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Road to green urbanization: how does urbanization process affect the green land use efficiency

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Introduction: As the process of urbanization accelerates, high energy consumption, pollution, and low land use efficiency have led to many significant negative impacts on production and daily life.

Methods: In order to investigate the impact of urbanization construction on green land use efficiency and its potential mechanisms, the indicators of China's urbanization evaluation system are constructed, and the SBM-GML model is used to measure green land use efficiency. Based on this, data from 30 provinces in China from 2013 to 2023 are used to test them using fixed effects, mediating effects and threshold effects.

Results: (1) The construction of the urbanization process can directly contribute to the improvement of green efficiency in land use. This conclusion remains valid after conducting endogeneity and robustness tests. (2) The mediating effect test shows that the urbanization process can increase synergistic industrial agglomeration and promote the optimization of the industrial structure, thus indirectly promoting the improvement of green land use efficiency. (3) The threshold effect test shows that a threshold effect exists in the relationship between the level of economic development and green land use efficiency, based on the urbanization process. As urbanization deepens, the role of economic development in improving green land use efficiency gradually strengthens. (4) Heterogeneity analysis reveals that the construction of the urbanization process has a more significant impact on driving green land use efficiency in cities in eastern China.

Discussion: This paper suggests optimizing the allocation of land resources in the process of accelerating urbanization and improving the efficiency of land use in terms of green. Attention should be given to the regional differences in carbon emissions during urbanization, and it is essential to continuously optimize the realized low-carbon urbanization model. Special attention should be paid to enhancing carbon emission control in underdeveloped regions, in order to promote the nationwide improvement of green land use efficiency.

KEYWORDS

urbanization process, green land use efficiency, super-efficient EBM, synergistic industrial agglomeration, threshold effect

1 Introduction

As the material foundation for human survival and a key support and fundamental source for constructing ecological civilization, transforming the inefficient and rough land use pattern is crucial for promoting the high-quality, sustainable development of the region (Hou and Wu, 2024). Since the reform and opening up, guided by 'land finance' and high-speed transportation, the spatial structure, scale, and growth mechanism of Chinese cities have changed significantly (Wei et al., 2023). China's urbanization rate has increased from 17.92% in 1978 to 67% in 2024, far exceeding the global average. During China's rapid urbanization, the level of industrialization has surged, the urban population has grown significantly, and the scale of urban land use has expanded, leading to a sharp rise in energy consumption and a corresponding increase in carbon emissions. This poses a serious challenge to both the land use system and the climate system (Wu et al., 2024a, b). As the fundamental element and spatial carrier of urban production and life, the green and use of urban land emphasizes integrating the concept of green and low-carbon development throughout the entire process of urban land utilization (Li et al., 2023a, b). Therefore, improving the green land use efficiency (GLUE) and resolving various structural contradictions in production are key to achieving the 'dual carbon' goal and promoting sustainable urban development.

Urbanization is an inevitable trend of economic and social development and a necessary path to modernization (Duan et al., 2022). Existing studies on the impact of urbanization on GLUE mainly focus on three aspects. First, urbanization has a positive impact on GLUE (Xiang et al., 2023). With the advancement of urbanization, land resources are effectively allocated and the structure of urban construction land is optimized, thus improving urban GLUE. Second, urbanization has a negative impact on GLUE (Li and Luo, 2015). In the process of urbanization, the agricultural population is transferred to cities and towns, the demand for urban infrastructure increases, urban land becomes a scarce resource, a large amount of arable land is occupied, the construction land is rapidly expanding, and the urban spatial planning lags behind the development of cities and towns. In addition, the land development strategy centered on economic growth has led to irrational spatial structure and lower land use efficiency. However, the impact of urbanization on GLUE is nonlinear, and the overall relationship is similar to a "U" shape (Yue and Xue, 2020). When the level of urbanization is low, the GLUE will decrease with the advancement of urbanization; however, after the development of urbanization to a certain extent, with the ISO and the improvement of technology, the land use structure tends to be rationalized, and the use of land resources is increasingly intensive, and the urban GLUE will be significantly improved.

In summary, the significant impact of the urbanization process (UP) on the green efficiency of land use has become a key issue in current research. The network externalities associated with its spatial correlation make it one of the key factors in promoting the efficient and intensive use of land resources. Exploring the impact of urbanization on green efficiency is not only an essential step toward achieving efficient and intensive land use, but also a crucial path for synergistically advancing high-quality economic development and ecological protection. This study not only contributes to the formulation of more scientifically grounded urbanization policies, but also provides theoretical support for the realization of green and low-carbon development.

The existing literature has developed a framework for studying the UP and GLUE, but several deficiencies remain. First, the evaluation system of the UP is still underdeveloped and remains in the exploratory stage. Second, there is a lack of research, particularly on urban GLUE, and the causal relationship between the UP and GLUE is not yet well understood. Finally, the transmission mechanism of the UP on GLUE is unclear, with insufficient consideration of the influence of synergistic industrial agglomeration (SIA) and industrial structure optimization (ISO).

Compared to existing studies, the potential marginal contributions of this paper are as follows: First, the paper constructs UP indicators. Building upon existing research, a comprehensive UP indicator system is developed, focusing on four dimensions: population, economy, society, and ecology, to provide more scientific and standardized support for China's urbanization evaluation system. Second, while the existing literature lacks studies on the land use carbon efficiency within the context of urbanization, leading to an incomplete understanding of the influencing factors, this paper uses data from 30 provinces in China from 2013 to 2023 and conducts a series of endogeneity and robustness tests to explore the impacts of the UP on GLUE, providing important references for improving China's UP and land use carbon efficiency. Third, existing studies have not sufficiently addressed the roles of SIA and ISO, which may result in an overestimation of the positive impact of the UP on GLUE. This paper clarifies the transmission mechanism of the UP on GLUE from the perspectives of SIA and ISO.

The rest of the paper is organized as follows: the second part is the literature review; the third part presents the theoretical analysis and research hypotheses; the fourth part discusses the research design, including data sources, variables, and models; the fifth part covers baseline regressions, endogeneity tests, robustness tests, mediation mechanism tests, and heterogeneity analyses; the sixth part examines further research on the threshold effect of the level of economic development; and finally, the paper concludes with the study's conclusions and policy recommendations.

2 Literature review and hypotheses development

2.1 Literature review

2.1.1 Study on the measurement and influencing factors of GLUE

GLUE is an input-output efficiency indicator that characterizes the inputs and outputs associated with regional land use activities. Its essence is the result of the combined effect of the inputs of capital, labor, energy, technology and other factors, as well as the outputs of economic efficiency and environmental pollution in the process of land-use activities under the constraint of carbon emissions. This concept extends the definition of GLUE by emphasizing the effective use of the smallest unit of input factors and resources to obtain the maximum "desired" outputs (e.g., economic benefits) and the minimum "non-desired" outputs (e.g., environmental pollution (carbon emissions)).

Existing studies have mainly used carbon emissions as the "undesired" output to measure GLUE, and the methods used are also mainly based on traditional models, such as the SBM model (Pang and Wang, 2020), data envelopment analysis (Yang et al., 2024) and stochastic Frontier analysis (Dong et al., 2020). With the passage of time, scholars have paid more and more attention to the green efficiency from land use. In addition, studies have explored the influencing factors of GLUE and found that the regional heterogeneity of GLUE is a result of the combined effects of land use structure, economic development, technological innovation and industrial structure. However, traditional DEA models fail to adequately consider the impact of undesired outputs when measuring efficiency, which may lead to overestimation of efficiency. In addition, the SFA method, although capable of portraying random errors through parameterization, relies on specific functional form settings, which may lead to subjective bias.

In order to overcome these limitations, this paper adopts the SBM-GML model to measure GLUE, which can effectively deal with non-desired outputs and avoid the problem of overestimation of efficiency due to the failure to consider non-desired outputs compared with the traditional DEA model. In addition, the SBM-GML model incorporates the global Markov index, which can dynamically portray the trend of GLUE and provide a reliable measurement basis for the long time axis assessment. In the eastern region, due to the higher degree of industrialization, the GLUE is more influenced by technological innovation and industrial upgrading, while the efficiency improvement in the central and western regions relies more on infrastructure improvement and policy support.The SBM-GML model is more applicable to different regions, and is able to portray the efficiency levels and their evolution paths in different regions with greater precision.

2.1.2 Relevant studies on UP

The UP is people-oriented, green, low-carbon, and sustainable, emphasizing intensive efficiency and ecological livability. Over the years, scholars have studied the connotation of the UP, the construction of evaluation index systems, and the influencing factors. Wang et al. (2021) elaborated on the core connotation of "human-centeredness" in the UP from the perspective of "modernization." Fang et al. (2021) constructed an UP evaluation index system that covers both internal and external human factors, based on an explanation of the connotation of "human-centeredness" in the UP. Chen et al. (2024a), Chen et al. (2024b) constructed an UP evaluation index system based on the actual development of the Yangtze river delta region, incorporating five dimensions of urbanization—population, economy, space, society, and ecology—in line with the development goals of the UP. Li et al. (2024a), Li et al. (2024b) found that the digital economy significantly promotes the development of the UP, based on panel data from 285 prefecture-level cities in China. Zhou and Lin. (2022) constructed a spatial econometric model using panel data from 104 prefecture-level cities in the Yangtze river economic belt (2010–2019) and found that the level of informatization significantly and positively promotes the development of the UP.

2.1.3 Research related to SIA

Due to external economies of scale, the agricultural population is flowing to towns and cities at an accelerated rate, leading to an increase in both the number and size of towns and cities. Marshall's theory on the externalities of SIA highlights the close link between external economies of scale and industrial agglomeration. According to classical economic theory, SIA can enhance economic efficiency by reducing transportation costs, promoting technology diffusion, and increasing market competitiveness. In the context of the UP, SIA has become a crucial factor in driving regional economic growth and improving GLUE.

In recent years, academic research on SIA has become increasingly in-depth, primarily focusing on its causes, influence mechanisms, and improvement strategies. One of the key drivers of SIA is the economy of scale effect. Studies have shown that SIA maximizes economic benefits by improving production efficiency, reducing unit costs, and optimizing resource utilization (Chen et al., 2019). Especially during the process of urbanization, urban agglomeration facilitates the concentration of resources such as labor, capital, and technology, which helps to enhance the green efficiency of land use. Peng et al. (2022) found that, with the accelerated development of SIA, the technological cooperation and innovation capacity among enterprises has significantly improved, which positively impacts the reduction of carbon emissions.

However, SIA also brings the problem of resource mismatch. On the one hand, the agglomeration effect may lead to the overconsumption of environmental resources, thereby exacerbating environmental issues. Lu et al. (2024) pointed out that in some regions, excessive SIA overloads the carrying capacity of land resources and the environment, leading to the deterioration of the ecological environment. On the other hand, the agglomeration effect may cause the resource allocation in certain industries and regions to become overly concentrated, neglecting the synergistic development of other regions and industries, thus creating an imbalance in resource allocation (Xing et al., 2023). This imbalance leads to an increase in emission intensity, thereby affecting the green efficiency of land use.

In terms of improving the impact of SIA on carbon efficiency, scholars have proposed various strategies. Guo et al. (2020) argued that green SIA can not only improve resource utilization efficiency but also play a significant role in emission reduction. Peng et al. (2021) pointed out that the government, through rational planning and policy support, can guide SIA toward environmentally friendly and low-carbon development, thereby improving GLUE.

2.1.4 Research related to ISO

ISO refers to the process of transferring production factors from inefficient traditional industries to more efficient modern industries during economic development, accompanied by technological progress, the refinement of the industrial division of labor, and changes in market demand. With the advancement of the UP, ISO has become one of the key means to improve GLUE. Academic research on ISO mainly focuses on its causes, influence mechanisms, and how to achieve industrial structure optimization.

Firstly, the reasons for the formation of ISO are discussed. One of the main driving forces behind ISO is technological innovation. With the progress of science and technology, especially the continuous development of digital and green technologies, the production methods in traditional industries have undergone fundamental changes. Tan et al. (2024) found that the extensive application of emerging technologies, particularly in smart manufacturing and clean energy, has facilitated the efficient transformation of industrial structures and the optimization of resource allocation. As industries evolve toward higher technology, greater value-added production, and low-carbon environmental protection, the green efficiency of land use is also significantly improved. Additionally, changes in market demand are key factors in ISO. With increasing consumer demand for high-quality, low-carbon, and environmentally friendly products, traditional industries face the pressure to transform and upgrade. For example, Zhang et al. (2024a), Zhang et al. (2024b) suggest that in the process of China's economic transformation, shifts in consumption patterns—driven by rising incomes and improved living standards—have spurred the development of green consumption and service industries. Traditional high-carbon-emission industries have been gradually replaced by low-carbon, environmentally friendly, and high-value-added industries, thereby enhancing the GLUE.

Secondly, the impact of ISO on the green efficiency of land use is discussed. One of the key objectives of ISO is to achieve the efficient use of resources and the reduction of carbon emissions. Numerous studies have shown that optimizing the industrial structure can significantly improve the green efficiency of land use. Dong et al. (2020) pointed out that as the proportion of high-technology and service industries increases, energy consumption and carbon emissions are gradually reduced, thereby achieving the low-carbonization of land use. In the context of the UP, ISO can promote the development of green industries, reduce the excessive consumption of land resources, and simultaneously improve green efficiency.

Finally, to realize the positive impact of ISO on carbon efficiency, government policy guidance is crucial. Li and Liu (2023) suggest that the government should promote the rapid development of green technologies and low-carbon industries through tax incentives, subsidies, and green finance. Additionally, promoting the greening and upgrading of industrial clusters can further enhance resource utilization efficiency and inhance green output by strengthening industrial synergies and technology sharing.

2.1.5 Research on the impact of UP on the GLUE

Both the UP and GLUE are key issues explored by scholars. From the perspective of urbanization policy implementation, most existing research has analyzed the connotation and spatial-temporal evolution of urbanization from multidisciplinary perspectives such as economics, sociology, geography, and others (Yang et al., 2023a; Yang et al., 2023b). It has also revealed the economic, social, and ecological effects of urbanization through the lens of coupling relationships and spatial spillover effects (Zhang et al., 2024a; Zhang et al., 2024b; Zhu et al., 2023a; Zhu et al., 2023b).

From the perspective of GLUE, this concept originated from the study of eco-environmental efficiency. The term "eco-environmental efficiency" emerged in the 1990s (Tang et al., 2021) and has since been widely applied to agricultural production, tourism development, and land use (Jin et al., 2024; Wu and Liang, 2023; Su et al., 2024).

Regarding research on measuring land use carbon efficiency, You and Wu (2010) first developed the traditional DEA model, which was later replaced by the SBM model as the mainstream measurement tool. In addition to measuring the carbon efficiency of individual land use types, such as construction land (Wang et al., 2024) and agricultural land (Janus and Ertunç, 2023), green efficiency in different regions, such as the Yellow River Basin (Rong et al., 2022), Jiangsu Province (Li et al., 2024a), Nanjing (Chuai and Feng, 2019), Zhejiang (Zhu et al., 2023a, b), and Ningxia (Huang and Li, 2022), has also been incorporated into these measurements.

Internationally, scholars have mainly focused on measuring greenhouse gas (GHG) and energy emissions in regions such as the EU (Kortelainen, 2007), OECD (Zhou and Ang, 2008), the UK (Cecchini et al., 2018), and Italy (Molinos-Senante et al., 2022). Concerning the influencing factors of land use carbon efficiency, scholars have found that factors such as industrial structure and greening levels (Luo et al., 2022), low-carbon pilot policies (Penazzi et al., 2019), carbon emission trading pilots (Merfort et al., 2023), and collaborative technological innovation (Chen et al., 2022) all significantly affect GLUE.

Regarding the relationship between the UP and green efficiency, Shi et al. (2024) found that a coupled and coordinated relationship exists between the UP and agricultural green efficiency in China's provincial areas. Additionally, Jiang and Wang (2022) discovered a spatial effect of the level of urbanization on the green efficiency of the tourism industry.

In addition, the current study draws on limited international experience, while European and American countries have accumulated rich practical experience in improving green land-use efficiency. For example, the United Kingdom controls urban sprawl and improves land use efficiency through the "green belt" policy (Pourtaherian and Jaeger, 2022); Germany promotes a compact city development model to optimize land resource allocation (Wellmann et al., 2020); and the United States uses tax incentives to promote the construction of green buildings and low-carbon communities (Jabeen et al., 2025). These experiences can provide lessons for China to optimize land use efficiency under the "dual-carbon" goal (Wu et al., 2024a, b). Therefore, future research needs to further compare the policy tools, land management systems, and urban planning strategies of different countries to enhance the international perspective of the study.

Generally speaking, the existing studies have laid a foundation for exploring the impact of UP on GLUE, but the following shortcomings still exist: (1) the research methods are mostly based on traditional methods such as DEA and SBM, and there is a lack of multi-methods comparative analysis or dynamic evolution perspective; (2) there is insufficient exploration of the impact mechanism, and the impact on GLUE has not yet been adequately revealed from the perspectives of industrial agglomeration and industrial structural adjustment; (4) there is less reference to international experiences; and (5) there is a need to further compare different policy tools and land management systems and urban planning strategies in order to enhance the international perspective of the study. (3) Less reference to international experience, especially in the context of "dual-carbon", the discussion on how to improve GLUE through intelligent and green means is still insufficient.

2.2 Research hypotheses

2.2.1 The direct mechanism of UP on GLUE

China's top-down administrative policy dictates that urbanization development is government-led and driven from the top. As a result, local governments wield significant power in the allocation of land resources and the selection of advantageous industries, which directly impacts the speed and quality of urbanization. For a period after the reform and opening-up, taxes related to land concessions became a crucial source of local financial income, and 'land finance' promoted large-scale urban land expansion, which had negative effects on the ecological environment. Under fiscal incentives and the traditional, crude, and aggressive urbanization development model, local governments focused on industrial investment projects with quick returns and low risks, often neglecting the provision of public goods such as environmental governance. This neglect has contributed to increased energy consumption and carbon emissions (Sloot and Scheibehenne, 2022).

At the level of population urbanization, it can improve the overall education level, provide intellectual support for the low-carbon and efficient use of resources and energy, as well as for environmental protection (Chen et al., 2024a; Chen et al., 2024b), and help reduce energy consumption. The general improvement in population quality, along with increased publicity and education on green environmental protection, will raise public awareness of green, low-carbon practices and environmental protection (Li et al., 2023a; Chen et al., 2024b). This will, in turn, increase demand for green, low-carbon products across society and drive the green, low-carbon transformation of land use, including arable land, grasslands, forest land, and watersheds.

At the level of economic urbanization, it promotes the optimization of regional industrial structure and the creation of agglomeration effects, providing strong support for the development of low-carbon technologies and green industries (Bakirtas and Akpolat, 2018). With the rapid development of the regional economy and industrial upgrading, the popularization and application of green technologies help improve the efficiency of land resource use. In the process of economic urbanization, the combination of a modernized industrial system and a low-carbon economic model promotes the green and efficient use of land resources. Additionally, economic urbanization fosters the growth of green investment by increasing the agglomeration of capital, technology, and talent, which further accelerates the low-carbon transformation of land use structure.

At the level of social urbanization, it has promoted the mobility of urban and rural populations, diversified social structures, and enhanced public awareness and acceptance of environmental protection and green, low-carbon lifestyles (Zhang et al., 2023). With the acceleration of urbanization, residents' green consumption awareness has been strengthened, driving the growth in demand for green products and low-carbon technologies. Social urbanization has also led to improvements in public service facilities and facilitated the construction of low-carbon transport, green buildings, and other infrastructure, thereby increasing GLUE. Public support for and participation in environmental protection policies have promoted the formation of a green, low-carbon lifestyle across society, further advancing the sustainable development of land use.

At the level of eco-urbanization, it focuses on eco-environmental protection and the sustainable use of resources, promoting the construction of green infrastructure and the implementation of ecological restoration projects (Wang et al., 2023). Eco-urbanization emphasizes protecting the ecological environment and reducing carbon emissions, while also promoting the development of urban greening, eco-agriculture, and environmentally friendly industries, thus optimizing GLUE. In the process of eco-urbanization, the planning and construction of green spaces and eco-protected areas help improve the carbon absorption capacity of land, thereby achieving the goal of a low-carbon economy. At the same time, eco-urbanization fosters harmonious symbiosis between human activities and natural ecosystems, promoting the transformation of land use toward low carbon and green, which reduces carbon emissions and enhances the eco-efficiency of land use.

In summary, under the constraints of the green low-carbon, efficient, and intensive objectives, and within the context of the ecological civilization development concept, the UP will increase the output benefits of land use per unit area and improve the green efficiency of land use. Accordingly, the following hypotheses are proposed.

Hypothesis 1: The national comprehensive pilot policy of UP will improve the GLUE.

2.2.2 The mediating mechanism of UP on the GLUE

In the process of urbanization, the land use structure is gradually optimized through the advancement of urbanization and the clustering of industries in the region. This industrial concentration not only effectively improves the allocation efficiency of land resources but also promotes the innovation and application of technology, particularly breakthroughs in green production and low-carbon technologies (Wei et al., 2022; Han and Cao, 2024). With the concentration of industries, cooperation and competition among enterprises intensify, which helps improve overall resource use efficiency and reduces the over-exploitation and waste of land resources. Industrial concentration increases the intensity of land use through scale and synergy effects, promotes the green use of land resources, and enhances GLUE (Wang et al., 2018).

In addition, in the context of urbanization, the government promotes the agglomeration of green industries and the rapid development of low-carbon technologies through reasonable land policies and industrial guidance, thereby achieving the efficient use of land resources and improving green efficiency (Wang et al., 2018). Especially in the construction of science and technology innovation parks and green industrial parks, SIA plays an important role and provides theoretical and practical support for the improvement of GLUE in the region. Accordingly, hypothesis 2 is proposed.

Hypothesis 2: UP improves GLUE by promoting SIA.

In the process of promoting urbanization, with the continuous ISO, the green transformation and efficient development of the regional economy have gradually become the dominant trend. ISO promotes the improvement of GLUE by facilitating the introduction and application of low-carbon and green technologies (Dong et al., 2021).

With the gradual elimination of traditional high-pollution and high-energy-consuming industries and the rapid development of green industries, the efficiency of land use has been significantly improved, and the efficiency of green output has been effectively improved. In particular, in emerging industry clusters and green industrial parks, the intensive use of land resources has been promoted through the clustering of advanced technologies and high value-added industries, thus enhancing GLUE (Ge et al., 2024). ISO not only promotes the widespread application of green technologies but also improves land use intensification by promoting the agglomeration of green industries and technologies (He et al., 2021). Efficient and low-carbon SIA can create higher economic benefits on limited land resources while reducing carbon emissions through technological innovation, optimizing resource allocation, and reducing unnecessary land waste.

In addition, ISO also brings about the transformation of production methods and promotes the greening and intelligentization of the industrial chain, thus further enhancing the efficiency of land resources (Dong et al., 2020). In the context of urbanization, the government encourages the agglomeration of green industries and technological innovation through the implementation of reasonable industrial guidance policies, which not only promotes the optimization and upgrading of the regional industrial structure but also fosters the green and efficient use of land resources. The government's policy support promotes the green transformation of traditional industries and further improves GLUE by guiding funds, technologies, and talent toward green and low-carbon industries.

Hypothesis 3: UP increases the GLUE through ISO. After a series of theoretical analyses, this paper produces the technical roadmap shown below (Figure 1).

3 Research design

3.1 Model construction

In order to test hypothesis 1, i.e., the impact of the UP on GLUE, this paper constructs a two-way fixed effect model (Equation 1).

$$\mathrm{GLUE}_{it} = \mathbf{a_0} + \mathbf{a_1}\mathrm{UP}_{it} + \mathbf{aControls_{it}} + u_i + \delta_t + \varepsilon_{it} \tag{1}$$

Among other things, GLUE_{it} is the green land use efficiency; UP_{it} is urbanization process; $\mathbf{Contrals_{it}}$ is control variable; $\mathbf{a_0}$ is the constant term; $\mathbf{a_1}$ is the coefficient of the core explanatory variable; a is the parameter to be estimated; u_i, δ_t, ε_{it} denote individual effects, time effects, and random perturbation terms, in that order.

3.2 Variable selection

3.2.1 Explained variable

GLUE: The non-desired output SBM model is used to assess the GLUE in 30 provinces in mainland China. Combined with Lu et al. (2023) and Bian and Zhong (2023), we selected land, capital, labor and technology as input indicators for measuring GLUE, and used the area of urban construction land, the *per capita* investment in fixed assets, the *per capita* number of people employed, the *per capita* R&D expenditure, and the *per capita* GDP as desired output indicators and the *per capita* net carbon emissions as non-desired output indicators, respectively. expenditure; land-per-capita GDP is used as the desired output indicator, and land-per-capita net carbon emission is used as the non-desired output indicator. It should be noted that an increase in the intensity of capital, labor, and technological inputs per unit area will raise the level of intensive land use and increase the economic expenditure on land use, and to a certain extent, affect the carbon balance of the region. The number of people employed refers to the total number of labor force in primary, secondary, and tertiary industries at the city level. Land parity refers to the ratio of the total amount of each indicator to the land area, which includes the sum of arable land, land area for construction, forest land, grassland, and wetland/watershed per year in each city.

Based on the above indicators, it is assumed that there are n decision-making units (provinces) with input vectors: X=$(x_{ij})\in R^{M}*$n, The desired output vector is: Y=$(y_{ij})\in R^{E}*$n, The non-expected output vector is: Z=$(z_{ij})\in R^{U}*$n, let X > 0, Y > 0 and Z > 0 Equation 2.

$$\rho = \min \frac{1 - \frac{1}{M}\sum_{i=1}^{M}\frac{S_i^x}{X_{i0}}}{1 + \frac{1}{E+U}\left(\sum_{k=1}^{E_1}\frac{S_k^y}{y_{k0}} + \sum_{q=1}^{U_1}\frac{S_q^z}{z_{q0}}\right)} \tag{2}$$

The constraints are shown as Equation 3:

$$\begin{cases} x_{i0} = \sum_{j=1}^{n}\beta_j x_j + S_i^x, \forall i \\ y_{k0} = \sum_{j=1}^{n}\beta_j y_j - S_k^y, \forall k \\ Z_{q0} = \sum_{j=1}^{n}\beta_j z_j + S_q^z, \forall q \\ S_i^x \geq 0, S_k^y \geq 0, S_q^z \geq 0, \beta_j \geq 0, \forall j, i, k, q \end{cases} \tag{3}$$

where ρ is the combined efficiency value assuming constant returns to scale; M is the number of input indicator categories, E is the number of desired output indicator categories, and U is the number of non-desired output indicator categories; β is a vector of weights; $\sum_{j=1}^{n}x_j$ is the input matrix; $\sum_{j=1}^{n}y_j$ is the desired output matrix; $\sum_{j=1}^{n}z_j$ is the non-desired output matrix; S^x is the amount of input redundancy; S^y is the amount of desired output shortfalls; S^z is the excess of non-expected output. When ρ = 1, S^x, S^y and S^z are absent (i.e., the province is green performant.) Please see Table 1 for the input and output variables of the SBM model.

3.2.2 Explanatory variable

UP: Based on the Five-Year Action Plan for the In-depth Implementation of the People-Centered Urbanization Strategy issued by the State Council, and with reference to existing studies, this study defines the UP as a process centered on the comprehensive development of human beings. It achieves orderly population movement and agglomeration, spatial layout optimization and intensive utilization, environmentally friendly and ecologically livable environments, economic restructuring and upgrading, sustainable development, as well as social harmony and public affluence equalization in the process of modern city construction. Based on the connotation of the UP, this study constructs a comprehensive evaluation index system of urbanization in four dimensions: population, economy, society, and ecology, and uses the entropy value method to measure the level of urbanization Table 2.

3.2.3 Mediating variables

(1) SIA: Since this study mainly analyzes the impact of SIA in the UP on the efficiency of green land useemissions, and since land data primarily come from the secondary industry, the data from the secondary industry are used to measure the level of SIA (AG).

Equation 4 is shown below:

$$AG_{ij} = \frac{E_{ij} \Big/ \sum_j E_{ij}}{\sum_i E_{ij} \Big/ \sum_i \sum_j E_{ij}} \tag{4}$$

where AG_{ij} is the level of j-industry agglomeration in province i, E_{ij} is employment in j-industry in province i, $\sum_j E_{ij}$ is employment in all industries in province i, $\sum_i E_{ij}$ is employment in j-industry in the 30 provinces, and $\sum_i \sum_j E_{ij}$ is total employment in the country.)

(2) ISO. Upgrading the industrial structure means improving the overall quality and efficiency of the industry. This includes not only changes in the proportion of the three industries within the national economy but also the optimization of the degree of coordination among industries. Based on the Cadet-Clarke theorem on the evolution of industrial structure (Sjödin et al., 2020), the overall ISO occurs in stages. This process is characterized by the transformation and upgrading of the primary industry to the secondary industry and ultimately to the tertiary industry. The proportion of the tertiary industry continues to increase, the proportion of the secondary industry rises and then declines, and the proportion of the primary industry gradually decreases. This study portrays the process of ISO through the relative change in the proportion of the output value of the three industries. According to this, the primary, secondary, and tertiary industries are assigned weights in descending order and multiplied by the proportion of the output value of each industry in the total output value. These are then combined in the measurement system, weighted, and used to obtain the index of the overall ISO, R (Equation 5).

$$R = \sum \text{Percentage of output value of the i} - \text{th industry} \times i \tag{5}$$

R value close to one indicates that the overall development level of industrial structure is lower; R value closer to three indicates that the overall development level of industrial structure is higher.

3.2.4 Control variables

With reference to existing research, this paper selects the following control variables: financial support (FS), measured as public financial expenditure as a proportion of GDP; human capital level (HCL), measured by the number of students enrolled in colleges and universities per total population; labor force level (LFL), represented by the natural logarithm of the number of employed people; industrialization level (IL), measured as industrial added value over gross regional product; and environmental regulation (ER), measured by completed investment in industrial pollution control over industrial added value. The results of the descriptive statistics of the variables are shown in Table 3.

3.3 Data sources

This study explores the relationship between the UP and GLUE based on panel data from 30 provinces (including municipalities and autonomous regions) in China from 2013 to 2023. The data come from the China Energy Statistical Yearbook, the China Rural Statistical Yearbook, the China Environmental Statistical Yearbook, the China Urban Statistical Yearbook, the National Statistical Bulletin of Scientific and Technological Funding Input, and the China Carbon Emission Accounting Database. In order to ensure the coherence of the data, the indicator interpolation method is used to address any missing values.

4 Empirical results

4.1 Benchmark regression results

The regression analysis of Equation 1 was conducted using a two-way fixed effects model, and the results of the benchmark regression on the influence of the UP on the efficiency of green land useemissions are reported in Table 4. In columns (1) and (2), the regression coefficients of the core explanatory variables are positive and pass the significance test, indicating that the UP can enhance GLUE, thus verifying hypothesis 1. As for the control variables, the regression coefficients for the labor force level and industrialization level are positive, suggesting that as the labor force and industrialization levels increase, the GLUE also increases. This may be due to technological progress and lifestyle transformation, which have made production activities more intensive. This intensification can effectively utilize land resources and increase the green output per unit of land. The effects of FS, HCL, ER, and the degree of government intervention on GLUE are not significant, likely due to the lag effect of these factors in practical application, insufficient implementation, or the limitations of the research period. The regression coefficient for FS is negative, indicating that FS fails to effectively promote GLUE and may even decrease it. This could be because financial investment is not precisely directed toward low-carbon initiatives.

4.2 *Endogeneity* analysis test

The omission of variables may lead to endogeneity problems in the model. Although this study has controlled for some variables affecting GLUE in the previous section, there may still be reverse

TABLE 1 Relevant indicators for the SBM model of non-expected outputs.

Variable	Indicator type	Form	Description of indicators	Indicator unit
GLUE	Input indicators	Land	Urban construction land area	hm^2
		Principal	Indicator description	$10^4/hm^2$
		Labor	Per capita fixed asset investment	Per/hm^2
		Technical	Per capita employment	10^4/hm2
	Output indicators	Economic benefits	Per capita R&D expenditure	10^4/hm2
		Environmental pollution	GDP *per capita*	t/hm2

TABLE 2 Indicator system for UP level.

Level 1 indicators	Level 2 indicators	Level 3 indicators	Specific definitions of indicators	Attributes
UP	Population urbanization	Percentage of employed persons in secondary and tertiary industries	Employed persons in secondary and tertiary industries/total employment	+
		Urbanization rate of resident population	Urban population/year-end resident population	+
		Urban registered unemployment rate	Data-direct	-
		Urban population density	Data-direct	+
	Economic urbanization	Economic level	GDP *per capita*	+
		Per capita disposable income of urban residents	Data-direct	+
		Percentage of tertiary sector value added	Tertiary value added/GDP	+
		General local budget revenue *per capita*	General budget expenditure of local finances/year-end resident population	+
		Total retail sales of consumer goods *per capita*	Total retail sales of consumer goods/resident population at the end of the year	+
	Social urbanization	Investment in education	Expenditure on education/general budget expenditure of local finances	+
		Scale of education	Average number of students enrolled in higher education per 100,000 population	+
		Level of healthcare	Number of beds in healthcare institutions	+
		Total number of public library books *per capita*	Data-direct	+
		Level of public transport development	Public transport vehicles per 10,000 population	+
	Eco-urbanization	Level of green space in parks	Parkland area *per capita*	+
		Daily urban wastewater treatment capacity	Data-direct	+
		Waste disposal level	Non-hazardous domestic waste disposal rate	+
		Forest cover	Data-direct	+

causality between the control variables and the UP. Therefore, with reference to established studies, all control variables are treated with a one-period lag to reduce the endogeneity problem of the model. Column (1) of Table 5 shows that the enhancement effect of the UP on GLUE still holds, and the significance and sign of the regression coefficients remain consistent with the benchmark regression results.

Secondly, cities with higher GLUE will be prioritized in the development of informatization, thus giving UP a "first-mover advantage", which makes the causality judgment in this paper face the problem of endogeneity. This paper tries to alleviate the endogeneity problem through the instrumental variable method, referring to the practice of Xu,et al. (2024), and taking the number of fixed-line telephone use in each city in 1984 as the instrumental variable of UP(Iv). The reason for choosing the number of landline telephone use per million people as an instrumental variable is that the impact of traditional telecommunication tools such as landline telephones on various socio-economic activities and the environment, which are carried by land, will diminish with the decline in the frequency of use, which satisfies the exclusionary characteristics of instrumental variables.

TABLE 3 Results of descriptive statistics of variables.

Variable	Variable name	Mean	Standard	Min	Max
Explained variable	GLUE	0.381	0.740	0.000	4.130
Core explanatory variables	UP	0.338	0.102	0.150	0.625
Intermediary variable	SIA	0.946	0.213	0.294	1.615
	ISO	0.186	0.186	−0.326	1.043
Control variables	FS	0.255	0.122	0.107	1.457
	HCL	0.022	0.006	0.009	0.045
	LFL	7.586	0.779	5.247	8.864
	IL	0.313	0.079	0.097	0.545
	ER	1.124	0.724	−1.163	5.481

From the regression results in columns (2) and (3) of Table 5, it can be seen that the effect of UP raising GLUE still holds and passes the significance test at the 1% level after accounting for endogeneity. In the weak instrumental identification test, the Gragg-Donald's Wald F statistic is greater than the critical value at the 10% level, and the test results reject the original hypothesis that the instrumental variables are weakly correlated, suggesting that the instrumental variables are reasonably selected. In conclusion, the previous results remain robust after considering the endogeneity issue.

TABLE 4 Baseline regression results.

Variable	(1)	(2)
UP	0.828** (0.299)	1.235*** (0.364)
FS		0.374** (0.156)
HCL		−4.171 (2.544)
LFL		0.197*** (0.069)
IL		0.371*** (0.131)
ER		0.008 (0.008)
Individual fixed effect	Yes	Yes
Time fixed effect	Yes	Yes
Constant	0.032 (0.099)	−1.744*** (0.624)
Observations	330	330
R-squared	0.9765	0.977

Cluster robust standard errors are in parentheses; *, **, *** indicate significant at the 10 percent, 5 percent and 1 percent levels, respectively. Same table below.

4.3 Robustness test

4.3.1 Changing the sample time

Considering that the National Development and Reform Commission issued the Outline of the 13th Five-Year Plan for National Economic and Social Development in 2016, which proposes to 'accelerate the pace of UP, improve the level of construction of new socialist countryside, strive to narrow the development gap between urban and rural areas, and push forward the integration of urban and rural development', the sample time is changed to 2016–2023. The regression results in column (1) of Table 6 show that the regression coefficient of UP is 1.394, which is significant at the 5% level. Therefore, it can be seen that the enhancement effect of UP on GLUE still exists after changing the sample timeframe, and the significance and sign of the regression coefficient remain consistent with the benchmark regression.

4.3.2 Excluding the effect of outliers

In order to avoid the influence of outliers on the regression results, a 5% truncation is applied to both ends of the explanatory variables. The regression results in column (2) of Table 6 show that the regression coefficient of the UP is 1.233, which is significant at the 1% level. Therefore, it can be concluded that the benchmark regression results remain robust after excluding sample selection bias.

4.3.3 Replacement of core explanatory variable

The urban social security participation rate can measure the soundness of the social security system and is a key indicator for assessing the effectiveness of livelihood protection work in the UP. It can also intuitively reflect the social security coverage in towns and cities (Bertinelli and Black, 2004). The level of urbanization was re-measured using the social security participation rate in each province's towns as a proxy for the core explanatory variable. The regression results in column (3) of Table 6 show that the regression coefficient of the urban social security participation rate is 0.701, which is significant at the 5% level. This indicates that after replacing the urbanization measurement indicator, the results are consistent with the baseline regression, further confirming that the UP significantly improves the efficiency of green land useemissions.

4.3.4 Excluding some samples

Municipalities directly under the central government typically attract a large inflow of factor resources due to their location

TABLE 5 Endogeneity problem test.

Variable	(1)	(2)Phase I	(3)Phase II
UP	0.712*** (0.273)		5.864*** (1.758)
Iv		0.119*** (0.035)	
F		10.941	
Individual fixed effect	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes
Control variables	Yes	Yes	Yes
Observations	300	330	330
R-squared	0.967	0.579	-

AR(2) and Sargan's test report p-values. The following table is identical.

advantages, favorable policies, market environment, and other conditions, which in turn generates a clustering effect. Therefore, to exclude the special political and economic status of Beijing, Tianjin, Shanghai, and Chongqing, as well as the potential influence of policy favoritism, this study excludes the data from these four municipalities to test the stability of the benchmark regression results. Column (4) of Table 6 shows that the regression coefficient of UP is 0.804, which is significant at the 1% level, and is largely consistent with the conclusion of the benchmark regression. This indicates that excluding the special municipalities does not affect the conclusion, and the empirical results are robust.

4.3.5 Increasing control variables

The more attention the government pays to environmental issues, the more it will increase the implementation of environmental regulations, thus causing a 'reverse emission reduction' effect. Based on the original model, this study adds the degree of government intervention as a control variable, measured by the ratio of local fiscal protection expenditure to local fiscal general budget expenditure. The regression in column (5) of Table 6 shows that the regression coefficient of the UP is 1.259, which is significant at the 1% level and is largely consistent with the benchmark regression results, indicating that the conclusions of this study are robust.

4.4 Mechanism test

In order to verify the indirect effect of the UP on GLUE, the model constructed above is used for analysis. The results in column (1) of Table 7 show that the regression coefficient of new towns is positive and significant at the 5% level, indicating that the UP has a positive impact on SIA. This also suggests that there may be a mediating effect of SIA in the impact of the UP on GLUE, although the specific effect needs to be further tested. Column (2) shows the regression results obtained after introducing both core explanatory variables and mediating variables. The positive effect of the UP on GLUE still holds, indicating that SIA plays a mediating role. Similarly, the mediating role of ISO also holds.

4.5 Heterogeneity

China is a vast country with unbalanced regional economic development, and there is significant heterogeneity in the development levels of urbanization and the efficiency of green land useemissions across different regions. Therefore, it is necessary to explore the regional heterogeneity of the UP on GLUE. In this study, the sample is divided into three regions: East, Central, and West, and Table 8 presents the regression results.

For the eastern region, the regression coefficient of the UP is 1.633, which is significant at the 1% level, indicating that the UP in the eastern region promotes improvements in GLUE. For the central region, the regression coefficient of the UP is - 0.398, which is significant at the 5% level but with the opposite sign, indicating that the urbanization pilot policy in the central region inhibits the efficiency of GLUE. For the western region, the regression

TABLE 6 Robustness tests.

Variable	(1)	(2)	(3)	(4)	(5)
	Change sample time	Troubleshooting outliers	Replacement of core explanatory variables	Excluding some samples	Adding control variables
UP	1.388** (0.596)	1.231*** (0.362)	0.821*** (0.138)	0.801*** (0.193)	1.264*** (0.363)
Individual fixed effect	Yes	Yes	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes	Yes	Yes
Constant	−1.817** (0.774)	−1.744*** (0.624)	−1.771** (0.624)	−1.391** (0.491)	−1.902*** (0.645)
control variables	Yes	Yes	Yes	Yes	Yes
Observations	240	330	330	286	330
R-squared	0.976	0.978	0.979	0.204	0.978

TABLE 7 Mechanism tests.

Variable	(1)	(2)	(3)	(4)
UP	0.663** (0.297)	1.161*** (0.351)	2.344*** (0.457)	1.028*** (0.316)
SIA		0.107*** (0.035)		
UIS				0.089** (0.039)
Individual fixed effect	Yes	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes	Yes
Constant	−1.581** (0.741)	−1.578* (0.613)	−8.326*** (1.422)	−1.008** (0.474)
Control variables	Yes	Yes	Yes	Yes
Observations	330	330	330	330
R-squared	0.881	0.976	0.798	0.978

coefficient of the UP is 0.096 and insignificant, indicating that the urbanization pilot policy in the western region does not significantly affect GLUE.

Comparing the regression coefficients of the UP across regions, it is found that the western region has the smallest and insignificant coefficient. On the one hand, the lagging infrastructure, low level of economic development, and insufficient application of green technology in the western region have led to a slow UP and difficulties in improving the green efficiency from land use. On the other hand, the low land use efficiency in the western region, coupled with a lack of support for green development and insufficient ecological protection measures, makes it difficult to effectively control carbon emissions during the UP, thereby hindering the improvement of the green efficiency level. The value of the regression coefficient for the UP in the central region is smaller than that in the eastern region, indicating that the effect of the pilot urbanization policy on GLUE in the central region is weaker than in the east. This may be because the eastern region has a stronger economic base, a greener industrial structure, widespread application of green technologies and innovations, and greater support from local governments for low-carbon development, which makes the UP in the eastern region more effective in promoting the improvement of GLUE. On the other hand, the central region has a relatively low level of economic development, still relies on traditional high-carbon industries, has insufficient application of green technologies, and experiences weak implementation of local government policies, leading to a limited effect on improving green land usecarbon efficiency. Therefore, the impact of the UP on GLUE in the central region is smaller than in the eastern region.

5 Further analyses

The results of the regional heterogeneity analysis indicate that the impact of the UP on GLUE differs significantly across regions (Niu et al., 2021). Accordingly, this study hypothesizes that this impact may exhibit a threshold effect related to economic development, meaning that at different stages of economic development, the effect of the UP on GLUE varies. To test whether these threshold effects exist, a panel threshold model is constructed based on Hansen's (1999) study (Equation 6).

$$\mathrm{GLUE}_{it} = \mathbf{a_0} + \mathbf{a_1}\mathrm{UP}_{it}I\left(q_{it} \le \gamma\right) + \mathbf{a_2}\mathrm{UP}_{it}I\left(q_{it} > \gamma\right) + \mathbf{aControls_{it}} + u_i + \delta_t + \varepsilon_{it} \tag{6}$$

Model (6) is a single-threshold model, and both double-threshold and multi-threshold models can be extended based on this model. The specific number of thresholds will be examined subsequently through the threshold effect. In Model (6), I is the threshold variable. This study uses the level of economic development level (EDL) as the threshold variable, measured by real GDP *per capita*, with a logarithmic transformation applied in the regression.

5.1 Threshold effect test

The threshold effect test is a necessary condition for determining whether the panel data can be used in the threshold model. The test results in Table 9 show that the p-values of the double-threshold and triple-threshold tests are greater than 0.1, while the p-value of the

TABLE 8 Heterogeneity analysis.

Variable	Eastern region	Central region	Western region
UP	1.634*** (0.631)	−0.396** (0.197)	0.013 (0.451)
Individual fixed effect	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes
Constant	−2.261 (1.717)	0.198 (0.369)	0.138 (2.372)
Control variables	Yes	Yes	Yes
Observations	121	110	99
R-squared	0.978	0.970	0.781

TABLE 9 Threshold effect bootstrap sample test results.

Modelling	F statistic	P Worth	Bootstrap	Threshold value			Estimated threshold
				10%	5%	1%	
Single threshold	43.47	0.043	500	32.961	40.683	57.968	10.614
Double threshold	14.64	0.289	500	36.046	64.896	124.854	

single-threshold test is less than 0.1, indicating that there is a single threshold effect in the model.

As shown in Table 9 above, the threshold estimate for the UP affecting GLUE is 10.614. To test whether this threshold estimate is valid, the study constructs a likelihood ratio function and a 95% confidence interval, with the results shown in Figure 2. The LR statistic corresponding to the threshold estimate of EDL is significantly smaller than the critical value, indicating that the threshold estimate passes the validity test.

5.2 Threshold effect regression

Table 10 shows the results of the threshold effect regression of the UP affecting GLUE. When the level of EDL is lower than the threshold value of 10.614, the regression coefficient of the UP is 0.843, which passes the significance test at the 1% level. When the level of EDL is higher than the threshold value of 10.614, the regression coefficient of the UP is 1.009, which also passes the significance test at the 1% level. Additionally, comparing the regression results of the two intervals around the threshold, the value of the coefficient has increased substantially. Overall, as the level of EDL increases, the promotion effect of the UP on land use carbon efficiency becomes greater. Therefore, there is a threshold effect based on EDL, i.e., the impact of the UP on GLUE in China exhibits a non-linear characteristic, gradually increasing as EDL progresses.

However, the threshold value of 10.614 requires further deepening of its economic interpretation. First, this threshold is based on sample data through a threshold regression model and is not artificially set. It may correspond to the critical point at which an economy moves from the middle-income stage to the high-income stage. At a lower level of economic development, factors such as infrastructure, industrial structure and technological innovation are not yet perfected, resulting in a lesser contribution of UP to GLUE, while factors such as industrial upgrading, application of green technology and optimization of urban planning start to play a greater role after the level of economic development crosses a certain threshold (10.614), thus enhancing the contribution of UP to GLUE.

It is also worth noting that there may be differences in the thresholds of different regions. For example, the eastern region is industrialized earlier and has a higher level of economic development, so it may require a higher threshold value to reflect the nonlinear impact; while the central and western regions may be able to observe the presentation of the threshold effect at a lower level of development. The appearance of this difference may be differently influenced by industrial structure, policy and environmental protection standards, and the stage of regional development.

6 Conclusions and implications

The UP, while promoting rapid urban economic development, has also brought about structural changes in land use and resource consumption. As the level of urbanization continues to rise, profound changes have occurred in land use patterns, industrial layout, and residents' lifestyles. However, despite the fact that urbanization has promoted economic growth and enhanced urban functions, the green efficiency of land use has not been significantly improved. On the contrary, in some areas, it has resulted in higher carbon emission intensity, reflecting inefficiencies in resource utilization and an increased environmental burden during the UP. Therefore, improving the green efficiency of land use by optimizing land use during urbanization has become a key issue in promoting green and low-carbon development. This not only helps to achieve environmentally sustainable development but also promotes the coordinated advancement of high-quality economic development and ecological civilization.

Different from previous studies, this paper provides a feasible explanation for optimizing the GLUE from the perspective of the UP. To explain the core logic, this paper: (1) empirically examines the impact of the UP on GLUE; (2) uses a mediating effect model to examine the role of SIA and ISO; (3) applies the threshold effect model to explore the threshold characteristics of EDL; and (4) analyzes the heterogeneous impact of the UP on GLUE from a regional perspective.

This paper selects data from 30 provinces in China from 2013 to 2023. After conducting empirical analyses using the fixed effects model, the mediating effects model, and the threshold effects model, the following findings are made: First, the UP improves the GLUE, and the results remain valid after endogeneity and robustness tests. Second, the mechanism analysis shows that the UP promotes GLUE by enhancing SIA and ISO. Third, the heterogeneity analysis reveals that the UP has a stronger effect on improving GLUE in the eastern region of China, while its impact is relatively weaker in the western region. Finally, the threshold effect analysis finds that once the EDL surpasses the threshold value of 10.614, the promotion effect of the UP on GLUE becomes stronger.

In the context of the "dual-carbon" goal and efficient land use, the UP and GLUE are included together in the research model. The findings of the study have the following implications for the promotion of pilot policies for the UP and the improvement of GLUE.

Firstly, the empirical results show that the UP helps promote the improvement of GLUE. Therefore, localities need to continuously

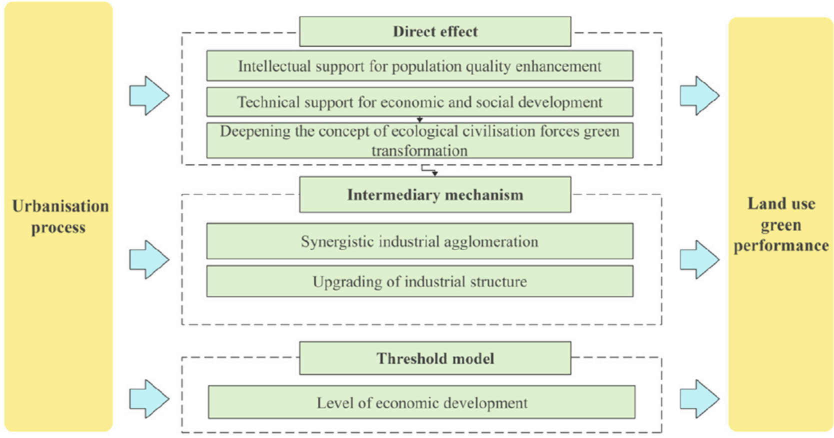

FIGURE 1
Technology roadmap.

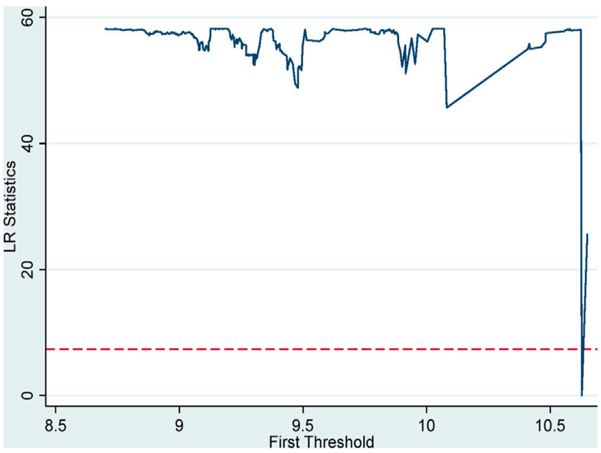

FIGURE 2
Threshold estimate test.

TABLE 10 Threshold estimation results.

Variable	Ratio	Robust standard error
UP(Ln EDL≤10.614)	0.876***	0.149
UP(Ln EDL>10.614)	0.834***	0.163
Individual fixed effect	Yes	Yes
Time fixed effect	Yes	Yes
Constant	−1.569*	0.564
Control variables	Yes	Yes
Observations	330	330
Within R-sq	0.176	

advance the construction of urbanization and comprehensively deepen the coordinated development of the four dimensions: population, economy, society, and ecology. In future development, emphasis should be placed on strengthening infrastructure across all dimensions of urbanization, optimizing urban spatial layout, and improving GLUE.

In the demographic dimension, it is necessary to promote the movement of the population to reasonable areas, optimize the functional zoning of cities, avoid over-expansion, and ensure that population concentration matches the carrying capacity of resources and the environment. In the economic dimension, it is necessary to increase investment in green industries and the low-carbon economy, promote efficient energy utilization and green building development, and further enhance the energy efficiency and resource allocation efficiency of the city. In the social dimension, it is necessary to strengthen the construction of social service facilities, promote the development of urban public services in the direction of being green, intelligent, and shared, improve the quality of urban life, and enhance residents' awareness of sustainable development. In the ecological dimension, it is necessary to strengthen the construction of green infrastructure, promote the implementation of ecological restoration and environmental protection policies, build a low-carbon city, and enhance the carrying capacity of the urban ecological environment. Through the comprehensive promotion of the UP, land use efficiency can be effectively improved, green transformation can be promoted, and the coordinated development of economy, society, and ecology can be realized, thereby laying a solid foundation for the improvement of green efficiency from land use and promoting green, low-carbon sustainable development.

Secondly, the empirical results show that the UP can further improve the GLUE by enhancing SIA and upgrading the industrial structure. Therefore, in future development, we should explore how the UP can effectively improve GLUE by optimizing industrial layout and promoting industrial transformation and upgrading.

Regarding SIA, urban spatial planning should be optimized to promote the concentration of industries in agglomeration areas, enhance resource allocation efficiency, and reduce the idle and wasteful use of land resources. By strengthening infrastructure construction and promoting the clustering of green industrial parks and low-carbon technology industries, not only can the synergistic effect of industries be improved, but carbon emissions in the process of industrial development can also be reduced while intensively utilizing land resources. In terms of ISO, the green transformation of traditional industries should be accelerated, the development of high-tech and high value-added industries should be encouraged, and the wide application of low-carbon technologies and sustainable development concepts should be promoted. The green efficiency of land use should be enhanced through industrial structure optimization. By reasonably guiding SIA and upgrading, the UP can promote the efficient use of land resources, provide solid support for the realization of low-carbon development goals, and create a win-win situation for economic development and environmental protection during urbanization.

Again, the empirical results show that the UP has a heterogeneous impact on GLUE, which can address the unbalanced characteristics of urbanization development levels triggered by regional location. Specifically, the eastern region has a higher EDL, stronger resource allocation capacity, and technological advantages. In the future, it can reasonably plan the layout of land use according to environmental carrying capacity, expand the space for the green development of land use in the process of urbanization, and focus on the efficient use of land resources and environmental protection to promote the low-carbon transformation of land use. At the same time, the eastern region should strengthen the development of green industries and promote an intelligent and green urban construction model to maximize the efficiency of GLUE.

In contrast, the empirical results show that UP has a heterogeneous impact on GLUE, so future policies should take differentiated measures for different regions. The eastern region should rely on its strong resource allocation capacity and technological advantages, promote the development of green high-end manufacturing and modern service industries, optimize the land use layout, promote the construction of the carbon trading market, and make use of digital technology to enhance the refinement of land resource management. The central region should focus on improving the efficiency of land use, strengthening urban planning and management, preventing disorderly expansion, optimizing the land use structure through town clusters and industrial clusters, and at the same time perfecting the green financial support system and promoting the implementation of policies such as green credit and optimal allocation of land resources. The western region, on the other hand, needs to strengthen ecological protection, enhance land use efficiency through green infrastructure investment, while establishing a cross-regional technology transfer platform, introducing advanced technology and management experience, improving the ecological compensation mechanism, and promoting green upgrading of the industrial chain. In addition, digital technologies such as intelligent monitoring systems and remote sensing technology are being used to improve the ability to dynamically supervise land resources and further enhance the decarbonization of land use. Through these measures, regional coordinated development will be promoted, the efficiency of carbon emissions from land use nationwide will be enhanced, and a win-win situation will be achieved in terms of both environmental and economic benefits in the process of new urbanization.

Finally, the empirical results show that the marginal effect of the UP on GLUE becomes more significant after crossing the threshold of EDL. This finding suggests that when the regional EDL reaches a certain threshold, the promotion of the UP has an accelerating effect on the improvement of GLUE. In this process, economic development provides more sufficient resources and technical support for the UP, promoting the application of green technology and the expansion of low-carbon industries, thus significantly improving the efficiency of land resource use and the effect of carbon emission reduction.

However, in regions with a lower EDL, due to the lack of sufficient financial, technological, and policy support, the effect of the UP on the improvement of green efficiency in land use is relatively lagging. Therefore, it is necessary to formulate phased policy measures in response to the differences in EDL across regions, especially in regions that have crossed the threshold. Policy guidance and technical support should be increased to maximize the positive impact of the UP on the GLUE and to promote the high-quality development of green and low-carbon economies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RY: Investigation, Methodology, Software, Supervision, Writing – original draft, Writing – review and editing. JW: Investigation, Methodology, Software, Validation, Writing – original draft. MX: Writing – review and editing, Software, Supervision, Validation. KX: Writing – review and editing, Conceptualization, Data curation, Formal Analysis, Writing – original draft.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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