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Original Research

How Does Urban Green Development Affect Land Use Efficiency? Empirical Analysis Based on 285 Cities in China

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Abstract

Investigating the mechanism of urban green development on land use efficiency holds significant practical implications for enhancing land use efficiency in Chinese cities and achieving carbon neutrality goals. Based on panel data from 285 prefecture-level cities in China from 2005 to 2020, this paper employs the super-efficiency SBM model, panel cluster analysis, and spatial visualization methods to analyze the spatiotemporal evolution and spatial differences of land use efficiency and explore the impact mechanism of urban green development on land use efficiency. The study reveals that: (1) Urban green development significantly promotes the improvement of land use efficiency, and this conclusion remains robust after conducting sensitivity tests, such as using terrain undulation and river density as instrumental variables. (2) Mechanism analysis indicates that urban green development mainly enhances land use efficiency through agglomeration effects, technological effects, and structural effects. (3) The impact of urban green development on land use efficiency exhibits heterogeneity. Compared to the eastern region, the promotion effect of urban green development on land use efficiency in the western and central regions is more significant; compared to coastal cities, the influence of urban green development on inland cities is more pronounced.

Keywords: urban green development, land use efficiency, urban land use

Introduction

Land, as the material foundation for human survival and development, inherently demands efforts to enhance the efficiency of its utilization due to its scarcity. Urban land, as a crucial spatial carrier for economic, social, and environmental activities, directly impacts the socioeconomic development of cities. With the acceleration of urbanization, local governments gradually regard land as a vital tool for promoting economic and social development, forming a pattern of "development-oriented land use." In this context, the supply and demand situation of land and its functions have undergone profound changes. A large amount of land has been transformed into industrial land, leading to issues such as high resource consumption, high pollution emissions, and inefficient utilization in urban land use activities [1, 2]. Particularly in recent years, as China's economy has entered a "new normal," the development model that sacrifices land resources

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and damages the ecological environment is clearly no longer suitable for the requirements of high-quality development in the new stage. Therefore, improving the efficiency of land resource utilization has become an important choice for China's economic and social transformation. How to effectively improve land use efficiency and achieve more comprehensive benefits on a limited land area has become an urgent issue that needs to be addressed in China.

In 2021, the General Office of the Central Committee of the Communist Party of China and the General Office of the State Council issued "Opinions on Promoting Green Development of Urban and Rural Construction," introducing the concept of green development into urban development planning. It requires the establishment of a sound mechanism for coordinating green development in regions and urban agglomerations and calls for future urban development to move towards "intensive, green, and low-carbon" directions. The report of the 20th National Congress of the Communist Party of China emphasized the need to significantly improve the level of urban planning, construction, and governance, accelerate the transformation of urban development modes, implement urban renewal actions, take green development as the leading principle, build livable, resilient, and ecological cities, and enhance the sustainable development capacity of cities. With the gradual deepening of the "Two Mountains" theory, urban green development has pointed out the direction for the high-quality development of national land space and has become an important driving force for economic high-quality development [2-4]. Therefore, can urban green development effectively resolve the dilemmas of diminishing returns to land factors and resource bottlenecks in the process of economic development to enhance land use efficiency? Thus, this study, starting from the perspective of urban green development, explores the impact mechanism of urban green development on land use efficiency based on the analysis of the spatiotemporal evolution characteristics of land use efficiency, providing a reference basis for addressing issues such as the imbalance of land use structure, the rational development of incremental land, and the efficient utilization of existing land in China.

Literature Review

With the acceleration of urbanization, the urban land area at different spatial scales in China continues to increase. Environmental externalities such as resource waste and ecological damage generated during urban land use activities are increasingly prominent. To effectively curb the disorderly expansion of urban land and achieve the maximization of land use degree and expected output, land use efficiency has gradually been included in the research scope of academia. In recent years, research on land use efficiency has mainly focused on basic theories [5, 6], optimization allocation [7, 8], intensive utilization [9], and spatial differentiation [10-14]. At the same time, scholars have explored factors influencing efficient urban land use from different perspectives, believing that economic development [15], technological progress [16], the degree of land marketization [17], and industrial integration [18, 19] are key factors in improving land use efficiency.

In the new development stage, to enhance the sustainable development capacity of cities, scholars have also focused on the discussion of urban green development. Existing literature mainly explores the concept and connotation [20], measurement level [21], and transformation of its development model [22] for urban green development. Meanwhile, scholars have also paid attention to the impact effects of urban green development, discovering its significant driving role in ecological protection [23], sustainable urban planning [24], improvement of air quality [25], and enhancement of social participation and environmental awareness [26]. Moreover, from an economic perspective, research has found that urban green development can accelerate the development of low-carbon economies [27], industrial agglomerations [28], and technological progress [29, 30]. Relevant to this study, some literature points out that urban green development can promote rational urban land planning and layout, encourage efficient allocation of land factors, and optimize the utilization of land resources to the maximum extent [31]. Green development-oriented urban green development also advocates the intensive utilization of land resources. For example, Cheng Ziteng et al. [32] believe that establishing a land use planning system oriented towards a low-carbon circular economy and innovating land use management models can effectively improve land use efficiency. In contrast, some scholars argue that the improvement of land use efficiency through urban green development may also have negative effects. For instance, Zhou Guipeng et al. [33] argue that conflicts in land use may exist among different stakeholders during the process of urban green development. For example, the construction of green spaces may occupy land resources originally intended for commercial development or residential construction, leading to conflicts and opposition among stakeholders and even resulting in waste and inefficient use of land resources.

In summary, as an important direction for the current economic transformation, urban green development has significant implications for regional land use efficiency. However, existing research is mainly theoretical analysis and logical induction, with little research on the impact mechanisms of urban green development on land use efficiency. In comparison with existing literature, the potential marginal contribution of this paper lies in: First, using ArcGIS Map 10.8 software to visually analyze the spatiotemporal distribution differences of land use efficiency in China and explore the causes of differentiated land use efficiency in China. Second, from the perspective of a unified framework at the urban level, this paper explores the impact mechanisms of urban green development on land use efficiency through agglomeration effects, technological effects, and structural effects.

Theoretical Basis and Research Hypotheses

Based on the Environmental Kuznets Curve theory[1], urban green development will generate new production factors and technological management methods, effectively reducing resource waste, environmental pollution, and dependence on traditional labor and energy resources during land use activities, thereby affecting land use efficiency. Overall, urban green development mainly impacts land use efficiency through agglomeration effects, technological effects, and structural effects pathways (Fig. 1).

Agglomeration Effects: Unlike the traditional "development-oriented land use" model, urban green development pays more attention to the ecological benefits of land factors and the intensity of land resource utilization [34]. Influenced by the green development concept, local governments tend to focus on reducing land waste through rational land planning and spatial integration measures. They also promote the popularization of "mixed land development models" by encouraging the mixed concentration layout of different functional land uses, further enhancing the intensity of urban land use to reduce land resource consumption and improve land use efficiency. With the organic combination of different functional land, the singular characteristics of land use are gradually broken, and the multifunctional use of land factors promotes the formation of urban land agglomeration. As land factors continue to spatially agglomerate, various links in the industrial chain are deeply integrated, improving the marginal transformation rate of production factors and the added value of land output in land use activities and accelerating the aggregation of non-land factors such as technology talents, capital markets, and industrial spaces [35, 36]. In this process, urban green development further stimulates the flow of urban land factors to emerging (environmental) industries with higher investment returns, accelerates regional industrial agglomeration, and enhances land use output efficiency on the basis of effectively reducing land pollutant emissions [37, 38].

Technological Effects: Technological innovation has a positive externality effect on land use efficiency [39-41]. The concept of green development has spawned a large number of new technologies for solving urban environmental problems, and the improvement of the technological level provides new ideas and means for urban planning and land resource management, manifested in the effective enhancement of urban land use efficiency through means such as smart city planning, sustainable building technology, and digital land management systems [42]. Specifically, smart city planning technology provides accurate ways for local governments to evaluate the best use of land through advanced algorithms and data analysis tools. Local governments can integrate urban land resources more finely to ensure the rational layout of various functional areas of the city while simultaneously improving land use efficiency and ecological environmental protection [43]. Secondly, the application of sustainable building technology makes urban buildings more environmentally friendly while also meeting the growing functional demands of cities, thereby improving land use efficiency [44]. Finally, the introduction of technologies such as digital land management systems provides more accurate tools for the utilization of urban land resources, enabling real-time monitoring and analysis of land use situations and helping local governments better understand the current status and trends of land use and adjust and optimize them in a timely manner to ensure effective land utilization [45].

Structural Effects: On the one hand, the promotion of urban green development will cause profound changes in the urban land use structure, involving not only adjustments to land use types but also reshaping the functions and spatial layout of urban land [46]. Under the influence of the green development concept, local governments will focus on optimizing the proportion of green lands such as parks, green belts, and ecological protection areas to improve the utilization of non-agricultural land, idle land, and industrial legacy land while improving ecological environmental quality and land use efficiency. On the other hand, in terms of industrial structure, urban green development requires higher levels of environmental protection policies and investments in green industries. This not only promotes the transformation of traditional industries into clean energy and environmental technology fields but also encourages high-quality production factors to continuously flow to emerging industries related to new energy, gradually replacing traditional high-energy-consuming industries, effectively optimizing resource allocation, and reducing extensive land use [47]. At the same time, the rise of emerging environmental protection industries creates a large number of job opportunities, accelerates the cross-regional flow of production factors such as manpower, capital, and technology, and the diffusion marginal effect exacerbates competition between regions, prompting continuous upgrading of industrial structure. In this process, the land use structure will also be optimized under its influence, thereby enhancing urban land use efficiency.

In summary, urban green development affects land use efficiency through agglomeration effects, technological effects, and structural effects. Based on this, the following hypotheses are proposed, and a diagram illustrating the impact mechanism of urban

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[1] The Kuznets Curve theory posits that in the early stages of economic development, environmental quality may deteriorate along with economic growth. However, at a certain turning point, environmental quality may gradually improve with further economic development.

green development on land use efficiency (Fig. 1) is drawn.

H1: Urban green development has a positive effect on improving land use efficiency.

H2: Urban green development can enhance land use efficiency by strengthening agglomeration effects.

H3: Urban green development can effectively improve land use efficiency through technological effects.

H4: Urban green development can positively impact land use efficiency by enhancing structural effects.

Research Methods and Data Sources

Model Construction

Establishment of a Baseline Model: To investigate the impact of urban green development on land use efficiency, this study constructs a baseline model with land use efficiency as the dependent variable and urban green development as the core explanatory variable, as shown in Equation (1):

$$TULUE_{it} = \alpha + \alpha_0 Grep_{it} + \alpha_c X_{it} + \theta_i + \lambda_i + \mu_{it} \quad (1)$$

In Equation (1), $TULUE_{it}$ represents the land use efficiency of city i in year t, $Grep_{it}$ represents the core explanatory variable urban green development, X denotes the set of control variables, θ_i, λ_i represent city and year fixed effects, respectively, and μ_{it} is the error term used to absorb the influence of other confounding factors.

Mediation Effects Model Setting: To further explore whether there is a mediation effect of urban green development on land use efficiency, this study constructs the following model for testing: here, *Mediator* represents the mediating variable (agglomeration effects, technological effects, and structural effects), β, ρ is the constant term, β_0, β_c, ρ_1, ρ_2, ρ_c is the coefficient to be estimated, and other variables are set as in the baseline model. The specific model is constructed as follows:

$$Mediator_{it} = \beta + \beta_0 Grep_{it} + \beta_c X_{it} + \theta_i + \lambda_i + \mu_{it} \quad (2)$$

$$TULUE_{it} = \rho + \rho_1 Grep_{it} + \rho_2 Mediator_{it} + \rho_c X_{it} + \theta_i + \lambda_i + \mu_{it} \quad (3)$$

Measurement and Explanation of Variables

Dependent Variable: Land Use Efficiency *(TULUE)*, calculated by incorporating input-output variables into the Super-Efficiency SBM model. Considering that the key to efficient land use lies in the coupling coordination of ecological, economic, and social aspects to maximize land use intensity and minimize non-expected output, traditional DEA models cannot evaluate the efficiency of non-expected output and suffer from slack variables in input-output variables [48, 49]. Therefore, this study adopts the SBM model to measure land use efficiency while ensuring the reliability of the results. The ratio of the added value of secondary and tertiary industries to

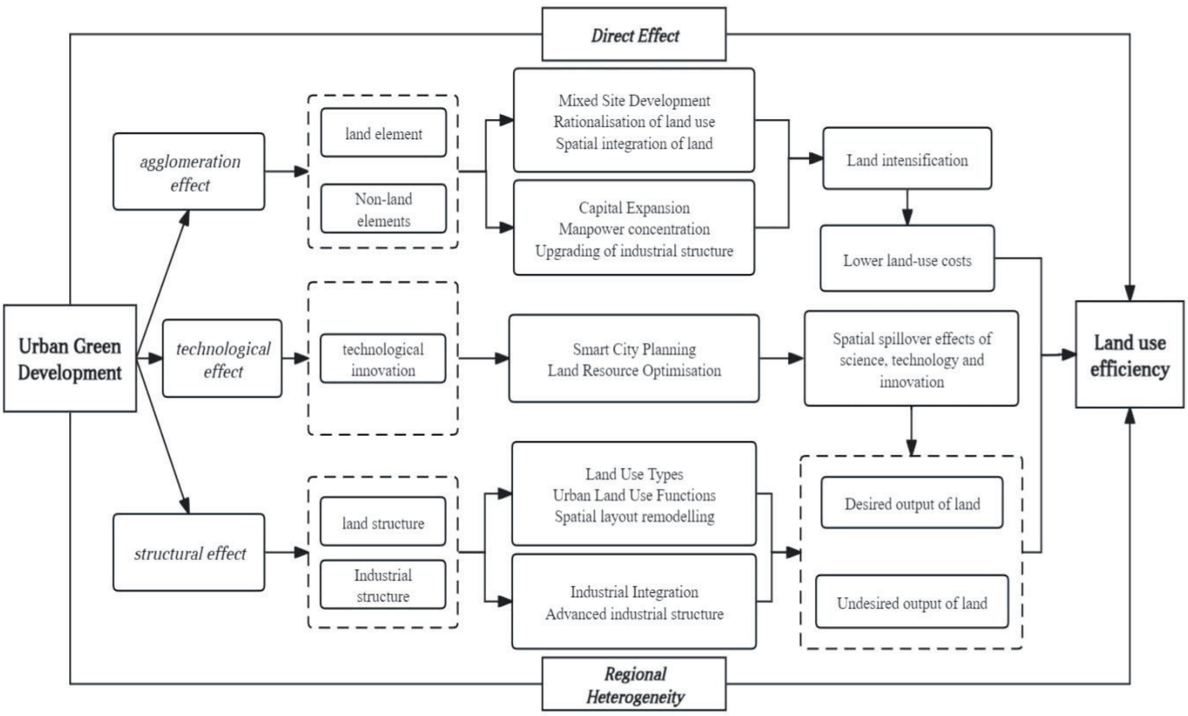

Fig. 1. Mechanism of urban green development on land use efficiency.

urban construction land area is selected as an alternative indicator of land use efficiency (*Tulue2*), with the calculation formula constructed as follows:

$$Min\,\theta^{*} = \frac{1+\frac{1}{m}\sum_{m=1}^{M}(s_{m}^{x}/s_{jm}^{t})}{1-\frac{1}{l+h}((\sum_{t=1}^{L}(s_{l}^{y}/y_{jl}^{t})+\sum_{h=1}^{H}(s_{h}^{b}/b_{jh}^{t}))} \quad (4)$$

$$\text{s.t.}\begin{cases} x_{jm}^{t} \geq \sum_{j=1,j\neq 0}^{n} \lambda_{j}^{t} x_{jm}^{t} + s_{m}^{x} \\ y_{jl}^{t} \geq \sum_{j=1,j\neq k}^{n} \lambda_{j}^{t} y_{jl}^{t} - s_{l}^{y} \\ b_{jh}^{t} \geq \sum_{j=1,j\neq k}^{n} \lambda_{j}^{t} b_{jh}^{t} + s_{h}^{b} \\ \lambda_{j}^{t} \geq 0, S_{m}^{x} \geq 0, S_{l}^{y} \geq 0, j=1,...,n \end{cases} \quad (5)$$

In the above equation, assume that there are n production decision units *D (n = 1, 2, ... , N)*, each *D* contains the number of inputs, desired outputs, and non-desired outputs, respectively, set as *m, l,* and *h*. θ^* is the value of land use efficiency; x^t_j, y^t, and b^t_j denote the value of inputs, desired outputs, and non-desired outputs of *Dj* in period *t*, respectively; s^x_m, s^y_l, and s^b_h are the relaxation vectors of inputs, desired outputs, and non-desired outputs, respectively; and λ is the vector of weights.

Drawing on existing research, input indicators are selected as urban construction land area [50], urban fixed asset investment [51, 52], and the number of employees in the secondary and tertiary industries [53], representing land, capital, and labor inputs, respectively. The value added of the secondary and tertiary industries is chosen to represent economic benefit output, while the area of urban parks and green spaces is used to represent ecological environmental benefit output. To comprehensively measure the non-expected outputs caused by different urban land use activities, this study includes commonly used indicators from existing literature, such as industrial sulfur dioxide emissions and industrial wastewater discharge. Additionally, the amount of household waste collected is introduced to represent the environmental pollution caused by urban land use activities [53].

Explanatory Variable: Urban Green Development *(GREP)*, This study adopts the approach of Liu Xiliang [54] and others in constructing the urban green development index system and, considering the particular scale of this study, decomposes it into 12 aspects closely related to urban green development from the dimensions of “environmental protection” and “economic development”, thus establishing a comprehensive evaluation index system for urban green development (Table 1). Additionally, the entropy method is applied to objectively assign weights to each indicator to obtain a comprehensive evaluation index for urban green development.

Mediating Variables: Including Agglomeration Effect, Technological Effect, and Structural Effect Indicators, as follows:

(1) Agglomeration Effect (*AGG*): The Agglomeration Effect refers to the positive effects generated by the concentration of enterprises, industries, or other economic entities in a specific geographical area, often manifested as a “concentration promotion” phenomenon. Relevant to this study, urban green development advocates for a more sustainable land use approach by controlling the disorderly expansion of industrial and commercial land through the addition of green spaces and public space layouts, leading to a trend of land use aggregation in different functional areas of the city. The agglomeration of urban land further optimizes the regional economy and structure, thereby positively impacting the improvement of land use efficiency. This study refers to Chen Shiyi [55] by using the ratio of urban non-agricultural output (the sum of the value added of the secondary and tertiary industries) to the administrative area of the city to measure economic agglomeration.

(2) Technological Effect (*GTI*): Patent applications are the most significant expression of technological innovation level, reflecting the achievements and quantity of scientific and technological research and innovation in a certain area over a period of time [52]. For this study, urban green development has spurred a large amount of green technology capacity related to environmental protection. The number of green patent applications per unit reflects, to some extent, the level of green technology innovation in the area. The higher the level of urban green technology innovation, the stronger the efficiency improvement brought about by its development in land use. Therefore, the total number of green patent applications is used to measure the level of green technology innovation (to avoid the influence of zero values on the research conclusions, add 1 to the total number of green patent applications and then take the logarithm).

(3) Structural Effect (*MIS*): Compared to the tertiary industry, the secondary industry, mainly heavy industry, relies more on production factors such as labor and capital, has a large demand for energy, and emits more pollutants. Therefore, when the proportion of the tertiary industry is relatively high, its production costs and non-expected outputs are smaller, and the production efficiency is higher. According to the research of Lu Xinhai et al. [10] (2023), the industrial structure *(Mis)* is used as the measure of structural effect (Industrial Structure = Value Added of Tertiary Industry / Value Added of Secondary Industry).

Control Variables: To improve the accuracy of the regression results and control for other factors that may affect land use efficiency, the following variables are selected based on the research of scholars

Table 1. Data sources for specific variable indicators and how they are measured.

Variables	Level 1 indicators	Level 2 indicators	Properties
Urban green development	Environmental Protection	Harmless treatment rate of domestic waste	+
		Urban green space area	+
		Urban green space coverage rate	+
		Comprehensive utilization rate of industrial solid waste	+
		Emission of industrial smoke and dust	-
		Urban sewage treatment rate	+
		Carbon emissions	-
	Economic Development	Gross Domestic Product	+
		Green Total Factor Productivity	+
		Public transport infrastructure	+
		Value Added of Secondary Industry	+
		Tertiary value added	+
Land use efficiency	Inputs	Land area for construction	+
		Urban fixed asset investment	+
		Employees in secondary and tertiary industries	+
	Outputs	Value added of secondary and tertiary industries	+
		Urban green space area	+
		Industrial Sulfur dioxide emissions	-
		Industrial wastewater discharge	-
		Domestic waste removal	+
Control variables	Level of economic development	GDP per capita	+
	Population density	Share of the total population at the end of the year	-
	Level of marketization	Share of fiscal expenditure in GDP	+
	Level of entrepreneurship	Number of Industrial Enterprises Above Scale	+
	Scientific and technological investment	Share of science and technology expenditure in fiscal expenditure	+

such as Chen Danling et al. [56]: level of economic development *(PGDP)*, population density *(DOP)*, degree of marketization *(MART)*, level of enterpriseization *(ECOME)*, and intensity of technological investment *(KJZC)*. Specific indicator information is detailed in Table 1.

Given the historical background of China's economic and social development[2], and considering the integrity of the data, this study conducts empirical analysis using data from 2005 to 2020 for 285 prefecture-level and above cities in China (excluding Hong Kong, Macao, and Taiwan). The data is sourced from various editions of the China Urban Statistics Yearbook, the China Environmental Yearbook, the official website of the State Intellectual Property Office (*SIPO*), and the EPS database. Additionally, missing data for very few cases is supplemented using the mean method.

Regional Characteristic Analysis of Urban Green Development and Land Use Efficiency

Temporal Evolution Trend

According to the comprehensive evaluation index system in Table 1, the green development level and land use efficiency index of the selected research sample cities in China from 2005 to 2020 were calculated separately using the method proposed by YANG Z et al.

[2] The construction of a resource-saving and environmentally friendly society was first proposed at the Fifth Plenary Session of the 16th Central Committee of the Communist Party of China in 2005, and was comprehensively implemented in the "Eleventh Five-Year Plan for National Economic and Social Development."

[57] (2023). Subsequently, the time trend graphs (Fig. 2) of both were drawn.

It can be observed from Fig. 2 that the overall trend of China's urban green development level and land use efficiency index is steadily increasing, and the upward trends are converging, indicating significant progress in both urban green development level and land use efficiency in China at present. Regarding urban green development, there is an overall steady upward trend, especially since 2009, when the growth rate of urban green development indicators has noticeably accelerated. However, between 2015 and 2017, the growth rate of urban green development slightly slowed down. Meanwhile, although the urban green development index continues to grow, its fluctuation is relatively small, with most data points being close to each other and showing little variation. The average annual growth rate is 7.69%. This may be attributed to China's ecological civilization being in the construction phase, while the traditional development model, which focuses solely on economic development, has profound impacts, posing significant challenges to environmental protection and ecological construction. It acts as a "roadblock", hindering the progress of urban green development, resulting in the insufficient driving force for urban green development, and affecting the overall level of urban green development.

As for land use efficiency, it also shows a year-on-year increasing trend during the research period, but compared to urban green development, the growth rate of land use efficiency is relatively faster. From Fig. 2, it can be seen that the land use efficiency index gradually rises during the research period, with a stable growth rate. The comprehensive index increased from 0.024 in 2005 to 0.061 in 2020, with an average annual growth rate of 8.48%. Possible reasons include the increasing demand for land use efficiency during the urbanization process. Through scientifically reasonable urban planning and land management measures, more optimization and improvement in land use are achieved, thereby promoting the improvement of land use efficiency. Additionally, the increasing awareness of environmental protection also contributes to the growth of land use efficiency.

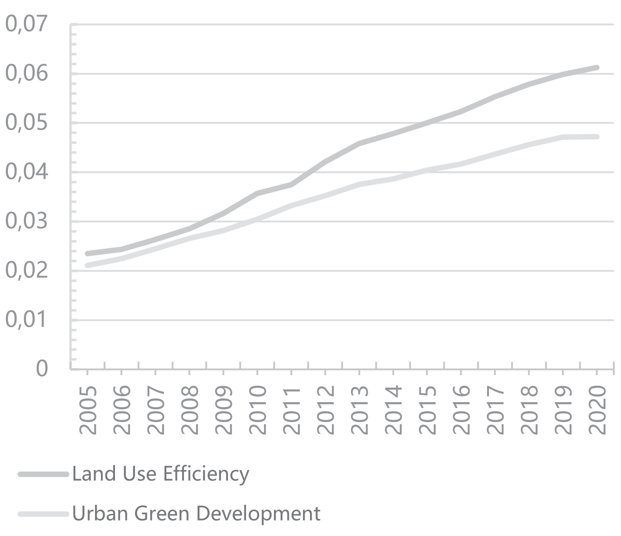

Fig 2. Temporal evolution trend graph of urban green development and land use efficiency from 2005 to 2020.

Spatial Evolution Characteristics

To visualize the spatial patterns of urban green development and land use efficiency in China, this study employed ArcGIS Map 10.8 analysis software to create temporal distribution maps from 2005 to 2020 using the natural breaks classification method[3]. (Fig. 3).

From Fig. 3, it is evident that urban green development in China exhibits distinct regional differentiation and hierarchical distribution characteristics. Overall, the green development levels of various cities show an upward trend, with cities such as Beijing, Shanghai, and Guangzhou demonstrating particularly outstanding levels of green development. Spatially, this manifests as a multi-nucleus spatial structure expanding outward from core urban clusters such as the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Pearl River Delta. This phenomenon may be attributed to the relatively high economic and technological levels of emerging urban clusters, coupled with rapid industrial upgrading. Additionally, these regions boast well-developed supporting service industries, high efficiency in resource and energy utilization, and outstanding performance in environmental pollution control, thus enjoying significant advantages in green development. Conversely, peripheral cities distant from the aforementioned urban clusters exhibit lower influence from green development diffusion. Concurrently, their slow progress in green development is exacerbated by the lower level of industrial structure and insufficient green technology, leading to increased emissions and diminished governance capacity.

Regarding land use efficiency, the temporal distribution map illustrates an overall pattern where the eastern coastal regions surpass the western inland areas. Moreover, core urban clusters such as the Beijing-Tianjin-Hebei region, the Yangtze River Delta, the Pearl River Delta, the Sichuan-Chongqing region, and the "Central China" urban cluster exhibit higher land use efficiency, radiating outward. These cities boast high levels of infrastructure, facilitating the concentration of talent, capital, and industries. Their urban development primarily focuses on high-return and low-pollution third industries, contributing to higher land use efficiency. However, with economic development, certain regions may face issues of excessive land development

[3] The analysis results are derived from the National Administration of Surveying, Mapping and Geoinformation's Standard Map Service Website, with map approval number GS(2023)2767. The base map remains unaltered throughout (similarly hereinafter).

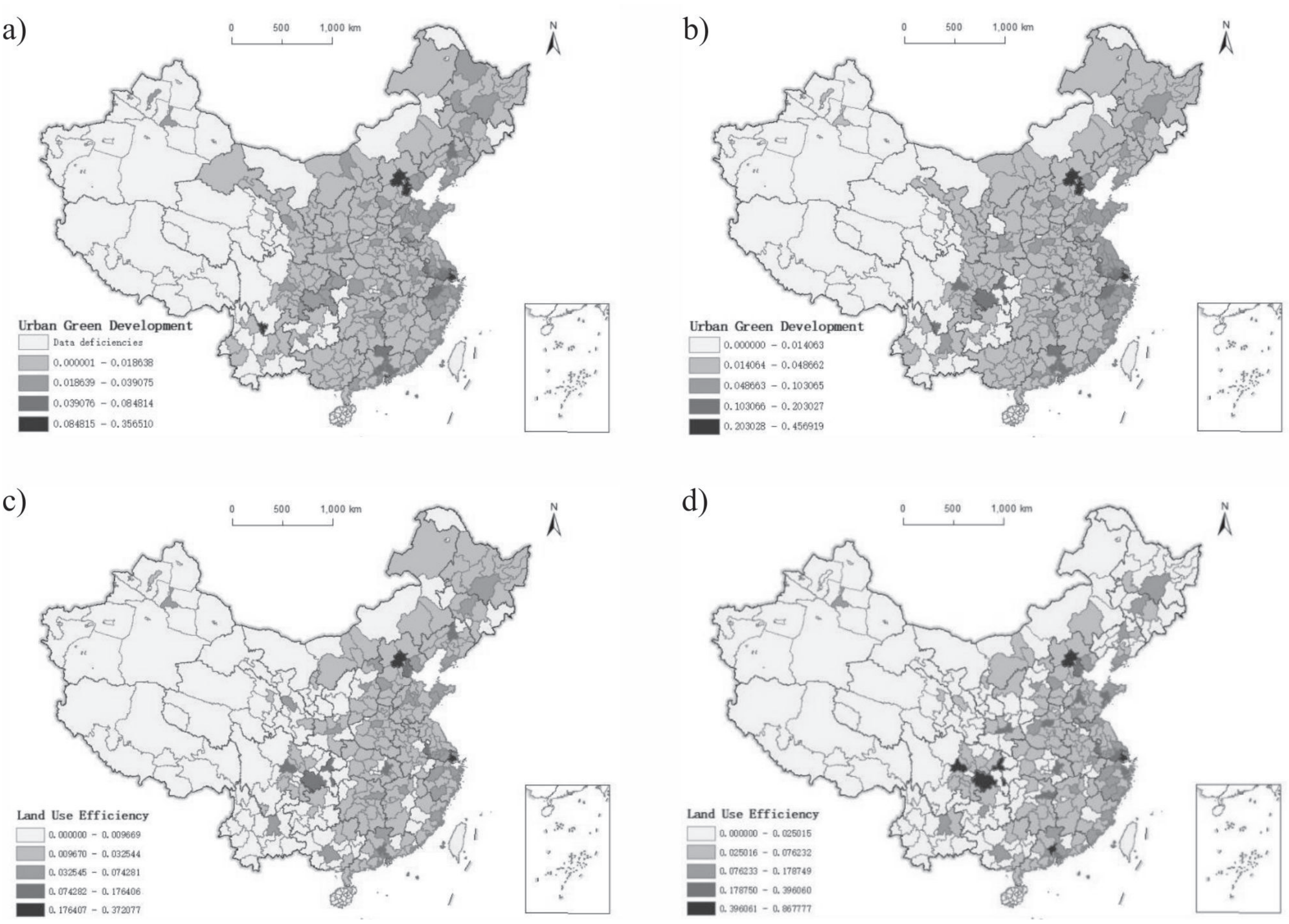

Fig. 3. The spatial distribution maps of urban green development and land use efficiency for the years 2005 to 2020.

and utilization, such as excessive real estate development, leading to decreased land use efficiency. Moreover, economic development may entail changes in industrial structure, with traditional industries gradually declining while emerging industries or service sectors may have different demands for land use, resulting in decreased land use efficiency.

It is noteworthy that in 2020, large areas in North China, Central China, and parts of South China experienced a decrease in land use efficiency. This may be attributed to constraints such as land use patterns, ecological protection regulations, and technological utilization rates. For instance, cities like Yan'an and Baiyin are situated adjacent to the Loess Plateau, where the widespread distribution of steep cultivated land, desertified land, and hilly terrain poses challenges such as adverse geological conditions, severe soil erosion, and fragile ecosystems. When developing land in these areas, cities may face higher costs associated with geological treatment and soil conservation, leading to increased land use costs [58-61]. As for the northwest and southwest regions, influenced by natural geographical factors, the distribution of high plateaus and mountainous terrain renders them less accessible and lacks the necessary conditions for rapid economic development over large areas. The agglomeration effect of land is not apparent, and the utilization level is not high.

Empirical Analysis

Benchmark Regression Results

Table 2 presents the stepwise regression estimates of the impact of urban green development on land use efficiency. From the regression results, it is evident that the coefficients of urban green development are positive at the 1% significance level, indicating that urban green development overall promotes the improvement of land use efficiency. Furthermore, this promotion effect remains unchanged with the increase or decrease of control variables, which is consistent with hypothesis H1. In fact, the continuous deepening of the concept of urban green development has had profound effects on the improvement of land use efficiency.

Firstly, by encouraging multifunctional use of land, urban green development enables single land elements to accommodate various purposes such as residential, commercial, agricultural, and ecosystem services, thereby more effectively utilizing land resources and improving land use efficiency. Secondly, urban

Table 2. Benchmark regression results.

	Tulue1	Tulue1	Tulue1	Tulue1	Tulue1	Tulue1
	(1)	(2)	(3)	(4)	(5)	(6)
LnGREP	0.045*** (0.003)	0.039*** (0.003)	0.040*** (0.003)	0.038*** (0.003)	0.036*** (0.003)	0.033*** (0.003)
LnPGDP		0.009*** (0.003)	0.009*** (0.003)	0.008*** (0.003)	0.028*** (0.003)	0.024*** (0.003)
LnDOP			0.019*** (0.003)	0.019*** (0.003)	0.017*** (0.003)	0.017*** (0.003)
LnMART				0.014*** (0.003)	0.014*** (0.003)	0.010*** (0.003)
LnECOME					-0.021*** (0.002)	-0.024*** (0.002)
LnKJZC						0.007*** (0.001)
Constant	0.209*** (0.011)	0.047 (0.048)	-0.051 (0.050)	-0.038 (0.050)	-0.213*** (0.051)	-0.140*** (0.051)
N	4560	4560	4560	4560	4560	4560
R^2	0.292	0.294	0.300	0.303	0.332	0.345
Time Fixed	YES	YES	YES	YES	YES	YES
City Fixed	YES	YES	YES	YES	YES	YES

Note: *, **, *** denote P<0.10, P<0.05, P<0.01, respectively, with robust standard errors in parentheses, same below.

green development emphasizes compact and high-density planning within cities to reduce excessive land consumption. Through more efficient land use, intensive construction, and urban regeneration, it reduces the costs of land development and construction [62, 63], further enhancing land use efficiency. Lastly, the acceleration of urban green development has led to the construction of green infrastructure such as urban parks, greenways, and green roofs, further improving the efficiency of land resource utilization.

Robustness Checks

To further enhance the robustness of the regression results, this study conducted the following robustness checks based on the benchmark regression: Trimming of Sample Data: Following the approach of Shen Shiming et al. (2023, [64]), the sample data were trimmed by 1% on both tails to minimize the interference of data outliers with the accuracy of the regression results. The trimmed sample was then regressed using the model. Exclusion of Special Cities: Considering that the green development level of directly administered municipalities, sub-provincial cities, and provincial capitals in China may already be relatively advanced, leading to potential differences in their impact on land use efficiency, these cities were excluded from the regression analysis to further enhance the accuracy of the test results. Lagging of Core Explanatory Variables: Following the study by Jin Shengtian et al. (2023, [65]), the lagged term of the core explanatory variable was used to replace the explanatory variable, aiming to alleviate the potential issue of autocorrelation in the regression results and thereby improve accuracy. Replacement of Dependent Variable: The ratio of urban industrial added value to urban construction land area (*Tulue2*) was selected as a substitute indicator for land use efficiency. The results of the four robustness checks (Table 3) indicate that urban green development significantly and positively influences land use efficiency at the 1% level. This suggests that the advancement of urban green development is conducive to improving land use efficiency, further confirming the conclusions drawn earlier.

Mechanism Testing

From the benchmark regression results, it is evident that urban green development can promote the improvement of land use efficiency. To further explore the mechanism through which urban green development affects land use efficiency, this study analyzes the mechanism from three aspects: the agglomeration effect, the technological effect, and the structural effect. The regression results are presented in Table 4.

Firstly, regarding the analysis of the agglomeration effect, Column (1) of Table 4 indicates that urban green development significantly affects land use efficiency at the 1% level, with a coefficient of 1.469. The results in Column (2) show that for every 1 unit increase in urban green development, economic agglomeration increases by 8.541 units. Column (3) demonstrates that the intermediate variable of economic agglomeration

Table 3. Robustness analysis regression results.

	Tulue1	Tulue1	Tulue1	Tulue2
	Tailoring	Excluding special cities	Lagging explanatory variables by one period	Replacement of explanatory variables
	(1)	(2)	(3)	(4)
LnGREP	0.043*** (0.002)	0.026*** (0.001)		5.738*** (0.773)
L.GREP			0.719*** (0.019)	
Constant	0.330*** (0.025)	0.174*** (0.013)	-0.025** (0.010)	-24.113*** (8.504)
N	4560	4032	3780	4560
R^2	0.419	0.511	0.602	0.329
Time Fixed	YES	YES	YES	YES
City Fixed	YES	YES	YES	YES
CV	YES	YES	YES	YES

significantly influences land use efficiency, with a significant p-value, indicating that economic agglomeration plays a partial mediating role, supporting H2.

Secondly, concerning the analysis of the technological effect, Column (4) of Table 4 shows that urban green development significantly affects land use efficiency at the 1% level. Column (5) indicates that for every 1 unit increase in urban green development, economic agglomeration increases by 6.035 units. Column (6) demonstrates that the technological effect significantly influences land use efficiency, with a significant p-value, suggesting that the technological effect plays a partial mediating role, supporting H3.

Finally, regarding the analysis of the structural effect, the results in Column (7) of Table 4 show that urban green development significantly affects land use efficiency at the 1% level. Columns (8) to (9) indicate that changes in industrial structure significantly influence land use efficiency, with a significant p-value indicating that industrial structure plays a partial mediating role, supporting H4.

Table 4. Mechanism test regression results.

	Clustering effect			Technology effect			Structural effect		
	Tulue1	AGG	Tulue1	Tulue1	LnGTI	Tulue1	Tulue1	Mis	Tulue1
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
GREP	1.469*** (0.025)	8.541*** (0.211)	1.297*** (0.029)	1.469*** (0.025)	6.035*** (1.087)	1.465*** (0.025)	1.469*** (0.025)	2.574*** (0.362)	1.449*** (0.025)
AGG			0.020*** (0.002)						
LnGTI						0.001* (0.000)			
Mis									0.008*** (0.001)
Constant	-0.028*** (0.006)	-0.372*** (0.049)	-0.021*** (0.006)	-0.028*** (0.006)	-1.303*** (0.253)	-0.027*** (0.006)	-0.028*** (0.006)	1.921*** (0.084)	-0.045*** (0.006)
N	4560	4560	4560	4560	4543	4543	4560	4560	4560
R^2	0.543	0.592	0.689	0.543	0.639	0.679	0.543	0.544	0.684
Time Fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES
City Fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES
CV	YES	YES	YES	YES	YES	YES	YES	YES	YES

Table 5. Heterogeneity analysis regression results.

	Tulue1	Tulue1	Tulue1	Tulue1	Tulue1	Tulue1	Tulue2	Tulue2
	Eastern	Northeast	Central	West	Coastal Cities	Inland Cities	Coastal Cities	Inland Cities
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
LnGREP	0.005 (0.007)	0.012*** (0.002)	0.064*** (0.004)	0.069*** (0.005)	0.014 (0.010)	0.049*** (0.003)	-3.413 (3.632)	7.019*** (0.746)
Constant	0.515*** (0.077)	-0.134* (0.072)	0.457*** (0.050)	0.236*** (0.080)	0.194** (0.097)	0.340*** (0.032)	-100.908*** (36.353)	-10.033 (8.302)
N	1392	544	1280	1344	592	3968	592	3968
R^2	0.441	0.380	0.450	0.324	0.542	0.315	0.206	0.377
Time Fixed	YES	YES	YES	YES	YES	YES	YES	YES
City Fixed	YES	YES	YES	YES	YES	YES	YES	YES
CV	YES	YES	YES	YES	YES	YES	YES	YES

Heterogeneity Analysis

Considering the vast territory of China and the imbalance in development among cities, the influence of green development on land use efficiency may vary across different regions. On one hand, differences in the development stage and positioning of cities lead to variations in urban scale, function, and industrial structure, thereby affecting land use patterns and efficiency. Developed first-tier cities typically have a relatively complete infrastructure, including transportation, residential, and commercial areas. In such cases, urban planning is relatively rational, resulting in higher land use efficiency [66]. Therefore, the impact of urban green development on improving land efficiency in these cities is limited. On the other hand, differences in geographical location and natural conditions also affect land use efficiency. Coastal cities often emphasize economic benefits in land planning and use due to their economic development and population aggregation, resulting in high land transaction costs. In contrast, inland cities have relatively abundant land supply, reducing fierce competition in land development and making it easier to achieve effective land use through planning and management.

To analyze the influence of urban green development on land use efficiency further, this study divides all cities into four major economic regions: eastern, central, western, and northeastern regions, based on the division method in China's "Fourteenth Five-Year Plan and 2035 Vision Outline." Furthermore, the study categorizes cities into coastal and inland cities based on their geographical location and introduces alternative variables (*Tulue2*) into the regression. Based on these two classification criteria, this study further explores the heterogeneous effects of urban green development on land use efficiency (regression results in Table 5).

The results in columns (1) to (4) of Table 5 show that urban green development is significantly positive in all regression analyses. This indicates that urban green development promotes the improvement of land use efficiency in the eastern, central, western, and northeastern regions, validating the robustness of the benchmark model. However, it is noteworthy that the regression coefficients in the eastern region are not significant, while those in other regions pass the 1% significance level test. This suggests that urban green development has a greater promotional effect on land use efficiency in the central and western regions compared to the eastern region, showing a marginally diminishing effect. In the comparison between coastal and inland cities in columns (5) to (8) of Table 5, only the samples of inland cities show significance, while coastal cities do not reach the significance level.

The possible reason is that the eastern region and coastal cities, due to their relatively advanced technology in new energy development, intensive urban land use, and environmental protection awareness, may experience a less direct impact of urban green development on land use efficiency than the central and western regions, as well as inland cities. Therefore, they may not produce significant direct effects. In the northeastern region, issues such as the slow upgrading of traditional industries, lagging environmental pollution control, and imbalanced land use structures are prominent. Under the influence of urban green development, the land structure is reasonably adjusted, leading to a significant improvement in land use efficiency. Additionally, in the central and western regions and inland cities, where socioeconomic development is relatively lagging, most cities are still in the early stages of urbanization, making it easier to integrate green development concepts into urban planning and construction. This significantly promotes the optimization of urban land resource allocation, thereby effectively improving land use efficiency.

Table 6. Results of the endogeneity test.

	First stage	Second stage	First stage	Second stage
	LnGrep	Tulue1	LnGrep	Tulue1
	(1)	(2)	(3)	(4)
LnGrep		0.4997*** (0.134)		1.0726*** (0.030)
Tude	-0.054*** (-8.49)			
Rivd			0.328*** (52.24)	
Constant	-7.603*** (-33.44)	-6.0788*** (1.090)	-4.296*** (-25.28)	-1.5397*** (0.350)
N	4560	4560	4560	4560
R^2	0.593		0.811	
Time Fixed	YES	YES	YES	YES
City Fixed	YES	YES	YES	YES
CV	YES	YES	YES	YES

Further Analysis

The potential endogeneity issue between urban green development and land use efficiency may lead to biased estimation results. To enhance the reliability of the study findings, this research further employs instrumental variable (IV) estimation. Regarding the selection of instrumental variables, "terrain ruggedness" and "urban river density" are chosen as two natural geographical indicators based on existing literature.

The selection rationale is primarily based on two considerations. Firstly, the terrain ruggedness of urban areas significantly influences the promotion of urban green development. Large-scale terrain variations often accompany increased complexity in construction and infrastructure development, thereby not only escalating the cost of green construction but also augmenting engineering challenges. Cities with greater terrain ruggedness face greater challenges in land planning and development. Secondly, in terms of river density, the concentration of rivers deeply affects the development potential and value of land. The density of urban rivers reflects the accessibility of water resources and ecosystems. A high-density urban river network accelerates the development efficiency of industrial, agricultural, and commercial land use. Moreover, terrain ruggedness and urban river density, as natural geographical conditions, do not directly impact land use efficiency. They belong to natural geographical indicators and remain constant over time, demonstrating strong exogeneity. Additionally, as both types of indicators are in cross-sectional data form, it is difficult to directly measure panel models during regression estimation. Therefore, drawing on the study by Liu and Ma (2023, [66]), terrain ruggedness multiplied by a time dummy variable is regarded as instrumental variable 1 *(Tude)*, and river density multiplied by the core explanatory variable is treated as instrumental variable 2 *(Rivd)*, reflecting the temporal changes in terrain ruggedness and river density across different cities. The estimation results of the instrumental variable method are presented in Table 6. The results indicate that, even after considering endogeneity, the effect of urban green development on enhancing land use efficiency remains significant at the 1% level.

Conclusion and Policy Recommendations

Based on the concept of green development, this study employs the super-efficiency SBM model to calculate land use efficiency, analyzes the impact mechanism of urban green development on land use efficiency, and empirically tests panel data from 2005 to 2020 using panel regression models and mediation effect models. The following conclusions are drawn:

From a temporal perspective, influenced by urban green development, the average land use efficiency in China shows a yearly increasing trend. From a spatial dimension, China's land use efficiency generally presents a pattern where the eastern coastal regions are higher than the western inland regions. Moreover, it radiates outward from urban agglomerations such as the Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Sichuan-Chongqing, and Central China regions. Urban green development significantly promotes the improvement of land use efficiency, and this conclusion remains valid after conducting multiple robustness tests, including selecting terrain ruggedness and urban river density as instrumental variables. Besides direct effects, urban green development also accelerates the flow and allocation of production factors between regions through agglomeration effects, technological effects, and structural effects, influencing the degree and mode of land use and promoting the improvement of land use efficiency.

Heterogeneity analysis indicates that the impact of urban green development on land use efficiency exhibits a trend of gradual enhancement from the eastern coastal regions to the western inland regions. Compared to cities in the eastern coastal regions, cities in the central and western inland regions are more likely to improve land use efficiency through urban green development. Economically developed regions with mature infrastructure and urban planning tend to maintain existing economic structures and development models, showing less significant effects of urban green development on land use efficiency.

Based on the above research conclusions, the following policy recommendations are proposed to further promote urban green development and unleash the potential for improving land use efficiency:

Promote the orderly diffusion of urban green development and improve the quality of policy supply. Local governments should further expand the depth and breadth of urban green development, continuously improve the construction of new energy demonstration cities, smart cities, and digital cities, and promote the improvement of land use efficiency.

Leverage the agglomeration effects, technological effects, and structural effects of urban green development to stimulate urban land vitality. Local governments should accurately grasp the role of urban green development in promoting the growth of land use efficiency, assist economically underdeveloped cities in central and western regions in implementing integrated "industry-university-research" construction, strengthen the transformation of new energy technology achievements, activate idle land in central and western regions, and utilize land efficiently. Additionally, rectify non-compliant land to provide theoretical support and practical guidance for regional sustainable land use and high-quality economic development.

Considering the influence of urban heterogeneity and spatial spillover effects, policy formulation should fully take into account the locational heterogeneity of cities, provide tailored policy arrangements for urban land use in different regions, and comprehensively leverage the constructive role of urban green development in land use efficiency. Moreover, for the four different spatial types of cities studied in the spatial spillover research, efforts should be made to reduce administrative barriers between cities while maximizing their functions, enhancing exchanges and cooperation, reducing the time and distance costs of urban green development spillovers, and promoting the steady improvement of land use efficiency through regional integration and coordinated development mechanisms.

Author Contributions

Conceptualization: LZ., ZY.; Methodology: LZ., ZY.; Data Curation: ZY.; Writing-original draft preparation: ZY.; Writing-Review and Editing: LZ., ZY.; Supervision: LZ.; Funding Acquisition: LZ.

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Conflict of Interest

The authors declare no conflict of interest.

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