregation and large dispersion” (Jin et al., 2018; Zhang et al., 2022a, 2022b).

In terms of influencing factors, PD, ER, IS, TE, and LII all contribute significantly positively to land green use efficiency, while ULS has a negative inhibitory effect, which is consistent with previous research (Hu et al., 2018; Li, 2018; Xue et al., 2022; Yu et al., 2019). The effect of EDL on ULGUE in the study by Xue et al. (2022) showed a U-shape, whereas in this paper, the EDL showed a significant negative effect, probably because this study considered non-desired output, and rapid economic development may have some negative impact on the environment, which is reflected in ULGUE as EDL has a slight negative effect on ULGUE.

### Contributions

First, in terms of efficiency assessment methods, DEA is gradually and widely used in the study of ULGUE, but among them, Super-SBM and SBM-Undesirable models are used more often (Chen et al., 2020; Wu et al., 2022; Q. Yang et al., 2022a, 2022b; Zhu et al., 2019), there are fewer studies on ULGUE using the Super-EBM model. At the same time, the Super-EBM model has its unique advantages: it is compatible with radial and non-radial input–output variables and can be used to measure DMUs with efficiencies above

1. In order to improve the accuracy of the evaluation results, this paper evaluated the ULGUE of YREB using the Super-EBM model. In the study of the influencing factors, the methods that have been used are spatial econometric models, geodetector models, scenario simulation models, and machine learning (Zhou et al., 2022a; Zhou et al., 2022b). To better assess the relationship between ULGUE and influencing factors, and considering that ULGUE calculated by the efficiency measurement model in this paper is “censored” data, the Tobit model is used in this study. Second, this study adds to YREB’s ULGUE research. Previous research has primarily focused on cultivable land (Luo et al., 2020; B. Yang et al., 2021), with little attention paid to urban construction land. There are also relatively few studies on ULGUE at the regional level of YREB. In this paper, the spatio-temporal evolution characteristics and influencing factors of ULGUE in YREB are systematically studied from the city dimension, which contributes to the study of ULGUE to a certain extent.

### Policy recommendations

Deepen the coordinated growth of the YREB’s upper, middle, and lower reaches based on the spatial difference of ULGUE. The downstream cities have the highest average efficiency, but not all downstream cities have achieved effective green land use, so it can strengthen the radiation driving effect of effective cities and achieve coordinated development among downstream regions. Although the central reaches of the YREB have a comparatively small average ULGUE value, they are well connected to the east, west, north, and south. By making transportation infrastructure construction more robust and further strengthening cooperation with surrounding cities, we can realize complementary resource advantages, industrial cooperation, and labor division, and promote the green use of urban land. The ULGUE of upstream cities is moderate. Upstream cities do not have advantages in location, but they can promote their own green land use by vigorously developing a green economy, allocating labor and capital rationally, expanding and becoming more open to the outside world, strengthening ties with middle and downstream cities, and promoting coordinated development.

Judging from the relationship between ULGUE and influencing factors, we should first vigorously promote high-quality economic development. China has entered a phase of high-quality economic growth, according to the statement of the 19th National Congress of the Communist Party of China. Innovation is vital to high-quality economic growth, which generates high added value, energy efficiency, and environmental preservation. Cities can pool their resources and development status to support the establishment of strategic emerging industries, such as new energy and new materials, and to synchronize economic growth with environmentally friendly development. The second is to formulate a policy of “population mobility” that encourages the growth of the center and western areas, strengthens infrastructure building, and advances medical insurance and education systems. The development of a city cannot be separated from its manpower base, and the attraction of a city to the population depends on the level of urbanization, and the two complement each other. The eastern section of ULGUE in YREB is greater than the central and western parts, and the eastern part’s urban development level is also greater than the central and western parts. There were a lot of people flowing to the eastern part. Therefore, central and western cities may implement preferential policies for a migrant population, vigorously build infrastructure, bolster systems that support people’s livelihoods, such as health care and education, attract people to move to the areas of the center and west, and give full play to the advantages of population agglomeration. The third is to increase ER intensity in different subjects. YREB people’s governments at all levels should strictly abide by the environmental protection guidance of the central government, formulate and improve relevant environmental protection policies according to local conditions, and intensify publicity to let all sectors of society know about relevant policies. All enterprises actively practice the green development path, strictly abide by the local emission standards, and complete the corresponding tasks of energy conservation and emission reduction. Citizens can constantly strengthen their awareness of environmental protection, adopt a low-carbon and environmentally-friendly lifestyle, and consciously assume the responsibility of environmental protection. Fourthly, to encourage innovation and the use of science and technology, raise TE. The main forces of production are science and technology, and innovation in these fields is crucial for fostering high-quality economic growth. The main bodies to promote scientific and technological

innovation are scientific research institutes, universities, and enterprises. YREB City can improve contact and cooperation among these organizations, promote coordinated government and industry-university-research development, and accelerate technological innovation and achievement transformation. The fifth is to optimize IS. The purpose of IS optimization is to coordinate the development of industries, improve efficiency, and achieve the optimal input–output ratio. YREB City can introduce relevant policies and measures to ensure the optimization of industrial structure and progressively phase out backward industries with high power consumption and pollution while actively developing green and low-carbon industries. Sixth, rational planning and use of urban construction land area. All localities should adopt the Standards of Urban Land Classification and Planning for Construction Land to guide the utilization of building land, ensure that the per capita construction land area and per capita green land area meet the standards, and ensure that the proportion of all kinds of land is reasonable. Additionally, consideration should be given to identifying the degree of environmental pollution caused by different land uses, and environmental protection measures should be taken for industrial land.

## Conclusions

In this paper, we measured the ULGUE of YREB from 2005 to 2019 using the Super-EBM model, analyzed the spatio-temporal evolution trend through data visualization and spatial autocorrelation, and analyzed the influencing factors of ULGUE using the Tobit model, and concluded that (1) the overall ULGUE showed an upward trend, and the ULGUE levels from 2005 to 2019, the YREB downstream > YREB upstream > YREB midstream, YREB megacity > YREB large city > YREB small and medium-sized city. (2) The spatial characteristics of ULGUE show “small aggregation and large dispersion,” with the distribution of both aggregation and outlier ranges, and the spatial distribution of ULGUE is variable. (3) The spatial and temporal evolution shows that the number of municipalities with high ULGUE is generally increasing, the spatial distribution is relatively scattered, and the coordinated development of YREB needs to be strengthened. (4) According to the results of the Tobit regression model, PD, ER, IS, TE, and LII have a significant

positive contribution to ULGUE, while the levels of EDL and ULS have a significant negative effect.

This study measured the ULGUE relatively accurately and revealed how each influencing factor affects the ULGUE value. The suggestions in this paper for YREB are feasible and can promote the coordinated development of YREB and the improvement of ULGUE to a certain extent. To further deepen the study of ULGUE, firstly, more refined evaluation indexes and influencing factors can be constructed, and secondly, different stages of urban development are considered to be included in the study to get differentiated ULGUE influencing mechanisms for better urban green development and sustainable development.

**Author contribution** Dalai Ma: conceptualization, software, and writing — review and editing. Jiawei Zhang: data curation and writing — original draft. Fengtai Zhang: methodology and visualization. Yaping Xiao: data curation and resources. Hongmei Tan: data curation. Zuman Guo: investigation. Bitan An: formal analysis.

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**Data availability** The authors do not have permission to share data.

## Declarations

**Ethical approval** All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

**Competing interests** The authors declare no competing interests.

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