land

MDPI

Article

Spillover Effects of Urban Expansion on Land Green Use Efficiency: An Empirical Study Based on Multi-Source Remote Sensing Data in China

Zhen Deng [1], Fan Xiao [2], Jing Huang [3], Yizhen Zhang [2,4,*] and Fang Zhang [1,*]

[1] College of Life Sciences, Anhui Normal University, Wuhu 241000, China; dengzhen@ahnu.edu.cn
[2] Key Laboratory of Regional Sustainable Development Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; xiaof2.20b@igsnrr.ac.cn
[3] Department of Environmental Science, University of Arizona, Tucson, AZ 85721, USA; jinghuang0@arizona.edu
[4] School of Geography and Tourism, Anhui Normal University, Wuhu 241002, China
* Correspondence: zyzwuhu@ahnu.edu.cn (Y.Z.); biozhf@ahnu.edu.cn (F.Z.)

Abstract: Land is an important carrier of resource elements, and improving land green use efficiency (LGUE) is the key to achieving "smart growth" in cities. This study takes 269 cities in China from 2008 to 2020 as the research object and integrates multisource remote sensing data, GIS spatial analysis, and spatial econometric models to explore the evolutionary characteristics of LGUE and the spatiotemporal effects of urban expansion on LGUE. The results show that (1) urban LGUE increases over time and has certain gradient distribution and spatial dependence characteristics; (2) urban expansion has a significant inverted U-shaped relationship with LGUE, indicating that maintaining reasonable urban expansion is the key to improving LGUE, but excessive urban expansion has a strong negative spatial effect on LGUE. In terms of spillover effect, for every 1% increase in the square term of urban expansion, the LGUE of the local city decreases by 0.0673%, but the neighboring city increases by 0.2283%; and (3) urban expansion has significant spatiotemporal heterogeneous effects on LGUE, and spatial development boundaries must be reasonably determined to achieve "smart growth". Currently, some cities in China are expanding rapidly, and we hope to provide key support for promoting the "smart growth" of cities and improving LGUE.

Keywords: land green use efficiency; evolutionary pattern; urban expansion; spatial effect

check for updates

Citation: Deng, Z.; Xiao, F.; Huang, J.; Zhang, Y.; Zhang, F. Spillover Effects of Urban Expansion on Land Green Use Efficiency: An Empirical Study Based on Multi-Source Remote Sensing Data in China. *Land* **2024**, *13*, 1102. https://doi.org/10.3390/land13071102

Academic Editors: Ying Hou and Baoyin Liu

Received: 4 July 2024
Revised: 18 July 2024
Accepted: 18 July 2024
Published: 21 July 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Changing extensive and inefficient land use and constructing an institutional system and governance concept for the coordinated development of "land-economy-ecology" are important guarantees for promoting green and efficient urban development [1–3]. In recent years, driven by economic development, rapid transportation, and "land finance", China's urban spatial structure and growth mechanism have undergone significant changes. According to relevant data, China's urbanization rate climbed from 17.92% in 1978 to 64.72% in 2021, far exceeding the world average for the same period. Although rapid urbanization has improved the efficiency of production factor allocation and residents' living standards and profoundly changed the economic and social development model, low-density spatial expansion policies have occupied a large amount of "green space" (forests, parks, wetlands, farmland, etc.) and have brought a series of negative effects to LGUE [4,5]. Therefore, scientifically assessing the spatiotemporal effects of urban expansion on LGUE is crucial to improving the economic, social, and ecological benefits of land use and achieving "smart growth" in cities.

LGUE is a comprehensive mapping of various production factors in geographical space, which mainly emphasizes the efficient and coordinated development of the "land-economy-ecology" system [6–9]; that is, under certain production technology conditions,

smaller land factor inputs are used to obtain optimal green economic benefits while reducing undesirable outputs, such as ecological damage and environmental pollution [10–12]. Currently, relevant scholars mainly explore LGUE based on two aspects. The first involves focus on the theoretical connotation, measurement methods, and policy recommendations of LGUE. Xie et al. [13] measured the green utilization efficiency of cultivated land in China by constructing an input–output index system and combining directional distance function. Koroso et al. [14] used field observations and remote sensing images to conduct a comprehensive analysis of Ethiopia's land resources, and found that under the influence of urban land leasing policies, Ethiopia's urban land use efficiency is very low and has serious blind expansion. Liu et al. [15] advocated that the spatial structural contradictions in some areas of China have gradually become prominent, and that local governments should elevate resource and environmental issues to a national strategic level, construct a resource-saving and environment-friendly society, and improve LGUE from the source. The second aspect involves exploring the evolutionary pattern and driving mechanisms of LGUE. Based on the Malmquist index and GIS spatial analysis, Xie et al. [13] found that the green use efficiency of urban industrial land in China has significant spatial and temporal heterogeneity, but the gap between cities is constantly narrowing. Li et al. [16] applied the SBM model and Tobit analysis and found that industrial upgrading and technological innovation have a strong impact on LGUE in resource-based cities. Zhong et al. [17] found that the land fiscal scale breakthrough threshold has a significant positive spatial effect on LGUE based on the Malmquist–Luenberger index and spatial economic model.

In the context of large-scale urbanization, urban expansion has gradually become a key variable affecting LGUE [18–20]. Urban expansion refers to the process of urban space extending or expanding to the suburbs under the influence of many factors such as economy, society, and population, which are highly intertwined and multidimensional [21]. Early relevant scholars mainly used traditional indicators such as residential density, land area, economic level, population size, urban land growth elasticity coefficient, spatial fragmentation, and landscape pattern to measure urban expansion [22,23]. With the popularization of ArcGIS10.3 software and remote sensing data, the accuracy and real-time performance of urban spatial identification have been improved, providing a new perspective for scientifically measuring urban expansion [24]. For example, Huang et al. [25] used high-resolution imperviousness data to measure the level of urban expansion. Although impervious areas can reflect the physical expansion of urban built-up areas, it is difficult to fully reflect the complexity and diversity of urban expansion, such as the transformation of urban functions and changes in population density. Considering the convenience, real-time nature, and low cost of nighttime lighting data acquisition, it can directly reflect the intensity of human activities and provide comprehensive information for monitoring urban expansion. Therefore, nighttime lighting data was selected as a proxy variable for measuring urban expansion in this study. Currently, the relationship between urban expansion and LGUE remains unclear. Existing research mainly advocates that urban expansion leads to reductions in urban green space, the intensification of the urban "heat island effect", and the deterioration of air quality [18,26]. In addition, some scholars argue that problems such as resource constraints, ecosystem damage, and low land use efficiency caused by urban expansion run counter to the concept of high-quality sustainable development [27,28]. Therefore, more scholars have advocated for the formulation of relevant policies and regulations to curb urban expansion from the source to promote "smart growth" [29,30]. Nevertheless, according to the urban development process and development stage, the outward expansion of urban land is inevitable, and its existence has a certain rationality. It is worth noting that some studies believe that reasonable urban expansion can not only reduce the concentrated emissions of pollutants, but also promote the division of labor and improve production efficiency [31].

Following a review of the literature, we found that relevant scholars have explored the theoretical connotations, evolutionary pattern, and driving factors of LGUE, but there is still room for improvement. Firstly, compared with traditional statistical data, nighttime light data is more timely and dynamic, directly reflects the intensity and spatial distribution

characteristics of regional human activities, and can accurately measure the degree of urban expansion. Therefore, we used a large panel data set of 269 cities in China from 2008 to 2020 combined with nighttime light data to measure the spatiotemporal effect of urban expansion on LGUE, which can improve the accuracy and robustness of the measurement results to a certain extent. Secondly, existing studies mainly focus on the impact of economic and social factors on LGUE, but it is still unclear how the externality of urban expansion affects LGUE and whether it can produce a positive spatial spillover effect. Finally, the land use intensity, efficiency, and structure of different types of cities are completely different; however, most previous studies have only regarded urban LGUE as an undifferentiated unit, and have often ignored the differences in urban LGUE, making it difficult to examine the heterogeneous effect of urban expansion on LGUE in detail.

To make up for the above shortcomings, this study may bring the following marginal contributions: (1) This study combines the super-efficient EBM model to measure LGUE, and fits DMSP and VIIRS nighttime light data from 2008 to 2020 to inverse urban expansion, and then integrates urban expansion and LGUE into a unified analysis framework, which provides new ideas for subsequent relevant research. (2) This study uses ArcGIS spatial analysis and spatial econometric models to examine the evolutionary characteristics of urban expansion and its spatial spillover effects on LGUE, which provides theoretical support for optimizing land resource allocation and strengthening urban green coordinated development. (3) This study uses the GTWR model to comprehensively explore the spatiotemporal heterogeneous effects of urban expansion on LGUE and provide a scientific basis for formulating spatial expansion policies based on local conditions. The main objectives of this study are as follows: on the one hand, China and the world's major emerging economies are currently facing large-scale urbanization, and we expect this study to provide a scientific basis for promoting "smart growth" in cities. On the other hand, we expect this study to provide empirical lessons for promoting intensive utilization of land resources and improving LGUE.

2. Theoretical Framework

Under the conditions of market economy, the vigorous development of industry, commerce, and residential buildings has directly led to a rapid increase in urban construction-related land use and the continuous expansion of urban space scale. Obviously, changes in the type and structure of land use bring some serious problems and challenges. On the one hand, the excessive pursuit of economic benefits in some cities may lead to over-exploitation and waste of land resources, damage to the ecological environment, and a reduction in arable land resources; on the other, the over-development of urban space has aggravated resource shortages and environmental pollution, leading to reduced biodiversity and ecological imbalance, which has had a strong negative effect on production and living conditions [32,33]. Obviously, the extensive and inefficient land use model cannot meet the requirements of high-quality development, and improving LGUE has become a key way to balance the contradiction between economic development and land resources.

As an important resource and ecological and material space carrier, land runs through the entire process of human social and economic activities. In the context of extensive economic development and rapid urbanization, it is urgent to combine multidisciplinary theories and methods to promote land transformation and development, alleviate ecological and environmental pressures, and achieve regional green and sustainable development. Existing research believes that urban expansion mainly affects LGUE through social-economic-environmental effects. In terms of social effects, urban expansion destroys the "spatial texture" and humanistic environment, intensifies social contradictions, segregates the rich and the poor, and begets uneven regional development, leading to social contradictions such as "urban villages" and the "decline of central urban areas" [27]. In terms of economic effects, urban expansion reduces the efficiency of public facilities use and the intensity of land use per unit area, which is inconsistent with the development logic of circular economy and economies of scale [34]. In addition, some cities are blindly expand-

ing their spatial scale and neglecting the intensive utilization of land resources, which is not only detrimental to the agglomeration of economic development, but also destroys human settlements [35]. However, some studies claim that urban expansion reduces land transfer prices, changes land use types, and promotes the transformation of more idle land into modern service industries and tourism, thus increasing the added value of land use [36,37]. In terms of environmental effects, urban expansion leads to air and noise pollution, which has serious negative impacts on human settlements and ecosystems [5]. At the same time, due to changes in urban ground cover and the presence of a large number of buildings, temperatures in urban areas tend to be higher than in neighboring areas, which in turn affects the living experience of citizens [38,39]. However, scholars holding the opposite view believe that a reasonable spatial expansion policy can not only optimize the efficiency of resource allocation, but also alleviate "big city diseases" such as traffic congestion and air pollution and enhance LGUE [40]. In this context, the core tenet of LGUE is to accelerate the synergistic development of land, economy, ecology, and human habitat. Therefore, it is necessary to optimize urban expansion plans, improve levels of urban management and the quality of life of residents, and ensure the green, healthy, and sustainable development of cities.

With the rapid development of urbanization and industrialization, urban expansion continues to reshape the regional spatial system and land resource use structure. Under the new situation of economic development, a new land use concept is urgently needed to comply with the direction, speed, and quality requirements of social and economic development. Therefore, only by changing the old concept of "development first and then governance" in land development and utilization and constructing an institutional system and governance concept for the symbiotic evolution and coordinated development of "land-economy-ecology" can land green total factor productivity be improved. This study combines multidisciplinary theories and methods, integrates urban expansion and LGUE into a unified research framework, and scientifically measures the spatiotemporal effect of urban expansion on LGUE. On the one hand, this study provides theoretical significance in terms of understanding the spatiotemporal evolution pattern of China's LGUE, promoting the transformation of land use structure, and realizing the efficient and coordinated development of "land-economy-ecology". On the other hand, clarifying the spatiotemporal effects of urban expansion on LGUE provides key scientific support for guiding the rational layout of urban space.

3. Data and Methods

3.1. Data Sources

Based on data availability, this study used 269 prefecture-level cities in China from 2008 to 2020 as the research unit. Data on urban construction land, employed persons in urban units, industrial wastewater, and sulfur dioxide were mainly from the "China Urban Statistical Yearbook" and "China Environmental Yearbook", and the interpolation method was used to supplement some missing data (Table 1). DMSP and VIIRS nighttime light data were taken from the NOAA website and NGDC data center (http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html), and we accessed the data on 18 May 2023. The PM2.5 concentration raster data from 2008 to 2020 was sourced from the website of the Dalhousie University Atmospheric Composition Analysis Group (http://fizz.phys.dal.ca/~atmos/martin/), and we accessed the data on 18 May 2023. Since the data accuracy was $0.01^\circ \times 0.01^\circ$ spatial resolution, this study used ArcGIS10.3 software to extract prefecture-level city PM2.5 concentration data.

Table 1. Data sources and basic information.

Data Name	Unit	Data Type	Data Sources	Data Processing
Urban expansion	1 km × 1 km 500 m × 500 m	DMSP–OLS and NPP–VIIRS remote sensing data sets	NOAA website and NGDC data center	Resampling-data correction-light fitting -consistency processing
PM2.5 concentration	$\mu g/m^3$	PM2.5 raster data	Dalhousie University Atmospheric Composition Analysis Group	Satellite retrieval of PM2.5 concentration
Urban construction land area	km^2	Economic and social attribute data	"China Urban Statistical Yearbook" "China Environmental Yearbook" "Statistical Bulletin"	—
Urban employed persons	10^4 persons			—
Total fixed asset investment	10^4 yuan			—
Real GDP	10^4 yuan			GDP deflator
Industrial wastewater	10^4 tons			—
industrial sulfur dioxide	tons			—

3.2. Indicator Selection for LGUE Measurement

LGUE is a new land use model after land intensive use and land sustainable use, which mainly refers to the optimal combination of land, economy, resources, and environment under the current development level and constraints [13]. The essence of LGUE is to maximize green economic benefits at the cost of minimal land resources and environmental losses [12]. The LGUE measurement not only includes the output of traditional economic factors, but also needs to include undesirable outputs such as ecological loss and environmental pollution [41]. According to the connotation of LGUE, the input–output indicators selected in this study were as follows [10]: 1. Input indicators: land resource input was expressed by urban construction land area; labor input was expressed by urban employment personnel; capital investment was expressed by the total fixed asset investment; 2. desirable output: real GDP was taken as the desirable output; and 3. undesirable outputs: based on the input–output nature of factors, wastewater, sulfur dioxide, and PM2.5 emissions were used as undesirable output indicators (Figure 1).

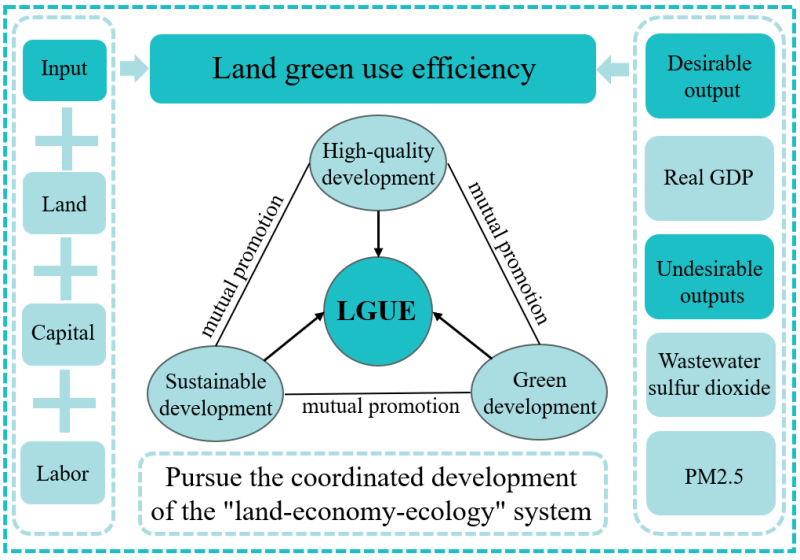


Figure 1. LGUE connotations.

3.3. Variable Selection

3.3.1. Core Explanatory Variables

Urban expansion (*UE*): Nighttime light data has higher spatial and temporal resolution, and has become one of the important proxy variables for measuring urban expansion [42]. Compared with the traditional urban expansion measurement methods, night light data can identify spatial differences inside the city at the pixel level, and can measure the spatial scope and degree of urban expansion more sensitively [19]. DMSP–OLS and NPP–VIIRS are currently the most commonly used classes of nighttime light data. Among them, DMSP–OLS nighttime light data is acquired by six types of satellites, the continuity between data is weak, and the spatial resolution is relatively low (1 km); NPP–VIIRS has higher spatial resolution (0.5 km) and better detection capability, but is prone to incidental noise. Since the spatial and temporal resolutions of DMSP–OLS and NPP–VIIRS light data are quite different, mutual correction and data fitting are required. The specific processing steps are as follows [43]: first, the nearest neighbor method was used to resample the image and adjust the pixel deviation between the two images. Secondly, Jixi City, Heilongjiang Province was selected as the correction location, and a quadratic function was used to perform mutual correction on the DMSP–OLS light data. Since China's economy grew positively without stagnation or regression during the study period, it was determined that the change in *DN* should also be consistent with that trend. Based on the above assumptions, the *DN* outliers were adjusted according to Formula (1):

$$DN_{(n,i)} = \begin{cases} 0 & DN_{(n+1,i)} = 0 \\ DN_n & DN_{(n+1,i)} > 0 \ \& \ DN_{(n-1,i)} > DN_{(n,i)} \\ DN_{(n,i)} & \text{other} \end{cases} \quad (1)$$

In addition, considering the strong detection ability of NPP–VIIRS, this study used 0.3 as the threshold to remove noise in NPP–VIIRS images, and assigned pixels with negative *DN* values to 0 [44]. Finally, the 2013 overlapping images were used to conduct *DN* value correlation analysis, and NPP–VIIRS was fitted to DMSP–OLS data. Table 2 shows that the R^2 of the power function was larger (0.8472), and the fitting effect was better. Therefore, this study used a power function to convert NPP–VIIRS light data from 2013 to 2020 into DMSP–OLS-like data (Figure 2).

Table 2. DMSP–OLS and NPP–VIIRS light data fitting functions.

Fitting Function	Equation	Goodness of Fit (R^2)
Linear function	$y = 1.4867x + 37{,}892$	0.8124
Logarithmic function	$y = 54{,}108ln(x) - 439{,}260$	0.596
Power function	$y = 31.671x^{0.7759}$	0.8472
Polynomial function	$y = -6 \times 10^{-7}x^2 + 1.7101x + 33{,}402$	0.8187

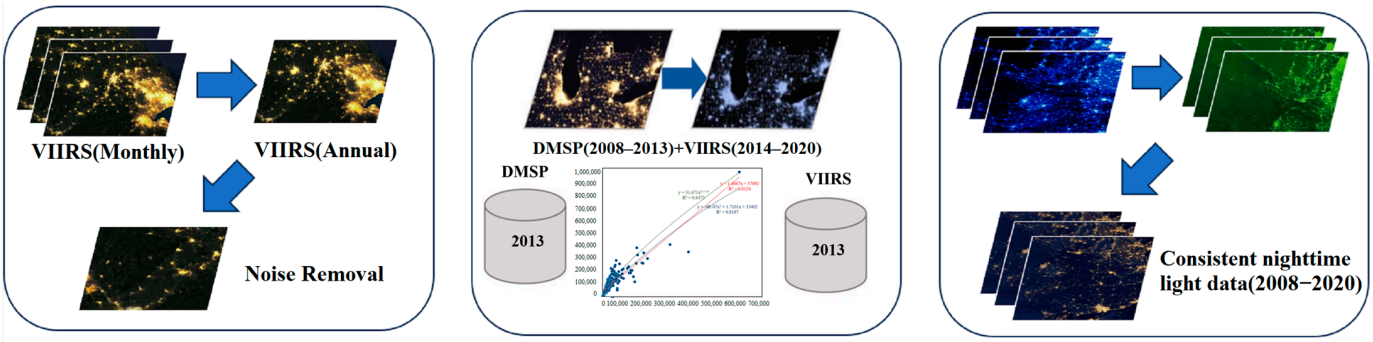


Figure 2. DMSP and VIIRS night light data consistency processing process.

Based on the above corrected consistent nighttime light data from 2008 to 2020, to avoid image noise, we referred to the relevant literature [45], used the light brightness 6 as the threshold to extract urban space, and constructed the urban expansion index (*UE*):

$$UE = \frac{1}{2} \times \left(\frac{\sum_{t=1}^{n} N_{ith}}{\sum_{t=1}^{m} N_{it}} - \frac{\sum_{t=1}^{m-n} N_{itl}}{\sum_{t=1}^{m} N_{it}} \right) + \frac{1}{2} \quad (2)$$

where *UE* represents the urban expansion index; m is the total number of pixels; N_{jth} means that the brightness of the t-th pixel in city j is higher than the national average pixel brightness; and N_{jt} represents the pixel t inside city j. In addition, the square term of urban expansion (UE^2) was introduced to examine the nonlinear relationship between further urban expansion and LGUE.

3.3.2. Control Variables

Urban expansion (*UE*): According to relevant research [46,47], industrial agglomeration, environmental regulation, fiscal expenditure, foreign direct investment, and technological innovation were selected as the control variables. (1) Industrial agglomeration (*IND*): represented by the proportion of industrial enterprises above the designated size to the national total. (2) Environmental regulation (*ER*): referring to relevant research, a comprehensive index of environmental regulation was constructed to represent the level of environmental regulation [48]. (3) Fiscal expenditure (*FIS*): represented by the proportion of local fiscal budget expenditure to GDP. (4) Foreign direct investment (*FDI*): represented by the city's annual actual foreign investment as a share of GDP. (5) Technological innovation (*TEC*): represented by the proportion of scientific expenditures in local financial expenditures. To reduce the effects of heteroskedasticity and variable fluctuations, variables were treated logarithmically, and missing data for individual cities were filled in using interpolation. Descriptive statistical analysis of all variables is shown in Table 3. In addition, the variance inflation factor (VIF) test showed that the VIF for all variables ranged from 1.082 to 2.558, indicating the absence of multicollinearity.

Table 3. The statistical description of all variables.

Variables	Obs	Mean	Std. Dev.	Min	Max
lnUE	3497	0.6816	0.2520	0.001	0.9912
lnIND	3497	6.6461	1.0717	3.0445	9.8411
lnER	3497	−4.5587	2.0900	−12.5499	8.3547
lnFIS	3497	−1.7359	0.5318	−4.1758	1.7985
lnFDI	3497	9.8815	1.9905	2.3025	14.9417
lnTEC	3497	5.7736	0.9195	1.5973	8.8142

3.4. Research Methods

On the basis of theoretical analysis, this study combined multi-source remote sensing data and economic and social attribute data, and also combined ArcGIS spatial analysis and spatial econometrics models, to explore the spatial effect of urban expansion on LGUE (Figure 3).

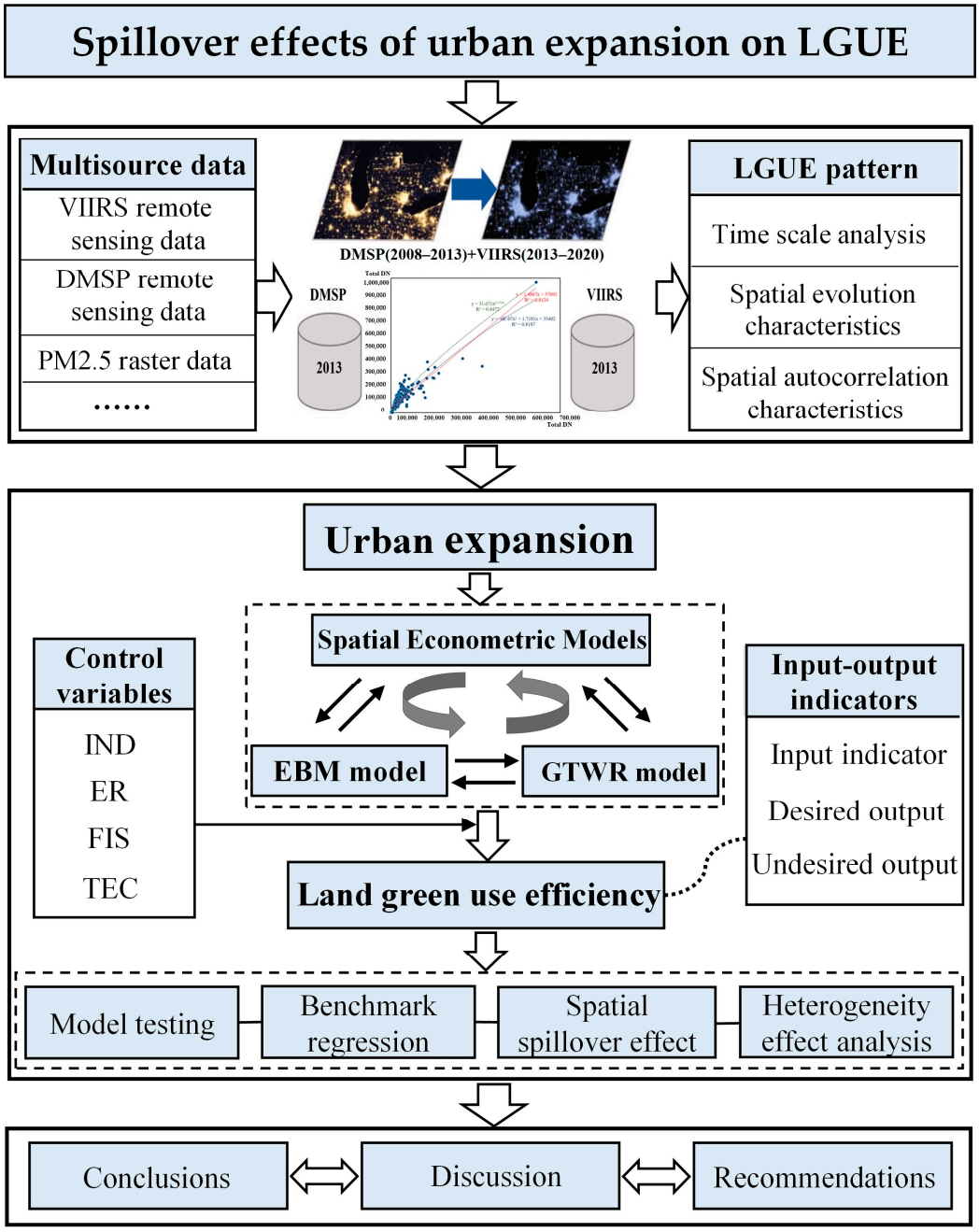


Figure 3. Flowchart of the study.

3.4.1. Super-Efficiency EBM-DEA Model

The DEA model is a special method based on linear programming, which usually uses the input–output ratio as an indicator to measure the production efficiency of the decision-making unit (*DMU*). The advantage of the DEA model is that it is not affected by dimensions and can measure the production efficiency of *DMU* under the condition of multiple inputs and multiple outputs [49]. However, traditional DEA models tend to ignore non-radial slack variables when evaluating efficiency [50]. To solve the defects in this model, Tone et al. [51] proposed the EBM-DEA model in 2010; this model can

simultaneously solve the defects in the radial and non-radial DEA models, and can truly evaluate the LGUE of the *DMU*. The specific model is as follows:

$$\gamma* = \min \frac{\theta - \varepsilon_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{i0}}}{\varphi + \varepsilon_\gamma \sum_{r=1}^{s} \frac{w_r^+ s_r^+}{y_{r0}} + \varepsilon_u \sum_{p=1}^{q} \frac{w_p^- s_p^-}{u_{p0}}}$$
$$s.t. \begin{cases} \sum_j^n x_{ij}\lambda_j + s_i^- = \theta x_{i0}, i = 1, 2, \ldots, m \\ \sum_j^n y_{rj}\lambda_j + s_r^+ = \varphi y_{r0}, r = 1, 2, \ldots, s \\ \sum_j^n u_{pj}\lambda_j + s_p^- = \varphi u_{p0}, p = 1, 2, \ldots, q \\ \lambda_j \geq 0, s_i^-, s_r^+, s_p^- \geq 0 \end{cases} \quad (3)$$

where γ^* represents the LGUE, and λ_j refers to the linear combination coefficient of DMU_j; *xij*, *yrj*, *upj* respectively represent the *i*-th input, *r*-th desirable output, and *p*-th undesirable output of DMU_j; *n*, *m*, *s*, and *q*, respectively, represent the number of decision-making units, the number of input factors, and the number of desirable and undesirable outputs; W_i^- and Wp^- represent their weights, respectively; and θ represents the radial planning parameter.

3.4.2. Spatial Econometric Model

Due to the strong spatial correlation characteristics of LGUE, the estimation results of traditional econometric methods may be biased, and appropriate spatial econometric models must be included for scientific evaluation [52]. There are three main types of common spatial econometric models. The spatial lag model (SLM) mainly focuses on the spatial correlation effect between variables; if the "spatial dependence" between explanatory variables has a significant impact on the model, the spatial lag model should be used. The spatial error model (SEM) includes interaction terms of error terms, focusing on revealing the impact of ignored independent variables on the explained variables. However, the spatial Durbin model (SDM) takes into account both the lag term of the explanatory variable and the autocorrelation of the dependent variables, and has strong explanatory power [53,54]. This study uses SDM to capture the spatial spillover effects of urban expansion on LGUE.

$$LGUE_{it} = \delta \sum_{j=1}^{n} w_{ij} LGUE_{it} + \beta_1 UE_{it} + \beta_2 UE_{it}^{\ 2} + \beta_3 IND_{it} + \beta_4 ER_{it} + \beta_5 FIS_{it} + \beta_6 FDI_{it} + \beta_7 TEC_{it} + \theta_1 \sum_{j=1}^{n} w_{ij} UE_{it}$$
$$+\theta_2 \sum_{j=1}^{n} w_{ij} UE_{it}^{\ 2} + \theta_3 \sum_{j=1}^{n} w_{ij} IND_{it}^2 + \theta_4 \sum_{j=1}^{n} w_{ij} ER_{it} + \theta_5 \sum_{j=1}^{n} w_{ij} FIS_{it} + \theta_6 \sum_{j=1}^{n} w_{ij} FDI_{it} + \theta_7 \sum_{j=1}^{n} w_{ij} TEC_{it} + \mu_{it} + \varepsilon_{it} \quad (4)$$

3.4.3. Spatial Weight Matrix

Considering that non-material factors such as economy, culture, and institutions also participate in the interaction of economic activities with spatial units, defining spatial correlation simply by geographical distance may be biased. Based on considering spatial distance, the asymmetric economic distance matrix (*W*1) assumes that cities with higher economic levels will have a stronger impact on neighboring cities, otherwise the opposite is true, which is consistent with the actual situation [50].

$$W1 = \begin{cases} 1/d_{ij} \times diag\left(\frac{GDP_i}{GDP_j}\right), (i \neq j) \\ 0, (i = j) \end{cases} \quad (5)$$

where GDP_i and GDP_j represent the *GDP* of cities *i* and *j* respectively; d_{ij} refers to the straight-line distance between the administrative centers of the two cities; and *diag*(. . .) represents a diagonal matrix.

3.4.4. Geographical and Temporal Weighted Regression

Traditional GWR models use cross-sectional data, which usually use the average of multiple years of data to construct the model, making it difficult to reveal differences between different years [55]. GTWR breaks through the limitation of traditional GWR that only considers spatial effects, and can effectively deal with space-time non-stationary problems [56]. In addition, most regression models regard LGUE as an undifferentiated unit, which easily ignores the differences in LGUE between cities. However, GTWR performs regression analysis on each city as a separate individual

and visualizes the regression results [57], which can more intuitively and carefully examine the spatiotemporal heterogeneous effects of urban expansion on LGUE.

$$Y_i = \beta_0(u_i, v_i, t_i) + \sum_k \beta_k(u_i, v_i, t_i) X_{ik} + \varepsilon_i \quad (6)$$

where Y_i represents the *LGUE* of the *i*-th city; $\beta_0(u_i, v_i, t_i)$ is the regression intercept of the *i*-th city; u_i, v_i, and t_i are the longitude, latitude and time of the *i*-th city, respectively; β_k (u_i, v_i, t_i) represents the regression coefficient of the *k*-th explanatory variable in the *i*-th sample city; X_{ik} represents the value of the *k*-th explanatory variable in the *i*-th city; and ε_i is a random interference term.

4. The Spatiotemporal Evolution Characteristics of LGUE

4.1. Time Series Evolution Characteristics of LGUE

During the study period, the mean and peak value of urban LGUE increased year by year, and its skewness and kurtosis were 1.120 and 1.375, respectively, indicating that the LGUE had an obvious positively skewed distribution. In addition, the mean value of LGUE was greater than the median and mode, indicating that it had certain polarization distribution characteristics (Figure 4). To further explore the time series evolution characteristics of the LGUE, this study performed kernel density analysis on LGUE from 2008 to 2020. Observed from the position of kernel density, the peak value of kernel density curve had an obvious rightward shift from 2008 to 2020, indicating that urban LGUE showed a gradual upward trend. In addition, the peak value of the kernel density curve dropped from 5.6 in 2008 to 2.7 in 2020, indicating that the number of cities with lower LGUE and the absolute difference between cities was continuously decreasing. It is worth noting that the kernel density curve during the study period showed an obvious right-tail phenomenon, and a peak was formed at an efficiency of 1 in 2020. This mainly reflects that the LGUE in some cities has been at a relatively high level in recent years, and the coordinated development of "land-economy-ecology" has basically been achieved.

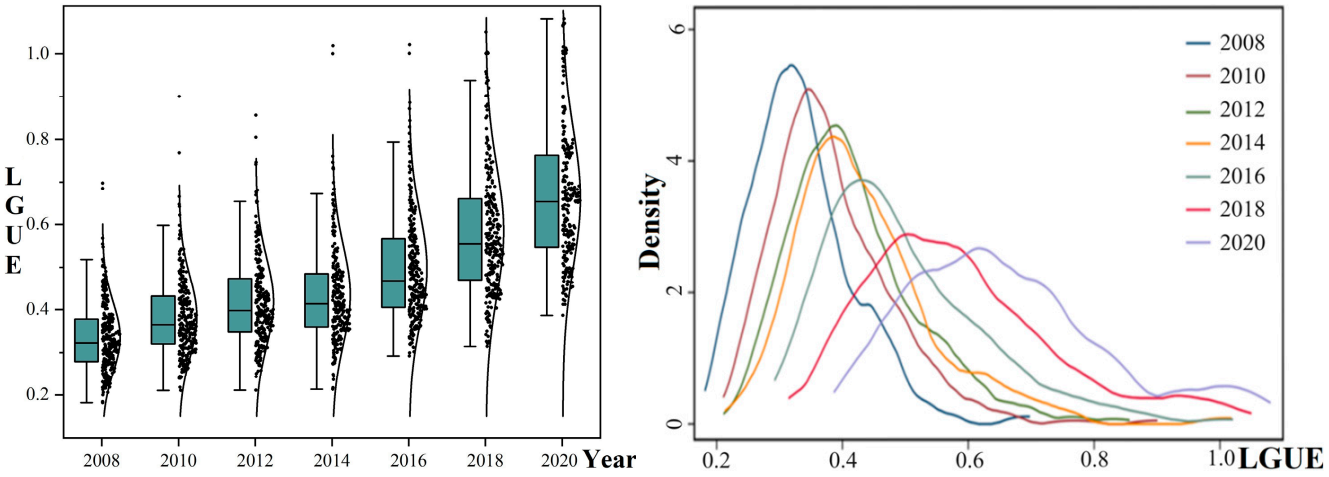


Figure 4. Time series evolution characteristics of LGUE.

4.2. Spatiotemporal Correlation Characteristics of LGUE

Combined ArcGIS spatial analysis was performed in order to examine the spatiotemporal correlation characteristics of urban LGUE from 2008 to 2020. Overall, urban LGUE continued to improve during the study period, but it had strong spatiotemporal non-equilibrium distribution characteristics (Figure 5). Specifically, from 2008 to 2011, the LGUE of most cities was between 0.180–0.557, indicating that the extensive economic development model since the financial crisis has led to an imbalance in the land use structure and the inefficient use of land resources. In 2015, LGUE improved in most cities, but still had a strong hierarchical and gradient distribution structure. Among them, the LGUE in the eastern coastal areas was higher, while the LGUE in the central and western regions, represented by Shangluo, Jingdezhen, and Pingliang, was relatively low. In 2020, LGUE had changed significantly in most cities. In addition, LGUE in some cities in the northeast and western regions had increased rapidly. In recent years, the northeast and western regions have revitalized idle land, fully tapped the potential of existing land, and improved the intensity and efficiency of land use. Interestingly, although LGUE in the central region has also been on the rise, the increase has been

relatively small. On the one hand, the central region has undertaken most of the industrial transfers from the eastern region, which is not conducive to industrial upgrading and structural optimization; on the other hand, during the development and construction process, some cities excessively pursue economic benefits and ignore environmental and ecological benefits.

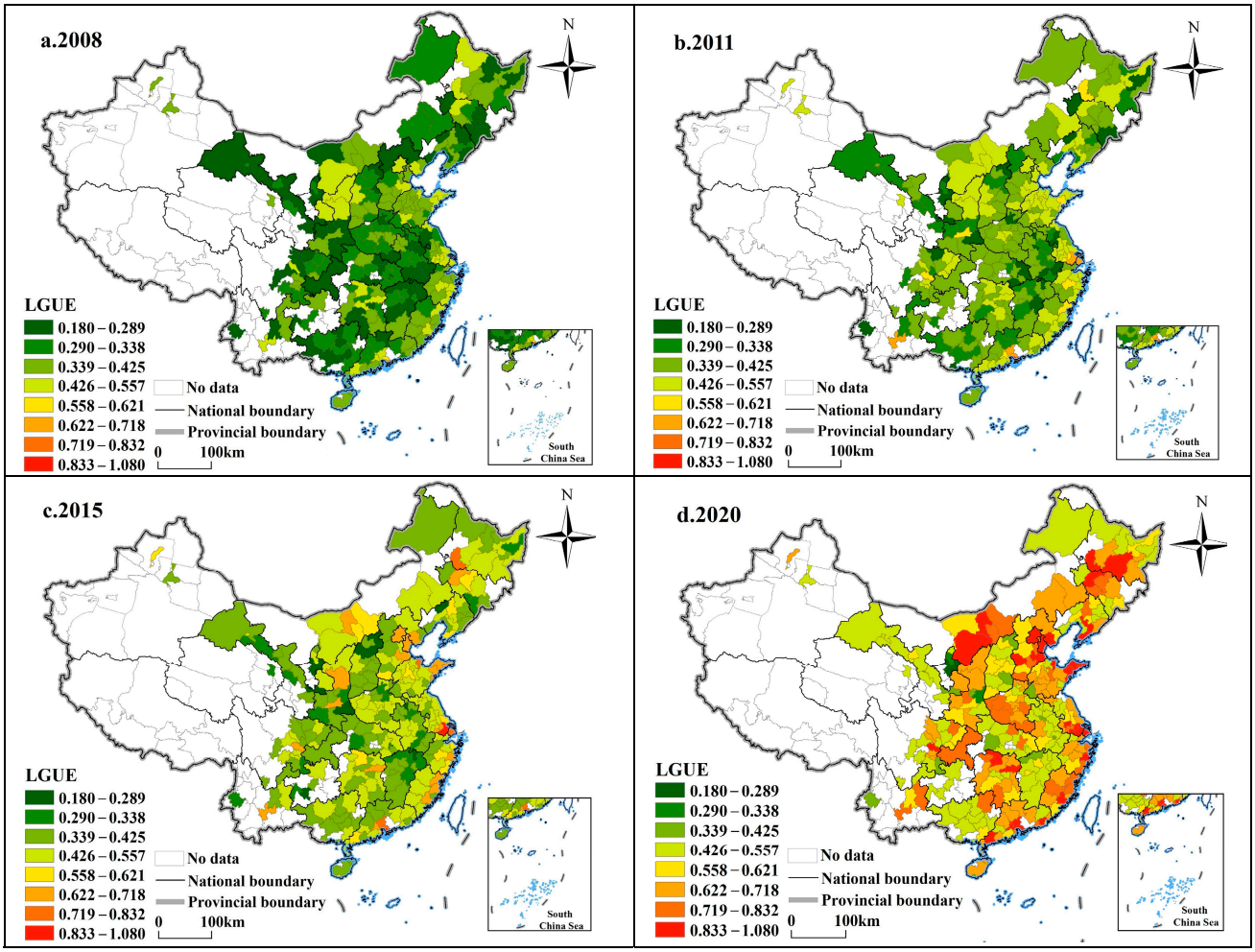


Figure 5. Spatial distribution characteristics of LGUE. (**a**) Spatial pattern of LGUE in 2008; (**b**) spatial pattern of LGUE in 2012; (**c**) spatial pattern of LGUE in 2016; and (**d**) spatial pattern of LGUE in 2020.

Based on the GeoDa1.14 analysis software and global Moran's I, this study explores the spatial autocorrelation characteristics of urban LGUE from 2008 to 2020 (Figure 6). During the study period, the global Moran's I of LGUE fluctuated between 0.4179~0.4343 (p = 0.001), indicating that LGUE has strong spatial dependence characteristics. On the one hand, the geographical environment, topography, and other natural conditions of geographically adjacent cities are relatively similar, resulting in their land types and land quality being basically the same. On the other hand, cities with similar economies and industries have relatively consistent land use structures and intensity, resulting in LGUE having strong spatial autocorrelation characteristics. Therefore, only by continuously narrowing the gap in economic and industrial development and promoting the free flow of factors can we accelerate the spatial connection between cities of different levels and promote the efficient and coordinated development of LGUE.

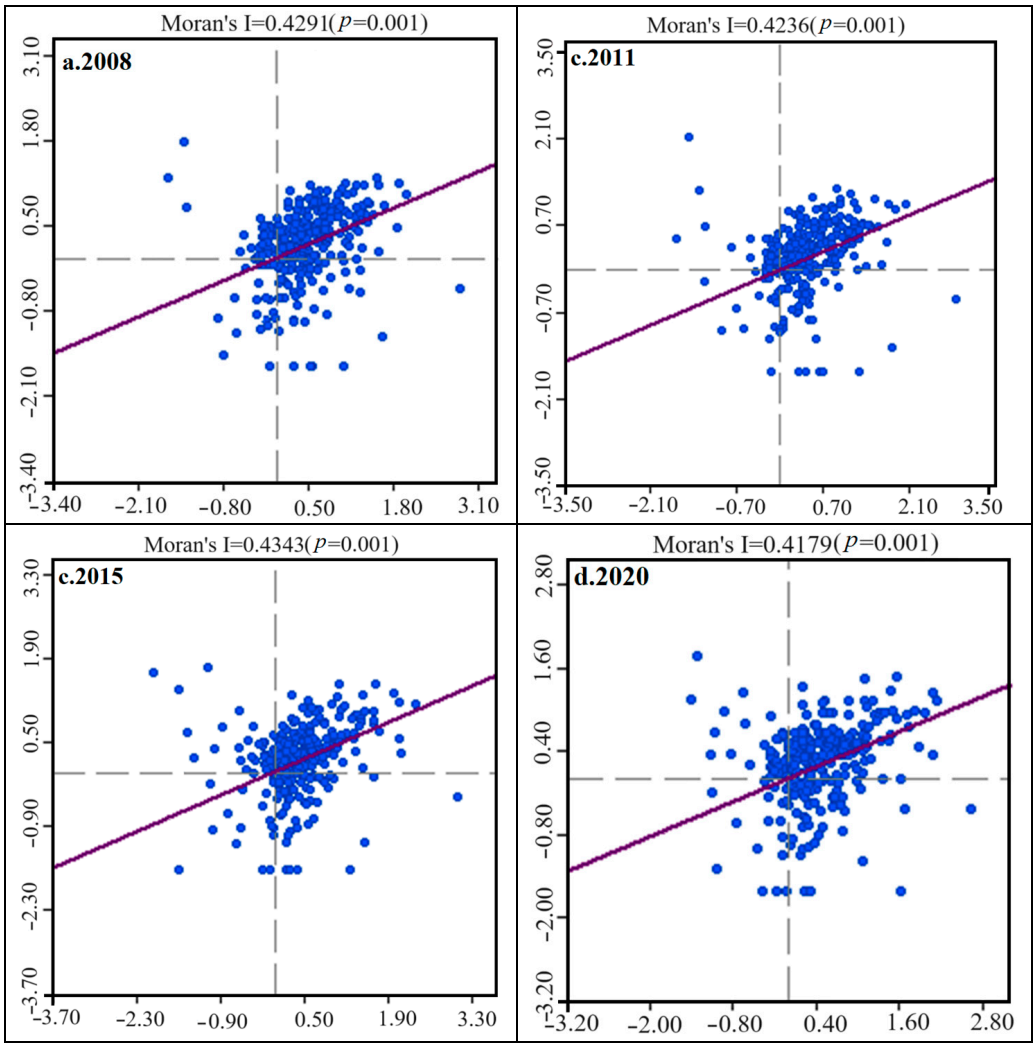


Figure 6. Global Moran's I of LGUE.

5. Empirical Analysis

5.1. Model Testing

A series of tests was needed before model evaluation to determine which spatial econometric model was more suitable for this study [58]. The results showed that under the asymmetric economic distance matrix, both LM and Robust-LM were statistically significant at the 1% level. However, both the LR test and the Wald test rejected the hypothesis that the SDM will degrade the SLM and the SEM. Meanwhile, the Hausman statistic value was 387.3833, indicating that SDM with fixed effects has stronger explanatory power (Table 4).

Table 4. Model testing.

Testing Method	*W1*	Testing Method	*W1*
LM-spatial lag	1123.347 ***	Wald-spatial lag	38.382 ***
R-LM-spatial lag	489.283 ***	LR-spatial lag	27.332 ***
LM-spatial error	389.982 ***	Wald	38.862 ***
R-LM-spatial error	18.663 ***	LR-spatial error	22.386 ***

Note: *** $p < 0.01$.

5.2. Baseline Regression Results

Table 5 reports the estimation results of the traditional panel model and SDM, respectively. The R^2 of the traditional panel model is relatively small, and the coefficients and significance levels of each variable are different from the SDM, indicating that ignoring spatial factors may lead to biased

estimates. In addition, we found that the log-likelihood (*Log-L*) and R^2 of the space-time fixed effects model are both larger than the time and space fixed effects models, indicating that the SDM fitting effect under the space-time fixed effects is better.

Table 5. Baseline regression results.

Explanatory Variables	Traditional Panel Model	Fixed Effect SDM		
		Space-Time Fixed	Space Fixed	Time Fixed
UE	−0.0937 (−0.9974)	0.036 *** (2.7798)	0.0372 *** (2.8772)	−0.5371 *** (−5.9611)
UE^2	−0.0046 (−0.1518)	−0.0954 ** (−2.2267)	−0.0975 ** (−2.2932)	0.1544 *** (5.1149)
IND	0.0300 *** (10.5605)	−0.0429 *** (−8.9015)	−0.0470 *** (−9.1685)	0.0244 *** (9.2188)
ER	0.0416 *** (44.6848)	0.0122 *** (20.4637)	0.0217 *** (21.0959)	0.0271 *** (28.2003)
FIS	0.0363 *** (8.6734)	0.0303 *** (6.6888)	0.0315 *** (7.0187)	−0.0469 *** (−9.4781)
FDI	0.0014 (1.0852)	0.0021 *** (2.9796)	0.0012 ** (2.2074)	0.0003 (0.2845)
TEC	−0.0246 *** (−7.7982)	0.0032 (0.8086)	0.0060 (1.0026)	−0.0108 *** (−3.1386)
WX	YES	YES	YES	YES
δ	—	0.4539 ***	0.6199 ***	0.4489 ***
R^2	0.6912	0.8928	0.8922	0.6179
$sigma^2$	—	0.0023	0.0023	0.0082
Log-L	—	5354.1495	5209.1919	2930.3667

Notes: ** $p < 0.05$, *** $p < 0.01$.

The results show that the coefficients of urban expansion and its square term are 0.036 and −0.0954, respectively, and pass the significance test at the 1% level, indicating that urban expansion and LGUE have a significant inverted U-shaped relationship. In other words, excessive urban expansion will have significant negative spatial effects on LGUE. On the one hand, reasonable urban expansion can effectively alleviate urban traffic congestion and over-concentration of functions, avoid the waste and idleness of land resources, and inject new vitality into sustainable urban development. On the other hand, reasonable urban expansion can change the land use structure and development type and promote economic and technological development, thereby increasing the added value and economic benefits of land use. Similar studies have proven that in the process of urban expansion, multi-functional agglomeration areas are formed, and urban operation efficiency and comprehensive competitiveness are improved [31]. However, some cities use "land finance" in exchange for extensive economic growth and the relief of financial pressure, leading to "leapfrog development" and the blind expansion of urban space. In particular, rapid urbanization has intensified resource consumption, environmental pollution, and social conflicts, and has had a strong negative impact on economic and social development and LGUE. Therefore, local governments must be wary of the blind expansion of urban land, strengthen land resource development and spatial planning, and create an efficient and intensive economic and industrial development model to achieve "smart growth".

5.3. Spatial Spillover Effects

Based on partial differential equations, this study further decomposes spatial effects into direct effects and spillover effects (Table 6). The results show that when urban expansion increases by 1%, the LGUE of local cities increases by 0.0287%, while the LGUE of neighboring cities decreases by 0.0457%. The spatial spillover effects of the square term of urban expansion on LGUE in local and neighboring cities were −0.0673% and 0.2283%, respectively, and both passed the significance test. The essence of urban spatial expansion is the transformation of lifestyles and production methods.

For local cities, reasonable urban expansion can optimize the industrial structure, revitalize existing land, reduce the disadvantages of insufficient public services and limited infrastructure capacity, and create a more perfect development environment. However, excessive urban expansion not only increases energy consumption and pollutant emissions, but also causes misallocation of land resources and extensive development. For neighboring cities, local urban expansion may produce a certain "siphon effect", resulting in the transfer of capital, industry, and technology from neighboring cities to local cities, thus weakening their economic development efficiency and land use intensity. It is worth noting that this study found that further expansion of local cities has a strong positive spatial spillover effect on neighboring cities. According to the polarized trickle-down effect, the economic radiation capacity generated by local urban expansion accelerates the diffusion of factors such as technology, industry, and capital, which is conducive to narrowing the development gap between cities and promoting the industrial upgrading and economic development of neighboring cities. In fact, to strengthen economic exchanges and industrial complementarity between cities and optimize spatial layout, a number of "satellite cities" are often distributed around core or developed cities.

Table 6. Spatial spillover effects.

Explanatory Variables	*UE*	UE^2	*IND*	*ER*	*FIS*	*FDI*	*TEC*
Direct effect	0.0287 *** (4.8737)	−0.0673 ** (−2.2344)	−0.0463 *** (8.5534)	0.0265 *** (17.6633)	0.0245 *** (5.8448)	0.0011 *** (2.5372)	0.0039 (0.8730)
Spillover Effect	−0.0457 *** (−3.3385)	0.2283 *** (2.6495)	−0.0212 ** (−2.237)	0.0055 *** (2.8444)	−0.0020 (−0.1235)	0.0034 * (1.6719)	0.0025 (1.2184)
Total effect	−0.0218 * (−1.8930)	0.1271 ** (1.9609)	−0.0535 *** (−4.5644)	0.0453 *** (8.8654)	0.0784 ** (2.2487)	0.0036 *** (2.4287)	0.0004 (0.5156)

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 6 reports the spatial spillover effects of each control variable on LGUE. Specifically, industrial agglomeration has a significant negative effect on LGUE in both local and neighboring cities. Although industrial agglomeration has strong "scale effects" and "technological spillover effects", the current level of industrial agglomeration in most cities in China is low, which may aggravate resource consumption and pollutant emissions, resulting in "diseconomies of scale". Environmental regulations significantly increase the LGUE of local and neighboring cities, which is consistent with the expectations of this study. This is mainly because proper environmental regulation can effectively force enterprises to carry out technological innovation and industrial structure adjustment, and promote the coordinated development of economy and environment, which proves the applicability of the "Porter hypothesis" to some extent. Fiscal spending significantly increases the LGUE of local cities. This is mainly because fiscal expenditure can provide financial guarantees in environmental protection, infrastructure construction, and other aspects, and can effectively expand the value of land development and utilization. The direct and spillover effects of foreign direct investment on LGUE are both significantly positive, indicating that foreign investment does not form a "pollution paradise" effect, but instead increases LGUE to a certain extent. The spatial effect of technological innovation on LGUE is positive, but it fails the significance test, indicating that technological innovation at the current stage has not significantly improved LGUE.

5.4. Spatiotemporal Heterogeneity Effect

This study uses the GTWR model to reveal the spatiotemporal heterogeneity effects across three time periods: 2008–2011, 2012–2015, and 2016–2020 (Figure 7). Figure 7a–c show that urban expansion had a significant positive spatial effect on LGUE in the northeastern and central and western regions from 2008 to 2020, but had a certain negative spatial effect on the Yangtze River Delta and Pearl River Delta urban agglomerations. As China's old industrial base, appropriate urban expansion in Northeast China can optimize the industrial structure and functional layout, promote "urban renewal", and accelerate economic and industrial development. However, the current spatial development policies in developed regions such as the Yangtze River Delta have not significantly improved the efficiency of resource allocation nor increased income per unit land area. In particular, the population and industries in some cities are highly concentrated, which has not brought obvious economies of scale and spillover effects; on the contrary, it has intensified the concentrated discharge

of pollutants and vicious competition, and weakened the vitality of economic development and green total factor productivity to some extent.

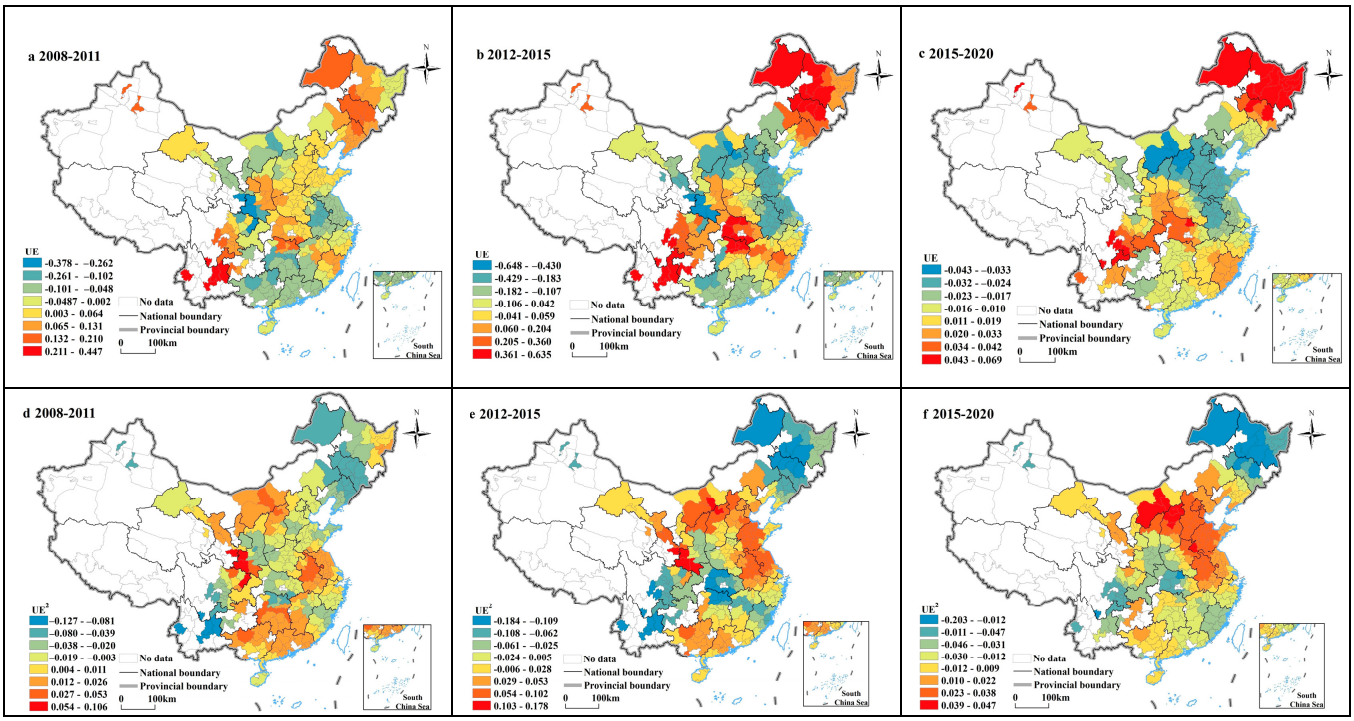


Figure 7. Spatiotemporal heterogeneity effects.

Figure 7d–f show that the square term of urban expansion from 2008 to 2020 has had a strong negative effect on LGUE in the northeastern and central and western regions, but the opposite is true for the Yangtze River Delta and the Pearl River Delta. This is mainly because due to the influence of geographical location, historical development, and resource distribution, the economic factors in the central and western regions are relatively scattered, and the ecological environment is fragile. Excessive urban expansion will lead to resource shortages, environmental damage, and energy consumption, which is not conducive to the coordinated and efficient development of the economy and the environment. However, the population and industry in developed cities are highly concentrated. Appropriate expansion of urban space can expand the scale of economic development, optimize the efficiency of land resource allocation, and promote the flow of resource elements within a larger spatial scope. In fact, in a period of rapid population and industrial development, developed cities such as Shanghai, Tokyo, New York, and London all increase their population and economic carrying capacity and enhance regional comprehensive competitiveness through urban expansion. Therefore, urban space development is not an excessive superposition of resource elements, but promotes the adaptation of land resources and economic industry development, and accelerates the coordinated and symbiotic development of "land-economy-ecology".

5.5. The Theoretical Analysis Framework of Urban Expansion on LGUE

Understanding how to correctly handle the relationship between regional development, resources, and environment and construct the concept of green land development is key to achieving coordinated and sustainable development of ecological, social, and economic systems. Through the above detailed analysis, this study systematically constructs the theoretical analysis framework of the spatiotemporal effect of urban expansion on LGUE (Figure 8). There is no doubt that urban expansion is a "double-edged sword" that affects LGUE through multiple effects. In terms of positive effects, reasonable urban expansion can transform land use types and structures, expand the scale effect of environmental governance, and promote industrial upgrading and economic development. In terms of negative effects, excessive urban expansion encroaches on green space, and changes regional climates, urban hydrology, soil physical and chemical properties, etc., exacerbating ecological damage and the misallocation of land resources. In addition, excessive urban expansion has also led to a series of social and environmental problems, such as the decline of central urban areas, disordered

spatial expansion, and extensive economic development, which is not conducive to sustainable urban development and efficient use of land resources. In terms of spillover effects, on the one hand, urban expansion has certain radiation effects, multiplier effects, and allocation effects, which can promote the spatial optimization and rational combination of resource elements and significantly improve the LGUE of neighboring cities. On the other hand, excessive expansion of urban space may also produce strong siphon effects and resource misallocation effects, thereby producing strong negative spillover effects on LGUE in neighboring cities. Therefore, local governments must adjust urban spatial expansion strategies according to local conditions, reasonably determine the scale and development boundaries of urban land, and fully release the comprehensive potential of green utilization of land resources through "smart growth".

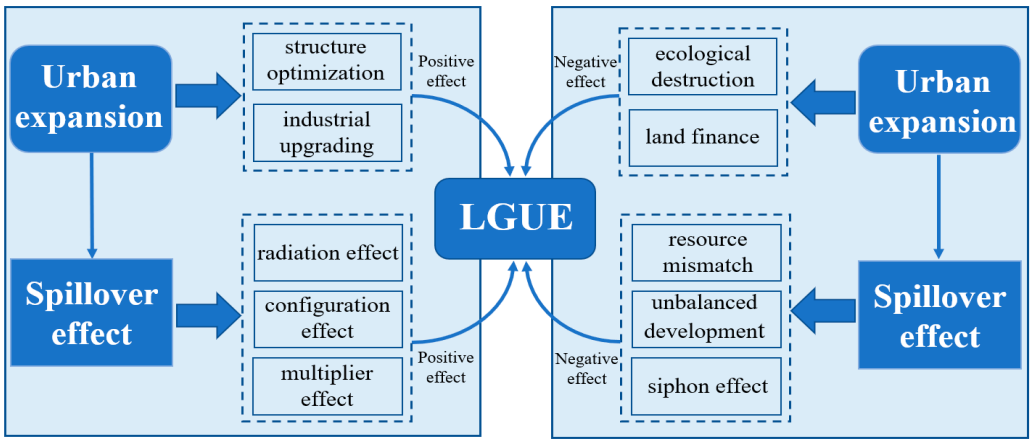


Figure 8. The theoretical analysis framework of urban expansion on LGUE.

6. Discussion

The green and efficient use of land resources is an important support for, and fundamental source of, ecological civilization construction. Under the concept of regional green and high-quality development, revealing the evolutionary pattern and driving factors of LGUE is the key to reasonably determining the scale of urban land and releasing the comprehensive potential of land use. First, this study found that LGUE in Chinese cities is generally low, and has an obvious gradient distribution structure. This finding is similar to Liu et al. [15], who combined the DEA model and found that LGUE in Chinese cities presents a strong circle distribution structure. However, we used the undesirable EBM-DEA model that can solve both radial and non-radial input-output problems, avoiding subjective weighting and human interference, and improving the accuracy of urban LGUE measurement results. In addition, we also found that LGUE in Chinese cities has increased over time, that the absolute difference in LGUE between cities has continued to shrink, and that the degree of coordinated and efficient use of land resources has gradually increased, which was consistent with our expectations. Similarly, Zhong et al. [17] showed that land use efficiency in the Yangtze River Delta urban agglomeration shows a gradually increasing trend, and that the imbalance and underutilization of land resources has been effectively alleviated. In recent years, the Chinese government has adjusted the industrial structure, accelerated green and high-quality development, and alleviated the extensive and inefficient use of land resources by formulating scientific urban spatial planning and transforming land use types.

Secondly, this study proves that there is a strong nonlinear relationship between urban expansion and LGUE, which is different from the existing studies. Most previous studies believe that urban expansion has multiple impacts on LGUE. In terms of positive effects, Fallah et al. [54] argue that urban expansion improves urban production efficiency and total factor productivity. Based on the Super-SBM model and spatial econometric model, Ma et al. [42] found that urban expansion accelerates the transformation and development of economic industry and significantly improves LGUE. Halder et al. [59] argued that due to economic development and financial pressure, some cities have implemented "land enclosure movements" and blindly expanded urban spatial boundaries, resulting in serious environmental damage, spatial fragmentation, and social conflicts. In terms of negative effects, Koroso et al. [14] have demonstrated that blind urban expansion has significantly reduced urban land use efficiency since Ethiopia implemented its urban land leasing policy in 1993. Lu et al. [12] believe that urban expansion leads to the dispersion of production and living space, which

is not conducive to the green and efficient use of land resources, and which inhibits urban LGUE to a certain extent. This study found a strong inverted U-shaped relationship between urban expansion and LGUE; that is, appropriate urban expansion can optimize industrial division of labor, transform land use types and structures, and thereby improve LGUE. However, excessive urban expansion has a significant negative impact on LGUE. Obviously, this study uses long-term nighttime light data and spatial econometric models to more comprehensively consider the nonlinear relationship between urban expansion and LGUE, providing new ideas and new horizons for subsequent research.

Third, in terms of spillover effect, urban expansion inhibits LGUE in local cities, but further urban expansion has significant positive spillover effect on LGUE in neighboring cities, which is different from the existing studies. Existing research mainly examines the relationship between urban expansion and LGUE, but often ignores its spatial spillover effects [60]. In fact, with the gradual improvement of research and the application of spatial econometric models, more scholars have realized that LGUE between cities is interdependent, and LGUE in developed cities has a significant impact on underdeveloped cities and small and medium-sized cities [61]. However, traditional non-spatial econometric models only consider the driving factors of urban LGUE and ignore the spatial spillover effects. Obviously, in the context of regional integrated development, local urban expansion may produce certain polarization effects and radiation effects, which will have varying degrees of impact on LGUE in neighboring cities. Therefore, as the connections between cities gradually deepen, considering the spatial spillover effects of urban expansion on LGUE in local and neighboring cities can better reflect the actual development situation.

Finally, urban expansion has significant spatiotemporal heterogeneous effects on LGUE, which supports the view of Chakraborty et al. [2], who believe that the impact of urban expansion on land use efficiency varies depending on city size. Similarly, He et al. [62] used a spatial regression model to prove that the impact of urban spatial fragmentation and spatial density on urban land use efficiency has strong spatial scale differences. However, most previous studies regard LGUE as an undifferentiated unit, which easily ignores the differences in urban LGUE and makes it difficult to explore the impact of urban expansion on LGUE from the urban individual level. In fact, every city has its own unique social, economic, cultural, and geographical characteristics. Regression analysis of cities as separate individuals can more accurately capture the spatiotemporal effects of urban expansion on LGUE, which helps to formulate more reasonable urban expansion and land use policies. This study uses the GTWR model to perform regression analysis on each city as a separate individual, which can more intuitively and carefully examine the spatiotemporal heterogeneous effects of urban expansion on LGUE.

7. Conclusions and Policy Implications

7.1. Conclusions

This study integrates multisource data and spatial econometric models to explore the evolutionary characteristics of LGUE and the spatiotemporal effects of urban expansion on LGUE. This study draws the following conclusions:

(1) During the study period, LGUE in Chinese cities had certain gradient distribution and spatial dependence characteristics, and the LGUE in some cities was generally low, indicating that structural imbalance and extensive abuse still exist in the land use process. However, the kernel density curve of LGUE gradually shifted to the right, and the peak value continues to decrease, reflecting that the absolute difference in LGUE between cities has gradually shrunk, and LGUE has increased, over time.

(2) The urban expansion coefficient and its square term are 0.0374 and −0.0834, respectively, both passing the significance test, indicating that there is a significant nonlinear relationship between urban expansion and LGUE; that is, appropriate urban expansion can optimize the industrial structure, improve the efficiency of land resource allocation, and achieve "smart growth" in cities. However, excessive urban expansion can lead to negative effects such as ecological damage, misallocation of land resources, and extensive development, inhibiting the efficient use of land resources.

(3) In terms of spatial spillover effect, for every 1% increase in urban expansion, the LGUE of the local city increases by 0.0287%, but the neighboring city decreases by 0.0457%; for every 1% increase in the square term of urban expansion, the LGUE of the local city decreases by 0.0673%, while that of neighboring cities increases by 0.2283%. In terms of spatiotemporal heterogeneity effects, the population, economy, and industry in the Yangtze River Delta and Pearl River Delta are more concentrated, enabling the carrying out of "urban renewal" through urban expansion and promoting the efficient use of urban land resources. However, the northeastern and central and western regions

must strictly abide by land use red lines, reasonably determine urban development boundaries according to local conditions, and fully release the comprehensive efficiency of green land use.

7.2. Policy Implications

In the context of "land finance" and large-scale urbanization, it has certain theoretical foundation and practical significance to explore the dynamic evolution characteristics of LGUE and the spatiotemporal effects of urban expansion on LGUE. The main policy implications of this study are as follows:

(1) Transform the land use structure, optimize the layout of construction land, and promote the coordinated and efficient development of land resources. Currently, China's LGUE has certain gradient distribution and spatiotemporal differentiation characteristics. China's eastern coastal areas have strong talent, policy, location, and technological advantages that can promote the transformation of land use from resource-driven to innovation-driven. However, misallocation of land resources, irrational supply, and extensive utilization of land resources in the central and western regions have resulted in overall low LGUE, which has been detrimental to the coordinated and efficient development of regional land resources in the long run. In the future, it is necessary to further optimize resource allocation, accelerate the adjustment of land use structure and industrial upgrading in the central and western regions, increase the intensity of land use through the agglomeration of factors, industries, talents, and funds, and control and reduce idle land from the source. Meanwhile, it is necessary to vigorously transform land use types, gradually eliminate "three-high" industries, accelerate the introduction of new energy, new materials, and other high-tech industries, and activate land use value and development efficiency.

(2) Expand the factor reallocation and resource optimization effects of urban expansion, and improve the comprehensive benefits of land resource utilization. This study demonstrates that urban expansion is a "double-edged sword". Reasonable urban expansion can adjust industrial layout and change the type and structure of land use, but excessive urban expansion will produce a series of negative effects. Therefore, it is necessary to formulate scientific and reasonable urban planning policies and clarify the direction of urban development, spatial layout, and functional positioning. Meanwhile, local governments should expand the multiplier effect and resource allocation effect of urban expansion, improve the level and quality of industrial development, optimize urban management level and operational efficiency, continuously strengthen cooperation and exchanges with surrounding cities, and achieve resource sharing and complementary advantages. In addition, during the process of urban expansion, ecological land loss, air pollution, water environment pollution, and the urban heat island effect must be fully considered to avoid damage to the natural environment.

(3) Design differentiated spatial expansion strategies based on local conditions to promote "smart growth" in cities. This study shows that resource elements in developed cities are overconcentrated, and urban expansion can relieve urban operating pressure, promote the flow of population, capital, technology, and other elements within a larger time and space range, and improve the efficiency of resource allocation. However, in the context of unbalanced regional development, the population and industries in the central, western, and northeast regions are rapidly losing ground, and excessive urban expansion not only reduces the intensity of land use, but also may lead to serious ecological damage and spatial fragmentation. Therefore, developed cities can construct multifunctional and multi-center spatial structures through urban expansion and functional transfer to relieve urban operating pressure and achieve optimal combination and rational allocation of resource elements. However, cities in the central, western, and northeastern regions must strictly control spatial growth boundaries, tap existing land potential, introduce market competition mechanisms, and increase the intensity of land development and utilization to achieve "smart growth". In addition, local governments should adhere to market orientation, standardize the land transfer system, achieve transparent land market operations, and avoid rent-seeking space and "corruption".

Overall, this study has certain scientific guiding significance for improving LGUE and promoting regional sustainable development, but it still has shortcomings. On the one hand, LGUE has rich connotations and covers a wide range of aspects. Understanding of how to integrate multiple factors and subjects such as economy, environment, and society to scientifically and accurately measure LGUE needs to be improved. On the other hand, this study mainly explores the spatiotemporal effects of urban expansion on LGUE, but its internal mechanism is still worthy of in-depth exploration. Furthermore, in the context of green and low-carbon development, carbon emissions are one of the most important undesirable outputs of urban expansion. For example, Ou et al. [63] demonstrated that rapid urbanization has led to drastic changes in the type and intensity of land use, which has become an important source of carbon emissions in developing countries. This study mainly explores

LGUE, that is, under certain production technology conditions, smaller land factor inputs are used to obtain optimal green economic benefits while reducing undesirable outputs such as ecological damage and environmental pollution. Therefore, we include sulfur dioxide, wastewater, and PM2.5 as undesirable outputs of this study. However, considering the harmfulness of rising carbon emission concentrations, it is necessary to incorporate carbon emissions into the super-efficiency EBM-DEA model in the future, so as to measure urban LGUE more scientifically.

Author Contributions: Conceptualization, Z.D. and F.Z.; methodology, J.H. and Y.Z.; formal analysis, Z.D. and Y.Z.; writing—review and editing, Z.D. and Y.Z.; visualization, Z.D and F.X.; supervision, F.Z. and Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the National Natural Science Foundation of China (Grant No. 31872230), and the Anhui Normal University Research Fund (Grant No. 762370).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Xia, S.; Han, J.; Li, A.; Ye, P.; Zhang, H. Impact of Free Trade (Pilot) Zone Establishment on Urban Land Use Efficiency—Empirical Evidence from Cities in China. *Land* **2024**, *13*, 969. [CrossRef]
2. Chakraborty, S.; Maity, I.; Dadashpoor, H.; Novotnỳ, J.; Banerji, S. Building in or out? Examining urban expansion patterns and land use efficiency across the global sample of 466 cities with million+ inhabitants. *Habitat Int.* **2022**, *120*, 102503. [CrossRef]
3. Yang, D.; Luan, W. Spatial-temporal patterns of urban land use efficiency in China's national special economic parks. *Ecol. Indic.* **2024**, *163*, 111959. [CrossRef]
4. Nwokolo, S.C.; Proutsos, N.; Meyer, E.L.; Ahia, C.C. Machine learning and physics-based hybridization models for evaluation of the effects of climate change and urban expansion on photosynthetically active radiation. *Atmosphere* **2023**, *14*, 687. [CrossRef]
5. Kosma, M.; Laita, A.; Duflot, R. No net loss of connectivity: Conserving habitat networks in the context of urban expansion. *Landsc. Urban Plan.* **2023**, *239*, 104847. [CrossRef]
6. Zhou, G.; Xu, H.; Jiang, C.; Deng, S.; Chen, L.; Zhang, Z. Has the Digital Economy Improved the Urban Land Green Use Efficiency? Evidence from the National Big Data Comprehensive Pilot Zone Policy. *Land* **2024**, *13*, 960. [CrossRef]
7. Chen, Q.; Zheng, L.; Wang, Y.; Wu, D.; Li, J. A comparative study on urban land use eco-efficiency of Yangtze and Yellow rivers in China: From the perspective of spatiotemporal heterogeneity, spatial transition and driving factors. *Ecol. Indic.* **2023**, *151*, 110331. [CrossRef]
8. Wang, Z.; Fu, H.; Liu, H.; Liao, C. Urban development sustainability, industrial structure adjustment, and land use efficiency in China. *Sustain. Cities Soc.* **2023**, *89*, 104338. [CrossRef]
9. Zhou, C.; Wang, J.; Wu, Z. Impact of China's Energy-Consuming Right Trading on Urban Land Green Utilization Efficiency. *Land* **2024**, *13*, 729. [CrossRef]
10. Tan, S.; Hu, B.; Kuang, B.; Zhou, M. Regional differences and dynamic evolution of urban land green use efficiency within the Yangtze River Delta, China. *Land Use Policy* **2021**, *106*, 105449. [CrossRef]
11. Li, G.; Fang, C.; Li, Y.; Wang, Z.; Sun, S.; He, S.; Qi, W.; Bao, C.; Ma, H.; Fan, Y.; et al. Global impacts of future urban expansion on terrestrial vertebrate diversity. *Nat. Commun.* **2022**, *13*, 1628. [CrossRef]
12. Lu, X.H.; Tao, X.Q.; Kuang, B.; Tang, Y.F.; Wang, M.C. Environmental assessment, environmental attention of government and green utilization efficiency of urban land. *China Land Sci.* **2023**, *37*, 104–112.
13. Xie, H.; Chen, Q.; Lu, F.; Wang, W.; Yao, G.; Yu, J. Spatial-temporal disparities and influencing factors of total-factor green use efficiency of industrial land in China. *J. Clean. Prod.* **2019**, *207*, 1047–1058. [CrossRef]
14. Koroso, N.H.; Zevenbergen, J.A.; Lengoiboni, M. Urban land use efficiency in Ethiopia: An assessment of urban land use sustainability in Addis Ababa. *Land Use Policy* **2020**, *99*, 105081. [CrossRef]
15. Liu, C.; Zhao, G. Convergence analysis of Chinese urban green land-use efficiency. *Environ. Sci. Pollut. Res.* **2022**, *29*, 89469–89484. [CrossRef]
16. Li, W.; Cai, Z.; Jin, L. Urban green land use efficiency of resource-based cities in China: Multidimensional measurements, spatial-temporal changes, and driving factors. *Sustain. Cities Soc.* **2024**, *104*, 105299. [CrossRef]
17. Zhong, S.; Li, X.; Ma, J. Impacts of land finance on green land use efficiency in the Yangtze River Economic Belt: A spatial econometrics analysis. *Environ. Sci. Pollut. Res.* **2022**, *29*, 56004–56022. [CrossRef]
18. Moschetto, F.A.; Ribeiro, R.B.; De Freitas, D.M. Urban expansion, regeneration and socioenvironmental vulnerability in a mangrove ecosystem at the southeast coastal of São Paulo, Brazil. *Ocean Coast. Manag.* **2021**, *200*, 105418. [CrossRef]
19. Wang, Z.; Wang, L.; Zhao, B.; Pei, Q. Analysis of Spatiotemporal Interaction Characteristics and Decoupling Effects of Urban Expansion in the Central Plains Urban Agglomeration. *Land* **2023**, *12*, 772. [CrossRef]

20. Xiong, H.; Ma, C.; Li, M.; Tan, J.; Wang, Y. Landslide susceptibility prediction considering land use change and human activity: A case study under rapid urban expansion and afforestation in China. *Sci. Total Environ.* **2023**, *866*, 161430. [CrossRef]
21. Zeng, J.; Cui, X.; Chen, W.; Yao, X. Impact of urban expansion on the supply-demand balance of ecosystem services: An analysis of prefecture-level cities in China. *Environ. Impact Assess.* **2023**, *99*, 107003. [CrossRef]
22. Jing, S.; Yan, Y.; Niu, F.; Song, W. Urban expansion in China: Spatiotemporal dynamics and determinants. *Land* **2022**, *11*, 356. [CrossRef]
23. Nor, A.N.M.; Corstanje, R.; Harris, J.A.; Brewer, T. Impact of rapid urban expansion on green space structure. *Ecol. Indic.* **2017**, *81*, 274–284. [CrossRef]
24. Rustiadi, E.; Pravitasari, A.E.; Setiawan, Y.; Mulya, S.P.; Pribadi, D.O.; Tsutsumida, N. Impact of continuous Jakarta megacity urban expansion on the formation of the Jakarta-Bandung conurbation over the rice farm regions. *Cities* **2021**, *111*, 103000. [CrossRef]
25. Huang, C.; Xu, N. Quantifying urban expansion from 1985 to 2018 in large cities worldwide. *Geocarto Int.* **2022**, *37*, 18356–18371. [CrossRef]
26. Xie, X.; Fang, B.; Xu, H.; He, S.; Li, X. Study on the coordinated relationship between Urban Land use efficiency and ecosystem health in China. *Land Use Policy* **2021**, *102*, 105235. [CrossRef]
27. Rimal, B.; Sloan, S.; Keshtkar, H.; Sharma, R.; Rijal, S.; Shrestha, U.B. Patterns of historical and future urban expansion in Nepal. *Remote Sens.* **2020**, *12*, 628. [CrossRef]
28. Chu, M.; Lu, J.; Sun, D. Influence of urban agglomeration expansion on fragmentation of green space: A case study of Beijing-Tianjin-Hebei urban agglomeration. *Land* **2022**, *11*, 275. [CrossRef]
29. Tian, S.; Wu, W.; Shen, Z.; Wang, J.; Liu, X.; Li, L.; Li, X.; Liu, X.; Chen, H. A cross-scale study on the relationship between urban expansion and ecosystem services in China. *J. Environ. Manag.* **2022**, *319*, 115774. [CrossRef]
30. Basu, T.; Das, A.; Das, K.; Pereira, P. Urban expansion induced loss of natural vegetation cover and ecosystem service values: A scenario-based study in the siliguri municipal corporation (Gateway of North-East India). *Land Use Policy* **2023**, *132*, 106838. [CrossRef]
31. Liu, X.; Xu, H.; Zhang, M. The effects of urban expansion on carbon emissions: Based on the spatial interaction and transmission mechanism. *J. Clean. Prod.* **2024**, *434*, 140019. [CrossRef]
32. Yang, Y.; Nan, Y.; Liu, Z.; Zhang, D.; Sun, Y. Direct and indirect losses of natural habitat caused by future urban expansion in the transnational area of Changbai Mountain. *Sustain. Cities Soc.* **2020**, *63*, 102487. [CrossRef]
33. Yang, K.; Sun, W.; Luo, Y.; Zhao, L. Impact of urban expansion on vegetation: The case of China (2000–2018). *J. Environ. Manag.* **2021**, *291*, 112598. [CrossRef] [PubMed]
34. Mahtta, R.; Fragkias, M.; Güneralp, B.; Mahendra, A.; Reba, M.; Wentz, E.A.; Seto, K.C. Urban land expansion: The role of population and economic growth for 300+ cities. *Npj Urban Sustain.* **2022**, *2*, 5. [CrossRef]
35. Wei, G.; He, B.J.; Sun, P.; Liu, Y.; Li, R.; Ouyang, X.; Luo, K.; Li, S. Evolutionary trends of urban expansion and its sustainable development: Evidence from 80 representative cities in the belt and road initiative region. *Cities* **2023**, *138*, 104353. [CrossRef]
36. Han, S.S. Urban expansion in contemporary China: What can we learn from a small town? *Land Use Policy* **2010**, *27*, 780–787. [CrossRef]
37. Wang, S.; Luo, X. The evolution of government behaviors and urban expansion in Shanghai. *Land Use Policy* **2022**, *114*, 105973.
38. Puplampu, D.A.; Boafo, Y.A. Exploring the impacts of urban expansion on green spaces availability and delivery of ecosystem services in the Accra metropolis. *Environ. Chall.* **2021**, *5*, 100283. [CrossRef]
39. Tian, P.; Li, J.; Cao, L.; Pu, R.; Wang, Z.; Zhang, H.; Chen, H.; Gong, H. Assessing spatiotemporal characteristics of urban heat islands from the perspective of an urban expansion and green infrastructure. *Sustain. Cities Soc.* **2021**, *74*, 103208. [CrossRef]
40. Fu, T.; Zhang, T. Whether urban boundary expansion can form a new driving force for economic growth: The case of some provincial capitals' boundary expansion. *Econ. Sci.* **2020**, *4*, 50–63.
41. Ma, D.; Zhang, J.; An, B.; Guo, Z.; Zhang, F.; Yan, Y.; Peng, G. Research on urban land green use efficiency and influencing factors based on DEA and ESTDA models: Taking 284 cities in China as an example. *Ecol. Indic.* **2024**, *160*, 111824. [CrossRef]
42. Levin, N.; Kyba, C.C.; Zhang, Q.; de Miguel, A.S.; Román, M.O.; Li, X.; Portnov, B.A.; Molthan, A.L.; Jechow, A.; Miller, S.D.; et al. Remote sensing of night lights: A review and an outlook for the future. *Remote Sens. Environ.* **2020**, *237*, 111443. [CrossRef]
43. Dong, H.; Li, R.; Li, J.; Li, S. Study on urban spatiotemporal expansion pattern of three first-class urban agglomerations in China derived from integrated DMSP-OLS and NPP-VIIRS nighttime light data. *J. Geo-Inf. Sci.* **2020**, *22*, 1161.
44. Li, X.; Zhou, Y.; Zhao, M.; Zhao, X. A harmonized global nighttime light dataset 1992–2018. *Sci. Data* **2020**, *7*, 168. [CrossRef] [PubMed]
45. Liao, Z.J.; Wang, L. Urban sprawl and high-quality economic development: The research of nighttime satellite light data in China. *Financ. Econ.* **2019**, *6*, 106–119.
46. Gao, X.; Zhang, A.; Sun, Z. How regional economic integration influence on urban land use efficiency? A case study of Wuhan metropolitan area, China. *Land Use Policy* **2020**, *90*, 104329. [CrossRef]
47. Zhang, J.; Zhang, P.; Liu, Y.; Lu, S.; Wu, G. An analysis of the spatiotemporal evolution and driving force of cultivated land green utilization in karst region of southwest China. *J. Clean. Prod.* **2024**, *434*, 140002. [CrossRef]
48. Wu, H.; Hao, Y.; Ren, S. How do environmental regulation and environmental decentralization affect green total factor energy efficiency: Evidence from China. *Energy Econ.* **2020**, *91*, 104880. [CrossRef]

49. Chen, Y.; Miao, J.; Zhu, Z. Measuring green total factor productivity of China's agricultural sector: A three-stage SBM-DEA model with non-point source pollution and CO_2 emissions. *China Econ. Rev.* **2021**, *318*, 128543. [CrossRef]
50. Zhang, Y.; Wang, T.; Ren, C.; Wang, L.; Zhang, K.; Song, R. Heterogeneous impacts and spillover effects of green innovation network and environmental regulation on water use efficiency: A spatiotemporal perspective from 269 cities in China. *Sustain. Cities Soc.* **2023**, *90*, 104361. [CrossRef]
51. Tone, K.; Tsutsui, M. An epsilon-based measure of efficiency in DEA e a third pole of technical efficiency. *Eur. J. Oper. Res.* **2010**, *207*, 1554–1563. [CrossRef]
52. Wang, H.; Cui, H.; Zhao, Q. Effect of green technology innovation on green total factor productivity in China: Evidence from spatial durbin model analysis. *J. Clean. Prod.* **2021**, *288*, 125624. [CrossRef]
53. Xie, R.; Fu, W.; Yao, S.; Zhang, Q. Effects of financial agglomeration on green total factor productivity in Chinese cities: Insights from an empirical spatial Durbin model. *Energy Econ.* **2021**, *101*, 105449. [CrossRef]
54. Elhorst, J.P. The dynamic general nesting spatial econometric model for spatial panels with common factors: Further raising the bar. *Rev. Reg. Res.* **2022**, *42*, 249–267. [CrossRef] [PubMed]
55. Shabrina, Z.; Buyuklieva, B.; Ng, M.K.M. Short-term rental platform in the urban tourism context: A geographically weighted regression (GWR) and a multiscale GWR (MGWR) approaches. *Geogr. Anal.* **2021**, *53*, 686–707. [CrossRef]
56. Wang, H.; Zhang, B.; Liu, Y.; Liu, Y.; Xu, S.; Zhao, Y.; Chen, Y.; Hong, S. Urban expansion patterns and their driving forces based on the center of gravity-GTWR model: A case study of the Beijing-Tianjin-Hebei urban agglomeration. *J. Geogr. Sci.* **2020**, *30*, 297–318. [CrossRef]
57. Zhao, M.; Wang, H.; Sun, J.; Tang, R.; Cai, B.; Song, X.; Huang, X.; Huang, J.; Fan, Z. Spatio-temporal characteristics of soil Cd pollution and its influencing factors: A Geographically and temporally weighted regression (GTWR) method. *J. Hazard. Mater.* **2023**, *446*, 130613. [CrossRef] [PubMed]
58. Myovella, G.; Karacuka, M.; Haucap, J. Determinants of digitalization and digital divide in Sub-Saharan African economies: A spatial Durbin analysis. *Telecommun. Policy* **2021**, *45*, 102224. [CrossRef]
59. Halder, B.; Haghbin, M.; Farooque, A.A. An assessment of urban expansion impacts on land transformation of Rajpur-Sonarpur Municipality. *Knowl.-Based Eng. Sci.* **2021**, *2*, 34–53. [CrossRef]
60. Koroso, N.H.; Lengoiboni, M.; Zevenbergen, J.A. Urbanization and urban land use efficiency: Evidence from regional and Addis Ababa satellite cities, Ethiopia. *Habitat Int.* **2021**, *117*, 102437. [CrossRef]
61. Zeng, L. The driving mechanism of urban land green use efficiency in China based on the EBM model with undesirable outputs and the spatial Dubin model. *Int. J. Environ. Res. Public Health* **2022**, *19*, 10748. [CrossRef] [PubMed]
62. He, S.; Yu, S.; Li, G.; Zhang, J. Exploring the influence of urban form on land-use efficiency from a spatiotemporal heterogeneity perspective: Evidence from 336 Chinese cities. *Land Use Policy* **2020**, *95*, 104576. [CrossRef]
63. Ou, Y.; Bao, Z.; Ng, S.; Song, W.; Chen, K. Land-use carbon emissions and built environment characteristics: A city-level quantitative analysis in emerging economies. *Land Use Policy* **2024**, *137*, 107019. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.