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Central city construction and urban land green utilization efficiency: evidence from Chinese urban agglomerations

Yi Xiao, Qingshen Kong, Haonan Yang, Huan Huang, Liang Chen & Ming Chang

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The impact of central city construction on the urban land green use efficiency: evidence from urban agglomerations in China

Abstract: Central city construction (CCC) functions as an important policy instrument for facilitating China’s green transformation, while urban agglomerations serve as the primary spatial carriers of this process. In the context of low land utilization efficiency and environmental pressure, this study examines how CCC influences urban land green utilization efficiency (ULGUE) within urban agglomerations (UAs). Using panel data from 2006 to 2021 for 213 cities across 19 Chinese UAs, this study measured ULGUE using the super-efficiency SBM model and investigated the impact of CCC on ULGUE via a difference-in-differences (DID) model. ULGUE is significantly enhanced by CCC, and the effect of CCC on ULGUE varies noticeably. CCC can further optimize land resource allocation and utilization efficiency by enhancing green innovation vitality, promoting industrial upgrading, accelerating internet agglomeration, and improving the urbanization level. CCC is a major national development plan that not only greatly advances new-type urbanization but also promotes the integrated and coordinated growth of UAs. Furthermore, it provides a productive methodology and theoretical reference for urban spatial structure optimization and sustainable land use in other developing countries.

Keywords: Urban land green use efficiency; Central city construction; Difference-in-differences model; Super-efficiency SBM model

1. Introduction

The UN's SDG 15 emphasizes the sustainable utilization of land factor endowments, the prevention and reversal of land degradation, and the preservation, restoration, and responsible management of terrestrial ecosystems to halt biodiversity loss (Guan et al., 2024; Li et al., 2024). Land is considered the spatial carrier of life development, production, and urban survival. The degree of land use is a crucial representation of how inputs and outputs are transformed within the geographical context of economic activity (K. Q. Chen et al., 2023; Guo, Zhang, Guo, Lu, & Xu, 2023). The city's land factor endowments provide the underlying material foundation that sustains the normal functioning of socially organized systems of production and daily life (Lu et al., 2024). Urban space nonagricultural developed land sprawl, various types of land structure imbalances, resource waste, cultivated land tension, environmental pollution and other negative effects lead to a decrease in urban overall land use efficiency (Y. Y. Yang, Ren, & Yan, 2023). This has destroyed the natural carbon sequestration function of land to a certain extent. Promoting efficient and green land development is among the most effective strategies for optimizing land use and maximizing land resource allocation (Y. Feng, Li, & Nie, 2023).

Land utilization efficiency maps urban social and economic activities at the territorial spatial level and reflects the well-being of urban development. Domestic and foreign scholars have focused on three aspects of land use efficiency: efficiency measurement, analyses of the influencing factors and policy implementation. Traditional land utilization efficiency provides an analytical basis for measuring the level of urban land factor endowment utilization (Wang, Wang,

& Ai, 2024). However, methods that consider only the input and output of a single land index have significant drawbacks, and researchers have focused more recently on assessing urban land green use efficiency (ULGUE) using multi-indicator building systems. However, many index evaluation system methods still employ subjective, index connotation-defined fuzzy methods. With respect to refinement and innovation, data envelopment analysis (DEA), whose rationalization of weights makes it a more objective rigorous algorithm, has become a mainstream method for determining production factors and measuring more input–output decision units. Scholars have employed various methods to measure land use efficiency, including the SBM-undesirable model (Tan, Hu, Kuang, & Zhou, 2021), the super-efficiency SBM model (Y. Feng, Li, & Nie, 2023; Zhou & Lu, 2023), the three-stage SBM-DEA model (N. Zhang, Sun, & Hu, 2024), the super-efficiency SBM model combined with partial least squares structural equation modeling (Zhu, Zhang, Wei, Li, & Zhao, 2019), and the global data envelopment method (Fei, Lin, & Chunga, 2021). In addition to the economic growth mode, which involves a single gradual pursuit of resource-saving and environmentally friendly transformation, the environmentally negative external products of ULGUE have become the main index of land use evaluation. The super-efficiency SBM model improved by the DEA model has been favored by many scholars. In terms of the influencing factors, industrial agglomeration (W. X. Zhang, Wang, Wang, Wu, & Wei, 2022), carbon emissions (Huang, Han, Zhang, Ning, & Zhang, 2024), road network investment, scientific technology (Song, Yeung, Zhu, Xu, & Zhang, 2022), government environmental attention (Lu & Tao, 2024), the urbanization rate (N. Zhang et al., 2024) and regional economic development (Chen et al., 2019) clearly affect land utilization efficiency. In terms of the impact of macro policies on land use, the pilot free-trade zone policy (Y. Feng et al., 2023), the “One Household One Plot” policy (Niu et al., 2025), digital transformation policies (Jiang, Yang, Wei, & Zhang, 2024), and smart city construction policies (Wang, Lin, Liu, Wang, & Xu, 2021) have diverse effects on land use, and their effects differ across different types of cities, such as those with different geographical locations, degrees of marketization, economic structures and human capital.

From the perspective of the urban planning layout with gradient attributes, the State Council of the National Urban System Planning (2006–2020) issued by the Chinese government in 2007 for the first time proposed that central cities (CCs) should be the core of the national urban system. Beyond their spatial primacy, CCs perform comprehensive functions in terms of governance, culture, logistics, innovation, and economic organization and thus play a decisive role in shaping the structural configuration and operational efficiency of the urban system. As a key pathway for China’s quality-oriented development, strengthening national central city construction (CCC) represents an essential prerequisite for improving the quality of urbanization and advancing the new-type urbanization process. With their nationally oriented functional positioning, CCs are required not only to consolidate their own development advantages but also to assume responsibility for regional coordination and spatial guidance. Through the concentration and reallocation of high-end production factors, the optimization of urban functional structures, and the enhancement of intercity connectivity, CCs promote the restructuring of regional production networks and spatial layouts. This process facilitates the outward diffusion of advanced industries, technological innovation, and modern governance practices to surrounding cities; strengthens interregional linkages within urban agglomerations; and ultimately contributes to more balanced, coordinated, and efficient development of the national urban system.

Given the short implementation period of new policies, systematic analyses of the existing literature is rarely carried out, and the empirical aspects only include its economic benefits, the measurement of a single indicator, and the construction of an indicator system. CCs have a catalytic effect on economic growth, and technological innovation enhances the uplifting effect (Ma, Shang, & Liang, 2024). The scientific and technological innovation efficiency of CCs has reached an effective level, and the overall trend has increased (Yang, Yang, Wang, Zhou, & Wang, 2024). To assess the sustainable development performance of cities in ethnically autonomous zones, researchers have developed a three-dimensional index evaluation method based on CCs (Shi, Yi, Li, & Wang, 2022). Beyond CCC, a suite of national and regional development initiatives, notably national urban agglomeration strategies and regionally coordinated planning frameworks, has been advanced in recent years to reinforce intercity connectivity and foster integrated development across administrative boundaries. The existing studies have indicated that these regional policies can shape environmental outcomes by reconfiguring industrial spatial structures, enhancing the provision of shared infrastructure, and enabling collaborative environmental governance among cities within the same urban agglomeration (Hu, Xu, Liu, Cui, & Zhao, 2023; Ding, Dai, Zhou, Chen, & Wan, 2026). Nevertheless, relative to its well-documented environmental effects, the environmental implications of CCC and associated regional planning policies remain insufficiently examined, particularly with respect to cross-city spillover effects.

In recent years, with the continuous advancement of regional coordinated development strategies, scholars have gradually explored the impact of regional policies on land use-related indicators from multiple perspectives. The existing studies generally agree that regional policies play a crucial role in reshaping spatial structures, guiding the flow of factors, and adjusting industrial layouts, which in turn significantly affect land use patterns and performance (Lu et al., 2024). Specifically, policies such as regional development strategies, urban agglomeration construction, and functional zone planning promote the intensive and efficient allocation of land resources to some extent by strengthening factor agglomeration and spatial linkage (Yu & Yuan, 2025). Moreover, the differences in policy goals, institutional arrangements, and implementation paths across various types of policies have led to distinct heterogeneous impacts on land use performance (Zhang, Wang, Goh, He, & Hua, 2024). Further research has shown that the effectiveness of regional policies depends not only on the design of the policies themselves but also on the combined influence of factors such as regional economic development levels, industrial structure characteristics, and differences in governance capacity (Guo & Jin, 2025).

Moreover, the existing studies have increasingly recognized that it is no longer sufficient to examine land use efficiency from a single dimension to fully reveal the complexity of the impact mechanism of regional policies. An increasing number of studies have incorporated factors such as land use structure, land development intensity, and environmental constraints into a unified analytical framework to more systematically characterize the internal mechanisms of land use changes (Song, Feng, Xia, Li, & Scheffran, 2021; Jiang et al., 2022; Zhu, Xia, Liang, Yuan, & Liu, 2025). However, from an overall perspective, research on how regional policies influence land use-related indicators through effects on factor allocation, spatial structure, and institutional environments remains relatively limited. Therefore, it is necessary to conduct an in-depth analysis of the paths and spatial heterogeneity of regional policy impacts on land use-related indicators from a comprehensive perspective, providing stronger empirical evidence for optimizing regional development strategies and enhancing land resource allocation efficiency.

The existing studies that have examined urban land green utilization efficiency have focused primarily on specific transmission channels, such as technological innovation, industrial structure upgrading, environmental regulation, and infrastructure improvement, highlighting the role of individual mechanisms in shaping green land use outcomes (Wang, Ren, Su, Chen, & Diao, 2026; Niu et al., 2025). While these studies provide valuable insights into particular pathways through which land use efficiency may be enhanced, their analytical perspectives remain largely fragmented and mechanism specific. The lack of an integrated analytical framework that systematically links multiple channels and accounts for their interactions limits a comprehensive understanding of how regional policies jointly influence land green utilization efficiency. This fragmentation underscores the need for a more unified and coherent framework to consolidate existing mechanisms and to more fully capture the complex pathways through which regional policies affect land green utilization outcomes.

This research employed the super-efficiency SBM model to assess ULGUE, utilizing panel data from 213 prefecture-level cities across 19 UAs spanning from 2006 to 2021. The difference-in-differences (DID) model was subsequently applied to analyze the effect of CCC on ULGUE and explore the underlying mechanisms of its influence. These are the potential marginal contributions that might be made: (1) From the perspective of land use at the geographical level, considering the macro policy of urban planning, namely, CCC, the research focuses on how CCC affects the spatial mapping of the input–output system of production factors and provides added value for the evaluation of the resource and environmental benefits of the CCC policy. (2) By focusing on four key transmission mechanisms, namely, green innovation vitality, industrial upgrading, internet agglomeration, and the level of urbanization, this study clarifies the internal logic through which CCC influences ULGUE and constructs a "3I" theoretical framework comprising innovation of function, improvement of structure, and integration of urban–rural areas to systematically evaluate the effects of macro level policies on land use efficiency. (3) The study findings are of substantial significance for improving central urban planning and land green governance, providing further scientific basis and practical reference for constructing a spatial system with complementary advantages, formulating territorial spatial planning policies, and coordinating urban green and sustainable development.

2. Theoretical analysis and research hypotheses

As key platforms and strategic nodes within the national development framework, CCs occupy a dominant position in the hierarchical urban system. Beyond enhancing their own functional capacity, CCC seeks to promote the integrated development of technological innovation, industrial systems, digital infrastructure, population dynamics, environmental resources, and production factors across UAs, thereby fostering highly interconnected and dynamic regional development systems.

Through this macrolevel institutional arrangement, CCC reshapes ULGUE by simultaneously influencing incentive structures and cost conditions. Sustained policy guidance and preferential support oriented toward green economic transformation facilitate continuous optimization in the allocation and structure of production factors, with these adjustments ultimately reflected in more efficient and environmentally friendly land use outcomes. As regional growth poles, CCs generate spillover incentives that encourage surrounding cities to internalize the costs of technological innovation, pollution control, and land use adjustment through market mechanisms, thereby accelerating the diffusion of energy-saving technologies and the upgrading of industrial output structures across UAs.

Moreover, the regulatory framework embedded in CCC raises the marginal cost of pollution-intensive activities by internalizing environmental externalities. Confronted with stricter environmental constraints and higher compliance costs, firms are induced to reorganize industrial chains and improve production processes to meet pollution reduction targets while maintaining profitability. This adaptive adjustment enhances the quality of land-based outputs and restricts environmentally harmful production within a limited range, thereby reinforcing improvements in

ULGUE.

Enhancing the vitality of green innovation (GIV) is a pivotal strategy for optimizing green land use efficiency in CCs. As a fundamental pillar of CCC, scientific and technological innovation serves as a core element within the evaluation framework of CCs (Zuo, Guo, Li, & Cheng, 2022). By nurturing green innovation, CCs can catalyze the advancement of green technologies, thereby enhancing resource efficiency and driving the adoption of cleaner, more sustainable production methods. This, in turn, mitigates resource waste and pollution in manufacturing processes while simultaneously refining the overall structure of resource utilization. Moreover, CCs can further amplify GIV by implementing policy interventions that promote the integration of green technologies, such as offering targeted incentives for enterprises to adopt sustainable practices and invest in green infrastructure. These policy-driven effects, coupled with cost-reducing innovations, foster a seamless transition toward more environmentally responsible industrial practices, ultimately reducing ecological footprints. In essence, the convergence of green innovation with well-crafted policies empowers CCs to champion the sustainable evolution of their urban economies, thereby fostering more efficient and environmentally conscientious land use practices.

Promoting industrial upgrading (AIS) is essential for advancing the sustainable use of urban land in CCs. By eliminating high-pollution, energy-intensive industries and prioritizing the growth of environmentally-friendly sectors, CCs can facilitate the transition to a greener economy. Under government-led environmental regulations, industries with high environmental costs are either compelled to exit or pressured to adopt greener practices, driving the necessary transformation for sustainable land use (Lin & Zhang, 2023). This transition is mediated by economic incentives, such as subsidies for green technologies and tax breaks for eco-friendly industries, which encourage businesses to adopt cleaner practices. Additionally, investment in green infrastructure serves as a critical intermediary, providing the necessary resources and facilities for the green industry, a key player in sustainability. As these industries grow, they create a supportive ecosystem for carbon reduction, allowing for a gradual decrease in emissions and the promotion of sector-wide greening. Together, these intermediary factors ensure that industrial upgrading leads to more efficient and environmentally conscious land use, advancing the sustainability goals of CCs.

Accelerating internet agglomeration (IAG) serves as the hub of the information network for enhancing ULGUE in CCs. By facilitating the digital transformation of traditional industries, CCs are able to harness production factors more effectively, further promoting both green growth and efficient land utilization. The rapid evolution of cloud computing, big data, and other internet-driven technologies provides essential technological foundations for the low-carbon transformation of industrial sectors (Lin & Zhang, 2023). These innovations enable a shift from conventional, scale-oriented production models to more agile, demand-responsive frameworks. This transition not only increases production efficiency but also optimizes resource allocation and fosters sustainable operational practices (T. Y. Huang, Quan, & Li, 2024). A crucial intermediary in this process is the integration of advanced digital infrastructure, which facilitates real-time monitoring, analysis, and optimization of resource use across sectors. Moreover, collaborative digital platforms stimulate the exchange of knowledge and ideas, accelerating the widespread adoption of green practices (Wang, Shi, Liu, Zhong, & Ran, 2025). These digital advancements empower CCs to optimize resource management, achieve sustainable land use, and further their overarching sustainability objectives, thereby contributing significantly to environmental and economic resilience.

The advancement of urbanization levels (URB) serves as a crucial catalyst for improving the efficiency of ULGUE in CCs. Strengthening the role of CCs within CCC enhances their capacity to drive regional development and refine spatial arrangements. This, in turn, fosters the agglomeration of labor, talent, and other critical resources, further accelerating urbanization while ensuring a continuous influx of human capital vital for industrial progress. The concentration of these factors within CCs not only stimulates economic growth but also opens avenues for more sustainable urban planning practices. A key intermediary in this process is infrastructure development, which underpins the smooth functioning of a rapidly urbanizing population. Strategic investments in sustainable transportation, energy-efficient infrastructure, and green spaces guarantee that urban expansion aligns with environmental preservation. Moreover, the enhancement of governance and institutional capacity within CCs can steer urbanization in a direction that harmonizes development with ecological sustainability. By optimizing spatial resource allocation, such governance reduces urban sprawl, improves land use efficiency, and fosters the greening of urban landscapes. Ultimately, the extent of urbanization directly impacts the sustainable and efficient utilization of urban land, advancing the overarching goals of ULGUE (L. Li, Huang, Wu, & Yang, 2023).

On the basis of the aforementioned conclusions of theoretical derivation, this study proposes a “3I” (innovation of function, improvement of structure, integration of urban–rural) comprehensive theoretical analysis framework (Fig. 1). It can be used to systematically assess the effect mechanism of the implementation of macropolicy on land green utilization.

H1: CCC can significantly improve ULGUE.

H2: CCC can improve ULGUE by enhancing GIV, promoting AIS, accelerating IAG and improving URB.

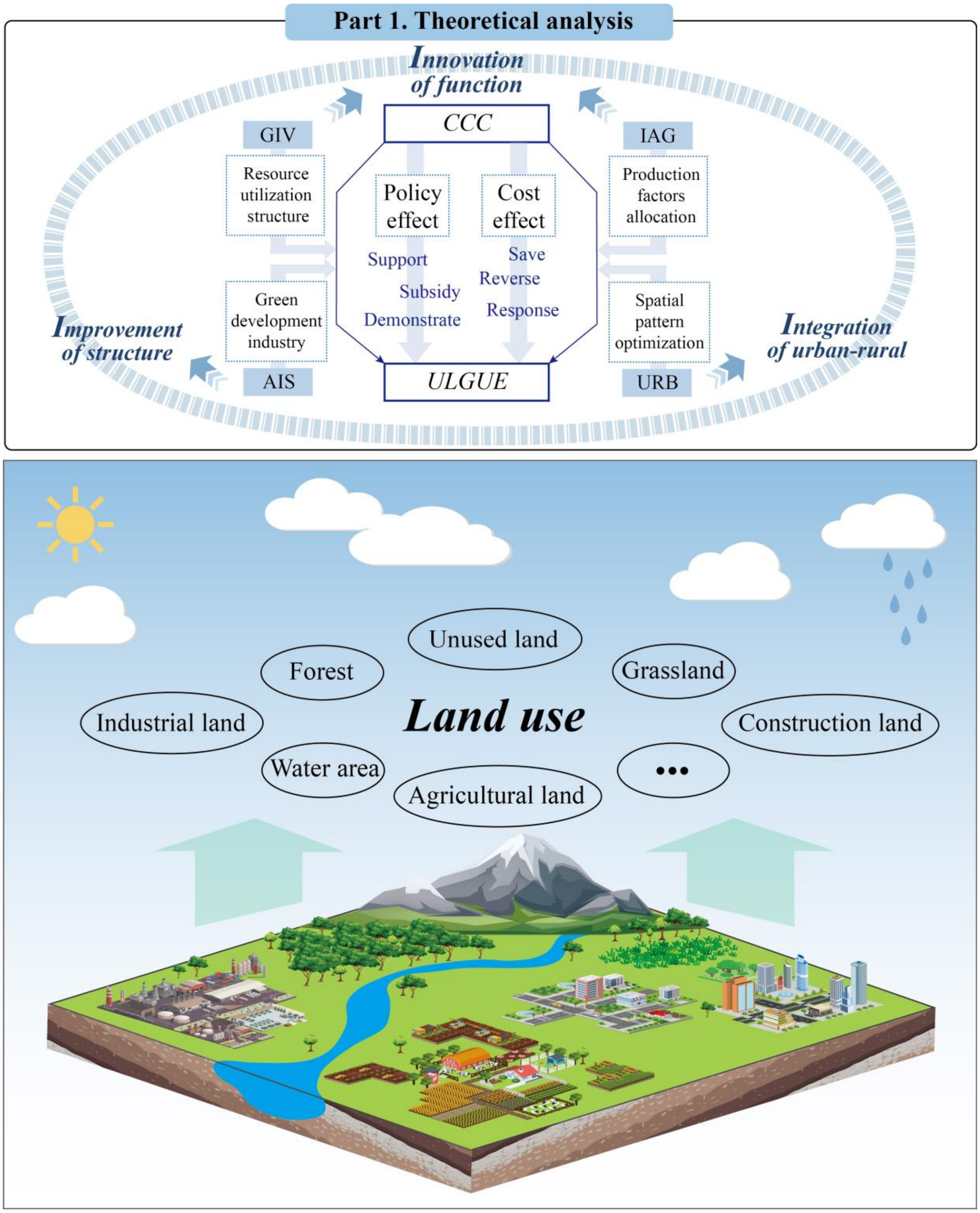

Fig. 1. Theoretical analysis framework.

3 Study design and material

3.1 Empirical models

3.1.1 Multiperiod DID model

Given the staggered rollout of the CCC policy across different urban agglomerations, a conventional two-period DID framework may fail to adequately capture the dynamic and heterogeneous treatment effects associated with varying implementation timings. In particular, when policy adoption is not synchronized, standard DID estimates can be biased by inappropriate comparisons between early and late treated units and by the inability to account for temporal variation in policy impacts. In this context, a multiperiod DID model provides a more suitable empirical strategy, as it explicitly incorporates differences in policy initiation timing and allows treated units to be compared with appropriate control groups in each period.

Compared with alternative approaches, this model can more effectively identify the average treatment effect while controlling for unobserved time-invariant heterogeneity and common time trends, thereby improving the credibility and robustness of the estimated policy effects. Accordingly, considering that there are five batches of the CCC policy, and that the implementation times differ, a multiperiod DID model is employed to assess the improvement effect of CCC on ULGUE. The detailed formula of this model is as follows:

$$ULGUE_{i,t} = \alpha_0 + \alpha_1 CCC_{i,t} + \alpha_m Controls_{i,t} + \varphi_i + \chi_t + \varepsilon_{i,t} \quad (1)$$

where $ULGUE_{i,t}$ is the *ULGUE* of city *i* in year *t*; $CCC_{i,t}$ is the *CCC* policy group; α_1 is the core assessment coefficient, which refers to the effect of CCC on ULGUE; $Controls_{i,t}$ refers to a set of control variables; φ_i, χ_t represent prefecture and temporal fixed effects, respectively; and $\varepsilon_{i,t}$ denotes random error items.

3.1.2 Mechanism test model

The following is the exact model used to determine the effects of CCC on ULGUE:

$$Mech_{i,t} = \beta_0 + \beta_1 CCC_{i,t} + \beta_m Controls + \varphi_i + \chi_t + \varepsilon_{i,t} \tag{2}$$

$$ULGUE_{i,t} = \gamma_0 + \gamma_1 CCC_{i,t} \times Mech_{i,t} + \gamma_m Controls + \varphi_i + \chi_t + \varepsilon_{i,t} \tag{3}$$

where $Mech_{i,t}$ represents the four mechanism variables, i.e., green innovation vitality, industrial upgrading, internet agglomeration and urbanization level; $\beta_0, \beta_1, \beta_m, \gamma_0, \gamma_1, \gamma_m$ represents the estimated coefficient; and the meanings of the remaining variables align with those of Eq. (1).

3.2 Research variable selection

3.2.1 Explained variable

In this study, the super-efficiency SBM model with constant-scale returns from the input perspective is used, and three dimensions, “input, desirable output, undesirable output", are introduced to measure ULGUE. To overcome the measurement results fixed ceiling and relaxation variable problem and reduce model bias, Eqs. (4) and (5) are constructed; the specific indicator system is shown in Table 1 (Y. Feng, Li, & Nie, 2023). This research uses the entropy method combined with industrial sulfur dioxide emissions, industrial wastewater emissions and industrial dust emissions to calculate the environmental pollution degree index (Dong, Wang, Zheng, Li, & Xie, 2020), which is regarded as the embodiment of negative environmental externalities to represent the undesired output indicator.

$$\rho^* = min \frac{\frac{1}{L}\sum_{i=1}^{L}\frac{\overline{x_i}}{x_{i0}}}{\frac{1}{M+N}\left(\sum_{r=1}^{M}\frac{\overline{y_r^g}}{y_{r0}^g}+\sum_{r=1}^{N}\frac{\overline{y_r^b}}{y_{r0}^b}\right)} \tag{4}$$

$$s.t.\begin{cases} \overline{x} \ge \sum_{j=1,\, j\ne k}^{t} \theta_j x_j \\ \overline{y^g} \le \sum_{j=1,\, j\ne k}^{t} \theta_j y_j^w \\ \overline{y^b} \ge \sum_{j=1,\, j\ne k}^{t} \theta_j y_j^b \\ \overline{x} \ge x_0, 0 \le \overline{y^g} \le y_0^g, \overline{y^b} \ge y_0^b, \theta \ge 0 \end{cases} \tag{5}$$

where L、M、N、t represent the quantity of decision units, input indicators, desirable output indicators, and undesirable output indicators, respectively; $x_{i0}, y_{r0}^g, y_{r0}^b$ represent the input indicators, desirable output indicators, and undesirable output indicators, respectively; $\overline{x_i}$、$\overline{y_r^g}$、$\overline{y_r^b}$ represent the corresponding relaxation variables; θ represents the weight vector; and ρ^* represents the target land's estimated green use efficiency value.

Table 1

Measurement indicator system for ULGUE

Indicator	**Indicator meaning**	**Specific definition**	**Unit**	**Reference**
Inputs	Land input	Urban built-up area	km^2	(Song, Yeung, Zhu, Xu, & Zhang, 2022)
	Labor input	Total number of employees in cities and towns	10,000 person	(N. Zhang, Sun, & Hu, 2024)
	Capital input	Gross fixed asset formation	10,000 yuan	(Song et al., 2022)

Desirable outputs	Economic output	Value-added value of secondary and tertiary industries	10,000 yuan	(Lu & Tao, 2024)
	Ecological output	Per capita park green space area	m^2/per person	(Lu & Ke, 2018)
	Social output	General fiscal general budget revenue	10,000 yuan	(Lu & Ke, 2018)
Undesirable output	Environmental negative externality	Environmental pollution degree	10,000 t	(Dong et al., 2020)

3.2.2 Explanatory variable

Central city construction (CCC), which is the interaction term between the region dummy variable (TREATED) and the period dummy variable (TIME), is the explanatory variable. The regional dummy variable equals 1 if the city is within the CCs and 0 otherwise. The period dummy variable is set to 1 if the policy was implemented before July 1st of this year and 0 otherwise.

3.2.3 Intermediate variables

(1) Green innovation universality (GIV) is characterized by the quantity of urban green patent applications (Li, Dong, & Dong, 2022).

(2) Industrial upgrading (AIS) is represented by the industrial structure level coefficient, which describes the evolution process of the three industries at the quantity level from the relative changes in the share ratio (Zheng et al., 2023). The precise formula for the calculations is as follows:

$$AIS_{i,t}=\sum_{n=1}^{3} y_{n,i,t}\times n,\quad n=1,2,3 \tag{6}$$

where $y_{n,i,t}$ denotes the share of the output of the nth industry in the regional GDP of city *i* in year *t*. From the standpoint of industrial layout, AIS illustrates the steady development of the industrial layout from the lead primary industry to the second and third industries.

(3) Internet agglomeration (IAG). This study used the geographical density method to represent the degree of regional internet agglomeration, and the detailed formula is as follows:

$$IAG_{i,t} = Inter_{i,t} / Area_{i,t} \tag{7}$$

where $Inter_{i,t}$ represents the number of urban internet broadband access users every year and $Area_{i,t}$ represents the area of the urban administrative area.

(4) Urbanization level (URB). This study defines the urbanization rate as the ratio of the permanent urban population to the total resident population.

3.2.4 Control variables

Citing of the current relevant research (Y. Feng et al., 2023; Lu & Tao, 2024; N. Zhang et al., 2024), this research chooses the following control variables: (1) government intervention (GOV) is measured by the percentage of expenditures in the local finance general budget relative to GDP; (2) the total savings rate (SAV) is represented by the household savings balance as a percentage of GDP at year-end; (3) population size (POP) is captured by the logarithmic ratio of urban population to urban area, reflecting population density; (4) the degree of openness (FDI) is proxied by the proportion of foreign capital utilization to GDP; (5) science and education investment intensity (SEI) is indicated by the ratio of science and education spending to GDP; (6) economic development level (PGDP) is represented by the logarithm of GDP per capita; and (7) financial level (FIN) is expressed as the ratio of financial institution loan balances to GDP at year-end. The descriptive statistics for these variables are presented in Table 2 and Fig. 2, and the specific content is presented in the supplementary information.

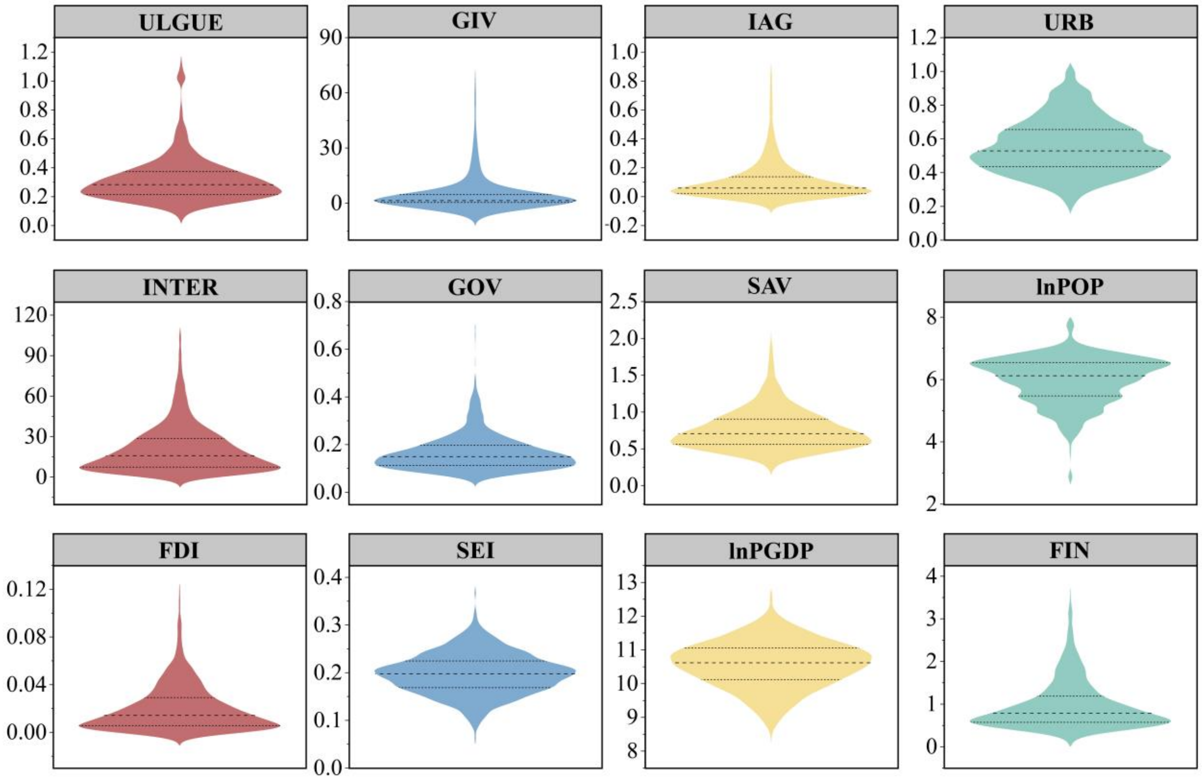

Fig. 2. Distribution characteristics of each variable.

Table 2

Descriptive statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
ULGUE	3408	0.284	0.187	0.027	3.934
CCC	3408	0.318	0.466	0	1
GOV	3408	0.167	0.081	0.044	0.712
SAV	3408	0.763	0.294	0.083	2.934
POP	3408	5.981	0.758	1.374	7.882
FDI	3408	0.021	0.024	0.000	0.353
SEI	3408	0.198	0.043	0.053	0.386
PGDP	3408	10.570	0.697	7.924	12.728
FIN	3408	0.986	0.644	0.075	9.623

GIV	3408	0.705	1.703	0.003	11.297
AIS	3408	2.292	0.147	1.913	2.836
IAG	3408	0.128	0.236	0.00	3.375
URB	3408	0.552	0.158	0.191	1.000

3.3 Study area

In 2010, the Ministry of Housing and Urban–Rural Development of the People's Republic of China issued the National Urban System Plan (2010–2020), naming the initial group of CCs as Beijing, Tianjin, Shanghai, Guangzhou, and Chongqing, and declaring scientific planning and positioning for their future development. By February 2018, the National Development and Reform Commission and the Ministry of Housing and Urban–Rural Development of the People's Republic of China sent letters and replies to Chengdu (May 2016), Wuhan (December 2016), Zhengzhou (January 2017) and Xi’an (February 2018), actively supporting and constructing them as CCs. The 213 prefecture-level cities in the 19 UAs clearly divided into the 13th and 14th Five-Year Plans are taken as the total research sample. In the UAs of the CCs, 129 prefecture-level cities served as the experimental group, whereas the remaining 84 prefecture-level cities served as the control group (Fig. 3).

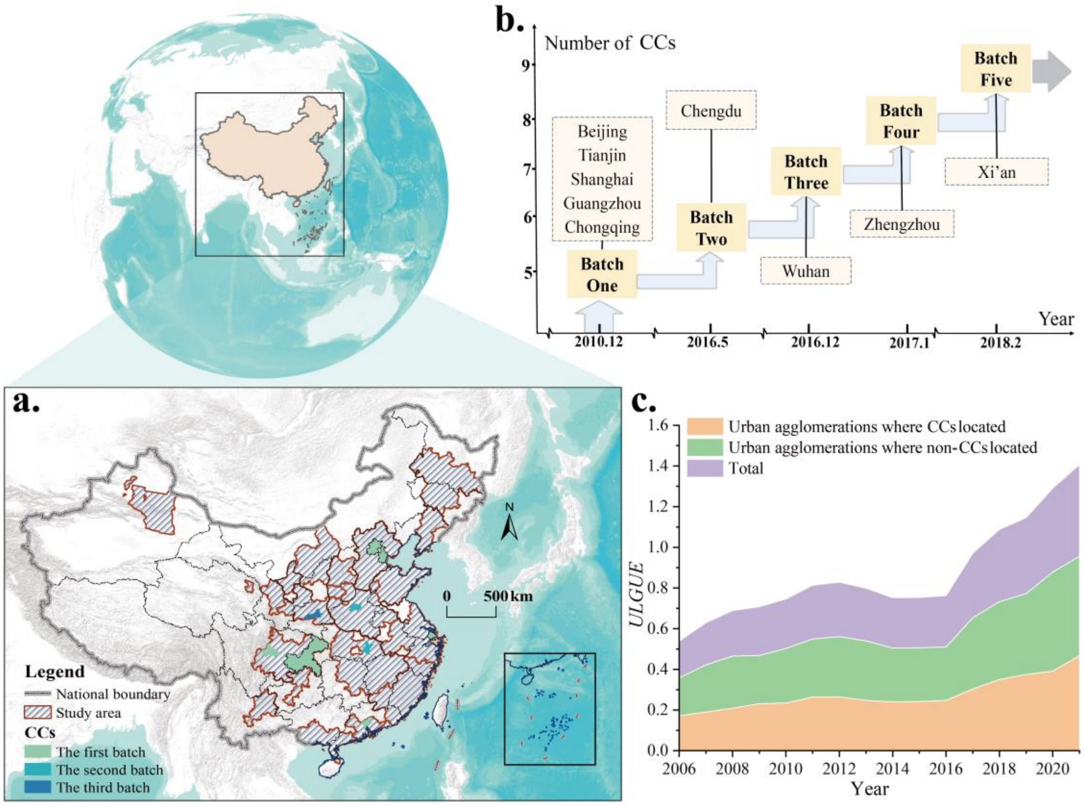

Fig. 3. Study area.

3.4 Required data sources

The statistics used in this study are city-level data obtained from the China City Statistical Yearbook, China Energy Statistical Yearbook, China Regional Economic Statistical Yearbook, and provincial and municipal Statistical Yearbooks. The patent data come from the China Research Data Platform (CNRDS). To ensure data integrity and consistency as much as possible, a small amount of missing data is supplemented by linear interpolation. The final research interval is from 2006 to 2021, and the research objects are 19 UAs, for a total of 213 prefecture-level cities. Moreover, missing values were addressed using a linear interpolation method. Specifically, for each variable with missing observations, values were interpolated on the basis of adjacent observations along the time dimension, thereby preserving the temporal continuity of the panel data. Given the relatively low proportion of missing values and the absence of systematic missingness, this method minimizes information loss while avoiding additional distributional assumptions, and it has been widely adopted in empirical studies using longitudinal data.

4 Results analysis

4.1 Spatiotemporal evolution analysis of ULGUE

The ULGUE of 19 UAs was statistically analyzed across different regions (Table 3) in this study. Moreover, the temporal variation characteristics of ULGUE are characterized in Fig. 4. Table 4 lists the specific names and abbreviations of the 19 UAs. The years 2006, 2013 and 2021 were selected as time nodes, and the natural breakpoint method was adopted to divide the ULGUE of each region into five categories: Levels I to V (Fig. 4). The spatial pattern of ULGUE in 19 UAs was described to analyze the quantity variation and spatial distribution of different regions in different years.

Table 3

Interregional statistical results of *ULGUE*

Year	[0, 0.1]	(0.1, 0.2]	(0.2, 0.5]	(0.5, 1.0]	(1.0, 1.5]
2006	23	121	67	0	2
2009	11	90	106	5	1
2012	8	56	140	7	2
2015	7	60	139	7	0
2018	5	28	145	27	8
2021	3	25	125	33	27

ULGUE increased from 0.181 in 2006 to 0.451 in 2021 in terms of comprehensive transformation. The average annual growth rate was 9.938%, and the total average value was 0.284. The results in Table 3 show that from 2006 to 2015, ULGUE changed from a low value interval to a high value interval toward the center interval. Since 2015, the low and central ranges have approached the high range. In 2021, ULGUE was in the high value range in 27 typical cities, including Beijing, Shanghai, Guangzhou, and Shenzhen. Most of these cities are first-tier and second-tier cities, with sufficient reserves of funds, talent and other factors; they actively invest in green and clean production, the rational use of land and environmental pollution control and have achieved remarkable results. The number of cities with low ULGUE decreased from 23 in 2006 to three in 2021, indicating that low-value cities may be restricted by a large population base and that effective measures and methods still need to be found in the green use of land.

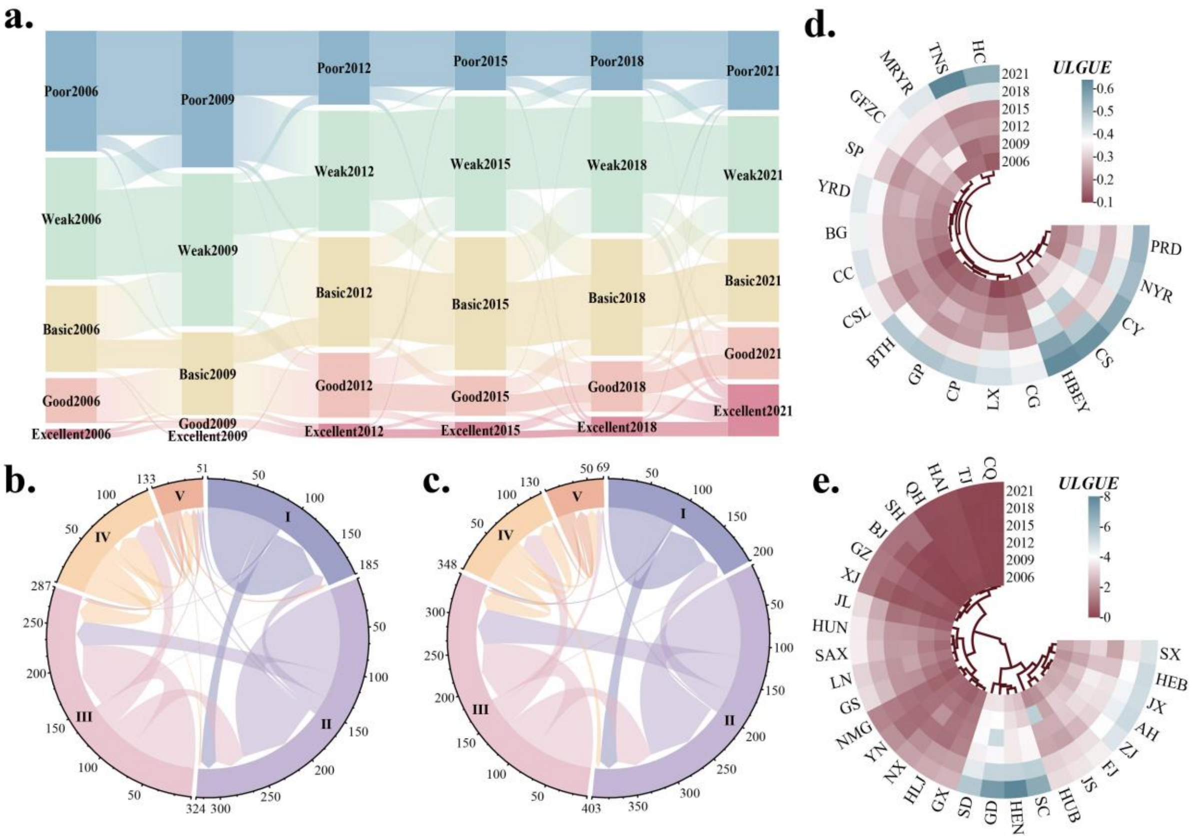

Fig. 4. Temporal variation characteristics of *ULGUE*.

Table 4

Abbreviations of the 19 Chinese UAs

No.	Abbreviation	Urban agglomeration	No.	Abbreviation	Urban agglomeration
1	BG	Beibu Gulf	11	CSL	Central and Southern Liaoning
2	CC	Chengdu-Chongqing	12	NYR	Ningxia-Yellow River
3	CY	Central Yunnan	13	CG	Central Guizhou
4	GP	Guanzhong Plain	14	SP	Shandong Peninsula
5	HC	Harbin-Changchun	15	TNS	Northern Tianshan Slope
6	GFZC	Guangdong–Fujian–Zhejiang Coastal	16	MRYR	Middle Reaches of Yangtze River
7	HBEY	Hohhot–Baotou Ordos–Yulin	17	YRD	Yangtze River Delta
8	CS	Central Shanxi	18	CP	Central Plains
9	BTH	Beijing–Tianjin–Hebei	19	PRD	Pearl River Delta
10	LX	Lanzhou–Xining			

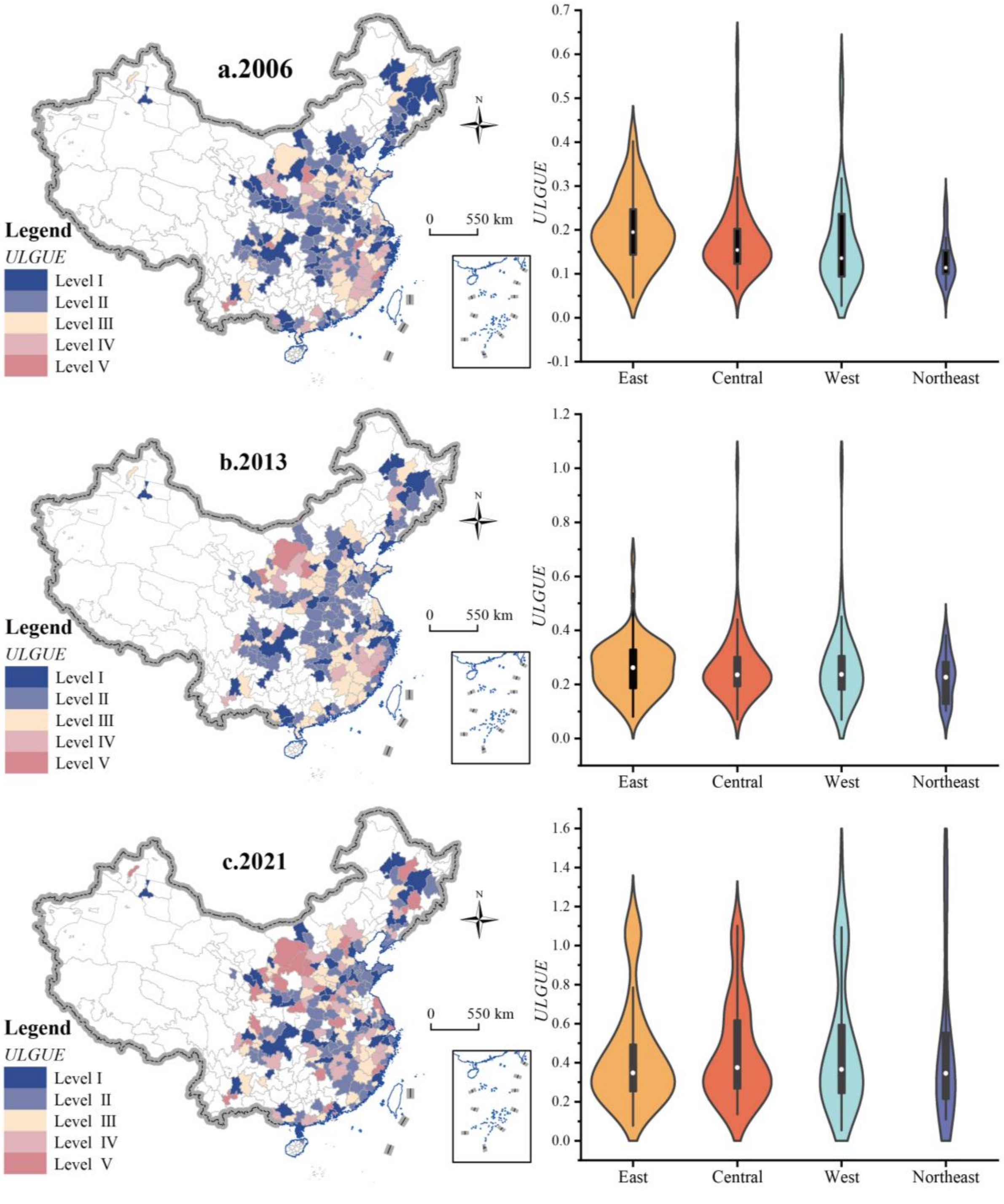

Fig. 5. Spatial–temporal pattern evolution of ULGUE for 19 UAs, 2006–2021.

ULGUE in the UAs was mostly Level I and II in 2006 (Fig. 5), accompanied by a state of concentration. Heilongjiang, Shandong, Zhejiang and Jiangxi Provinces are Level III and IV areas.

ULGUE of Chizhou, Guangan, Yuxi, Ningde and Lvliang is Level V. The spatial range of the Level III and II areas continued to expand in 2013. The spatial range of the Level I and V areas began to decrease, and only Inner Mongolia, Shaanxi, Jiangxi and Anhui had Level II UAs. In 2021, many cities were classified as Level V, showing a clear spatial clustering pattern. In the process of land utilization, UAs focus on improving social advantages in addition to economic advantages in regard to land usage, which helps to further realize the effective use of land, minimal pollution, and moderate intensification.

4.2 Benchmark regression results

Table 5 displays the findings on the basis of testing the effect of the CCC policy on ULGUE. The results reveal that when control variables are included, regardless of whether fixed effects are included, the core estimated coefficient is positive at the 1% level. The estimated coefficient of the implementation policy, as indicated in Column (4), is 0.044, indicating that compared with non-CCs, ULGUE of CCs displays a net improvement of 0.044, and CCC can effectively realize urban land green and efficient utilization; thus, Hypothesis 1 is preliminary validated. From a direct effects perspective, the construction of central cities significantly enhances the green utilization efficiency of urban land by optimizing land resource allocation and fostering the concentration of green industries. Central cities attract numerous green technologies and innovative sectors, which in turn promote efficient, low-carbon land use practices and reduce resource waste. Additionally, the improvement of infrastructure, particularly the development of green transportation systems, has facilitated the widespread adoption of public transportation, thereby reducing dependence on private vehicles and enhancing land utilization efficiency. Furthermore, central city planning policies prioritize ecological protection and the promotion of green buildings, ensuring sustainable land use and the efficient allocation of land resources.

Table 5

Benchmark regression

	(1) ULGUE	(2) ULGUE	(3) ULGUE	(4) ULGUE
CCC	0.206^{***}	0.425^{***}	0.048^{***}	0.044^{***}
	(0.019)	(0.016)	(0.017)	(0.017)
Controls	NO	NO	NO	YES
_cons	-1.471^{***}	-1.541^{***}	-1.421^{***}	-3.046^{***}
	(0.011)	(0.007)	(0.007)	(0.467)
Year fixed effect	NO	NO	YES	YES
City fixed effect	NO	YES	YES	YES
N	3408	3408	3408	3408
Adj. R^2	0.033	0.635	0.750	0.755

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; robust standard error in parentheses, the same as below.

4.3 Robustness tests

4.3.1 PSM-DID

This study adopted the PSM-DID model to overcome the influence of sample self-selection on the results (Xu et al., 2024). According to the matching values, the caliper nearest neighbor matching, radius matching and nearest neighbor matching methods are used. Further analysis reveals that regardless of the matching method used, the consistency and significance of the estimation results have been verified. Specifically, the results of nearest neighbor matching, radius matching, and propensity score matching all indicate that the estimated values remain stable and are statistically significant. This further supports the assumption of eliminating sample self-selection bias and enhances the credibility of the research conclusions. Additionally, the results in Table 6 show that the variation in the estimated values of the posttreatment effect after matching is relatively small, indicating that different matching methods have little effect on the conclusions and further validating the robustness of the model and the reliability of the conclusions.

4.3.2 Placebo test

To eliminate further non-observable factors, this research constructed new random treatment groups and control groups for the placebo simulation test. Fig. 6 illustrates that the estimated coefficients follow a normal distribution, centered at approximately 0, with most passing the 10% significance level test. These results indicate that in a randomly assigned scenario, this model does not exhibit systematic or persistent effects. This implies that the statistically significant estimates reported in the benchmark regression analysis are unlikely to be driven by unobserved confounding factors or spurious correlations. The placebo test has been passed.

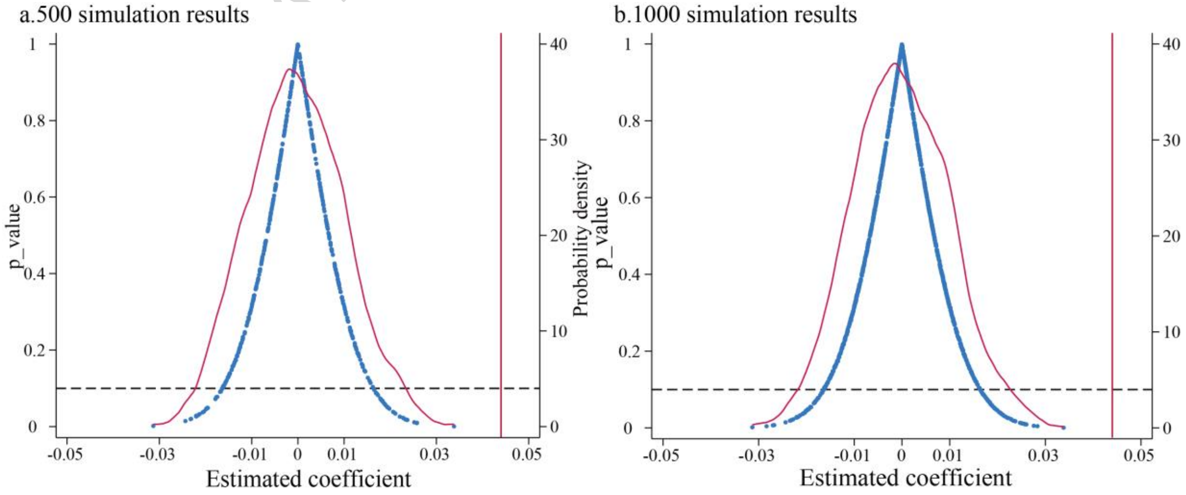

Fig. 6. Placebo test.

4.3.3 Parallel trend test

A parallel trend test was conducted to ensure that there was no systematic difference in ULGUE trends between CCs and non-CCs before the policy's implementation. As shown in Fig. 7, the estimated coefficients in the four years prior to policy implementation are statistically insignificant and fluctuate around zero, indicating that there is no systematic difference in the ULGUE trends between CCs and non-CCs before the introduction of CCC. These results support the parallel trends assumption and suggest that subsequent estimates are unlikely to be driven by preexisting differences. After the implementation of CCC-related policies, the dynamic treatment effect exhibits a clear temporal evolution. The coefficients gradually shift from near-zero or slightly negative values to positive values and display a fluctuating but overall upward trend over time. This pattern indicates that the effect of CCC on ULGUE is not immediate but emerges progressively as policy measures are implemented and supporting mechanisms take effect. The wavelike upward trajectory further reflects adjustment and learning processes during policy implementation. Overall, the dynamic results indicate that CCC has a sustained and strengthening effect on ULGUE rather than a short-term or transitory effect.

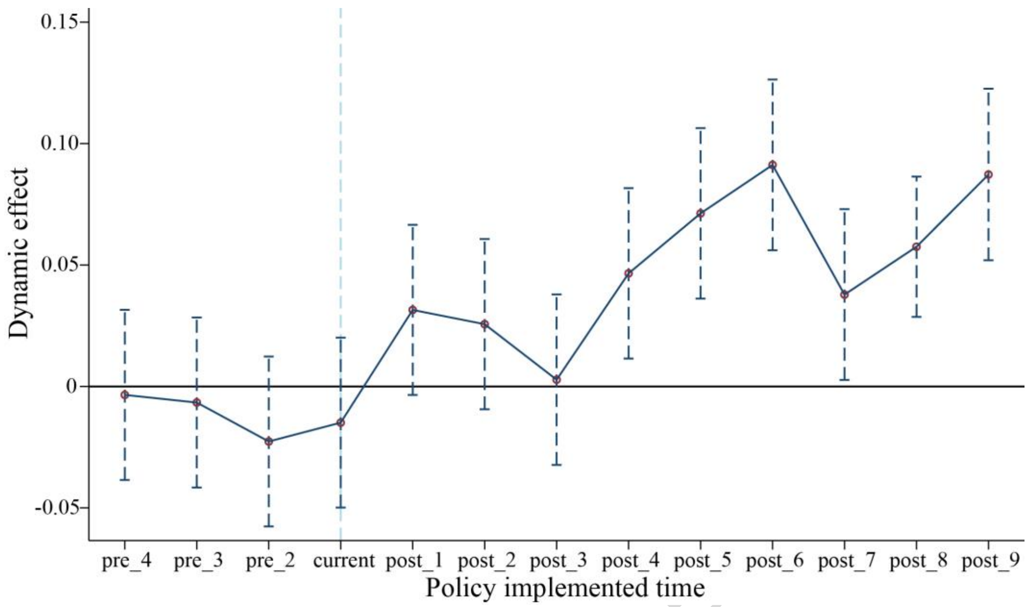

Fig. 7. Parallel trend test.

4.3.4 Excluding other policy effects

Policies such as the low-carbon city trials (low-carbon), new urbanization (new-urban), "Broadband China" demonstration city construction (broadband), and national e-commerce demonstration city (ecom) policies could affect ULGUE. This study introduced four policy dummy variables into the regression model to test its robustness. Considering the findings in Columns (4)–(7) of Table 6, after excluding the policies of the same period, the estimated coefficients were 0.037, 0.038, 0.066 and 0.032, respectively, and all of them satisfied the test of significance, indicating that they were not affected by the policy superposition.

Table 6

Robustness test I

	(1) Matching I	(2) Matching II	(3) Matching III	(4) Low-carbon	(5) New-urban	(6) Broadband	(7) Ecom
CCC	0.047^{***}	0.044^{***}	0.043^{**}	0.037^{**}	0.038^{*}	0.066^{***}	0.032^{*}
	(0.017)	(0.017)	(0.017)	(0.018)	(0.020)	(0.020)	(0.019)

low-carbon				0.038			
				(0.033)			
new-urban					0.017		
					(0.027)		
broadband						-0.054^{**}	
						(0.027)	
ecom							0.053
							(0.032)
Controls	YES	YES	YES	YES	YES	YES	YES
_cons	-2.797^{***}	-3.060^{***}	-3.157^{***}	-3.096^{***}	-3.051^{***}	-2.974^{***}	-3.180^{***}
	(0.520)	(0.470)	(0.471)	(0.469)	(0.467)	(0.468)	(0.474)
Year/City fixed effect	YES	YES	YES	YES	YES	YES	YES
N	3264	3407	3405	3408	3408	3408	3408
Adj. R^2	0.765	0.755	0.756	0.755	0.755	0.756	0.755

4.3.5 Endogeneity test

To address the potential endogeneity of CCC, this study employs three natural geographic variables, namely, the urban air ventilation coefficient (lnVC), annual precipitation (Rain), and river density (Stream), as instrumental variables. These variables satisfy the relevance condition by influencing the spatial suitability, environmental carrying capacity, and historical development constraints of cities, which in turn shape the likelihood and intensity of central city construction. Cities endowed with more favorable natural conditions are more likely to be designated central cities and to support sustained urban expansion and functional agglomeration, thereby establishing a strong correlation between the instrumental variables and the endogenous explanatory variable in shaping long-term patterns of regional urban development.

With respect to exogeneity, these natural geographic characteristics are largely predetermined and cannot be altered by short-term economic activities or policy interventions. After controlling for city fixed effects, year fixed effects, and a comprehensive set of socioeconomic covariates, lnVC, Rain, and Stream are unlikely to affect urban land green utilization efficiency through channels other than central city construction. Therefore, these variables do not directly influence the dependent variable but operate primarily through their impact on the development path of central cities, thereby satisfying the exclusion restriction. The validity of the instrumental variables is further supported by weak instrument tests and robustness checks, which confirm the reliability of the instrumental variable estimation.

The results of the series of tests show that both the Cragg–Donald Wald F statistic and the Kleibergen–Paap rk Wald F statistic are significantly greater than the critical value for weak identification, as determined by the Stock–Yogo test at the 1% significance level. This allows us to reject the null hypothesis that the instrumental variables are weakly correlated with the endogenous variables. In Table 7, the first-stage estimation results indicate that the estimated coefficients for the three instrumental variables, namely, the urban air circulation coefficient (lnVC), annual precipitation (Rain), and river density (Stream), are 0.143, 0.565, and 1.693, respectively, and are statistically significant at the 1% level. These results confirm that lnVC, Rain, and Stream are strongly correlated with the development of central cities. The second-stage estimation results show that after incorporating the instrumental variables, the coefficients maintain the same direction and significance as those from the benchmark regression and remain significantly positive. This further substantiates the finding that the construction of central cities significantly improves the efficiency of urban land green utilization, thereby reinforcing the robustness of the benchmark regression results.

Table 7

Robustness Test II

	Air flow coefficient		Average precipitation		River density	
	(1)	(2)	(3)	(4)	(5)	(6)
	CCC	ULGUE	CCC	ULGUE	CCC	ULGUE
CCC		0.047^{***}		0.042^{*}		0.117^{***}
		(0.017)		(0.022)		(0.037)
time×lnVC	0.143^{***}					
	(0.000)					
time×Rain			0.565^{***}			
			(0.009)			
time×Stream					1.693^{***}	
					(0.038)	
_cons	YES	YES	YES	YES	YES	YES
Year/City fixed effect	YES	YES	YES	YES	YES	YES
N	3408	3408	3408	3408	3408	3408

4.3.6 Impact threshold of confounding variables

To further assess the sensitivity of the estimated CCC effect to potential omitted variable bias, the study applied the impact threshold of a confounding variable (ITCV) framework. As shown in Table 8, the estimated ITCV for CCC is 0.1236. By comparison, the observed covariates display substantially smaller partial impacts, measured as the product of their partial correlations with CCC and with the outcome. Overall, the results indicate that the baseline inference regarding the positive CCC effect is relatively insensitive to omitted variable bias of a magnitude comparable to that captured by the observed controls. Accordingly, the ITCV results provide complementary support for the robustness of the main findings under the maintained assumptions of the ITCV sensitivity analysis.

Table 8

Robustness Test II

Variables	Coefficient	Standard error	*t* value	ITCV	Impact
CCC	0.131^{***}	0.019	6.78	0.1236	
GOV	2.079^{***}	0.131	15.86		0.0430
SAV	0.173^{***}	0.036	4.74		0.0168
POP	-0.125^{***}	0.012	-10.39		-0.0344
FDI	-1.142^{***}	0.352	-3.24		-0.0030
SEI	1.756^{***}	0.193	9.09		0.0023
PGDP	0.260^{***}	0.014	18.53		0.1134
FIN	-0.272^{***}	0.015	-18.29		0.0287

4.3.7 Other robustness tests

After excluding municipalities directly under the central government, the regression was re-estimated to control for their influence on the results. The results are listed in Column (1) of Table 9. Considering the abnormal extreme values and thick tail characteristics in the data, the tail of the data distribution of the control variables was reduced by 1%. Column (2) of Table 9 lists the outcomes; on the basis of the counterfactual idea, CCC is regarded as the explained variable, and ULGUE lagged 2–6 is taken as the explanatory variable. The regression results are shown in Columns (3)–(7) of Table 9. The calculated coefficients are 0.033 and 0.046, respectively, in Columns (1) and (2). The empirical examination results in Columns (3)–(7) are not significant, indicating that the original finding that CCC has a positive effect on ULGUE is valid and that the benchmark results are verified again.

Table 9

Other robustness tests

	Exclusion	Winsorization	Counterfactual tests				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)

CCC	0.033**	0.046***					
	(0.016)	(0.017)					
L2. ULGUE			0.031				
			(0.021)				
L3. ULGUE				0.034			
				(0.022)			
L4. ULGUE					0.034		
					(0.023)		
L5. ULGUE						0.035	
						(0.026)	
L6. ULGUE							0.015
							(0.029)
Controls	YES	YES	YES	YES	YES	YES	YES
_cons	-3.653***	-2.241***	-3.513***	-4.148***	-4.813***	-4.865***	-5.047***
	(0.441)	(0.545)	(0.528)	(0.547)	(0.551)	(0.613)	(0.686)
Year/City fixed effect	YES	YES	YES	YES	YES	YES	YES
N	3344	3408	2982	2769	2556	2343	2130
Adj. R^2	0.761	0.755	0.705	0.738	0.782	0.775	0.769

4.4 Heterogeneity tests

4.4.1 Strategic grade and geographical location of UAs heterogeneity

This research classifies the levels of UAs in which the CCs are located on the basis of the different development modes and strategic positioning of the 19 UAs and carries out a group regression. In addition, according to the geographical location of coastal UAs and inland urban classification, the heterogeneous effects of CCC on ULGUE are discussed from the perspective of urban strategy and geographical location.

Columns (1)–(4) of Table 10 show that, from the perspective of strategic grade differences, the CCC coefficient is significantly positive at the 1% level only for regional UAs. A plausible explanation is that UAs differ substantially in overall strength and development level. In national central UAs, CCs are therefore able to exert stronger spillover and radiation effects, thereby promoting ULGUE of the entire UA. Given the heterogeneity in geographic location, the contribution of CCs to ULGUE improvement is significantly greater in coastal UAs than in inland UAs. Inland UAs, primarily located in central and western China, are crucial land supply regions, but they are currently experiencing pronounced population decline and industrial contraction. Such resource misallocation weakens the efficiency of land allocation in inland cities across the central and western regions. In contrast, coastal UAs not only constitute the core areas for building world-class UAs but also benefit from core cities functioning as development engines, which makes it easier to enhance ULGUE.

4.4.2 Resource endowment heterogeneity

On the basis of the classification of resource-based cities in the National Sustainable Development Plan, an analysis of resource endowment heterogeneity was conducted (Y. D. Feng, Yuan, & Liu, 2023). The findings in Columns (5)–(6) of Table 10 demonstrate that while resource-based cities (RBCs) are currently not significant, CCC has a more comprehensive and obvious improvement effect on ULGUE of non-resource cities (non-RBCs). This may be because CCC primarily aims to enhance overall urban development by strengthening the economy, science, education, culture, and innovation through CCs rather than targeting specific structural constraints. Its policy focus is on improving comprehensive urban capacity and agglomeration functions, which can be more readily translated into higher-quality development in cities with relatively solid economic and industrial foundations. In contrast to policies such as low-carbon city pilots and carbon emission trading systems (W. Zhang, Li, Li, & Guo, 2020), CCC does not directly address the resource depletion and urgent transformation challenges faced by RBCs. In these cities, development constraints are more closely related to declining resource endowments and rigid industrial structures, and the absence of targeted measures for such issues may weaken the effectiveness of CCC in promoting green and efficient land use.

Table 10

Heterogeneity test I

	(1) National	(2) Regional	(3) Coast	(4) Inland	(5) RBCs	(6) Non-RBCs
CCC	-0.010	0.109***	0.121***	-0.053**	-0.034	0.084***
	(0.033)	(0.027)	(0.033)	(0.024)	(0.026)	(0.022)
Controls	YES	YES	YES	YES	YES	YES
_cons	-5.002***	-6.320***	-2.323**	-5.090***	-3.197***	-3.197***
	(1.353)	(0.746)	(1.176)	(0.566)	(0.693)	(0.668)
Year/City fixed effect	YES	YES	YES	YES	YES	YES
N	1472	1248	1568	1840	1200	2208
Adj. R^2	0.721	0.786	0.690	0.807	0.746	0.756

4.4.3 City-scale heterogeneity

In accordance with the permanent population (POP) results of the seventh census and reference released in 2014 on the adjustment of the city-scale standard notice, this research divides cities into four categories: megacities, large cities, medium-sized cities and small cities for grouping regression. Columns (1)–(4) of Table 11 show that CCC has a more pronounced effect on improving ULGUE in medium-sized cities. Compared with megacities and large cities, the land use pattern in medium-sized cities is still evolving and has not yet fully solidified, while these cities already exhibit a relatively strong capacity for resource agglomeration. This combination makes it easier for CCC to exert a visible marginal effect. In contrast, megacities and large cities have long relied on their substantial resource endowments and relatively efficient allocation mechanisms to adjust land use patterns through endogenous processes, resulting in more stable and mature land utilization outcomes. Consequently, the additional impact of CCC in these cities is relatively limited. Moreover, the effect of CCC is weaker in small cities, where constraints on resources, technological capability, and economic foundations are more binding, making it difficult to simultaneously promote economic growth and environmental sustainability in land use practices.

4.4.4 Batch heterogeneity

There are some differences in the implementation path of different batches of CCC. Considering the time difference and urban function difference of different batches of CCC, the following triple difference model is constructed for the batch heterogeneity test:

$$LGUE_{i,t} = v_0 + \sum_{n=1}^{3} v_n DCC_{i,t} \times B_n + v_m Controls_{i,t} + \varphi_i + \chi_t + \varepsilon_{i,t} \tag{8}$$

where B_n is the batch dummy variable, n is the batch variable, and n = 1,2,3. v_n is the estimated coefficient of the implementation effect of different batches of policies that need to be focused on. According to Eq. (1), the remaining variables have the same meaning.

Columns (5)–(7) of Table 11 indicate that the implementation effect of the first batch of CCC is significantly stronger than that of the second and third batches. This suggests that the first mover advantage in enhancing land utilization efficiency is more likely to emerge in the initial batch of UAs, which generally exhibit higher overall development levels and more favorable initial conditions. Moreover, compared with the first batch initiated in 2010, the second and third batches launched in 2017 and 2018 experienced much shorter construction periods and operated within a more limited functional scope. As a result, improvements in land use, particularly in terms of output quality and efficiency, remain relatively constrained, which weakens the observed effect on green land utilization. In addition, policy implementation lags may further lengthen the response time and slow the transmission of policy effects, thereby contributing to the comparatively weaker outcomes observed in the later batches.

Table 11

Heterogeneity test II

	(1) Megacities	(2) Big cities	(3) Medium-sized	(4) Small cities	(5) 1st batch	(6) 2nd batch	(7) 3rd batch
CCC	0.124	0.018	0.072^{***}	-0.057			
	(0.097)	(0.028)	(0.023)	(0.051)			
CCC×B1					0.068^{***}		
					(0.023)		
CCC×B2						0.011	
						(0.023)	
CCC×B3							0.005
							(0.050)
Controls	YES	YES	YES	YES	YES	YES	YES
_cons	6.624^{***}	-4.003^{***}	-6.790^{***}	-1.562	-3.230^{***}	-3.144^{***}	-3.170^{***}
	(2.483)	(0.769)	(1.067)	(1.140)	(0.465)	(0.469)	(0.467)
Year/City fixed effect	YES	YES	YES	YES	YES	YES	YES
N	336	1103	1200	592	3408	3408	3408
Adj. R^2	0.624	0.631	0.736	0.725	0.755	0.755	0.755

Note: Megacities (POP of more than 5 million); large cities (POP of more than 1 million and less than 5 million); medium-sized cities (POP of more than 500,000 and less than 1 million); small cities (POP of less than 500,000).

4.5 Mechanism tests

Following the confirmation of the positive impact of CCC on ULGUE and the theoretical discussion of its potential transmission mechanisms, this study structures the mechanism analysis by consolidating the four transmission channels into three analytically coherent dimensions. Green technological innovation and internet penetration are jointly classified as innovation of function, through which the policy enhances functional efficiency by activating innovation dynamics and mitigating information and coordination frictions. Industrial structure upgrading is examined under the improvement of structure, capturing policy-induced reallocations toward greener and more efficient production systems. Urbanization is incorporated into the integration of urban–rural spaces, highlighting the role of population agglomeration and factor mobility in reconfiguring land use patterns across urban and rural spaces. On this basis, the subsequent empirical analysis assesses each dimension sequentially, providing systematic and robust evidence on the specific pathways through which the policy improves urban land green utilization efficiency; the detailed results are reported in Table 12.

At the GIV mechanism level, Column (1) indicates that CCC exerts a significant positive influence on GIV, suggesting that the policy effectively enhances green innovation capacity by promoting the agglomeration of scientific and technological resources, strengthening innovation platforms, and improving urban innovation systems in central cities. This is consistent with the innovation-oriented positioning of CCC, which places green technological progress at the core of high-quality urban development. In Column (2), after GIV is incorporated into the ULGUE regression, the coefficient of CCC remains positive and statistically significant at the 1% level, with a magnitude of 0.033, indicating that CCC improves urban land green utilization efficiency partly by stimulating green innovation vitality. The enhancement of GIV contributes to the development and diffusion of green technologies, the optimization of production processes, and the reduction in environmental costs associated with land use, thereby increasing both the economic output and environmental performance per unit of land. This pattern indicates that CCC and GIV form a complementary interaction, whereby CCC strengthens the effectiveness of green innovation in improving ULGUE, and GIV serves as a key channel that amplifies the policy's impact on land use efficiency.

Columns (3)–(4) provide evidence that CCC operates through the industrial upgrading (AIS) channel to improve urban land green utilization efficiency. Specifically, CCC exhibits a positive and statistically significant association with AIS, with a coefficient of 0.024, indicating that the policy effectively accelerates the process of industrial upgrading. After AIS is included in the ULGUE equation, the coefficient of CCC decreases to 0.021 but remains statistically significant, suggesting that part of the policy effect is transmitted through industrial upgrading. This pattern implies that AIS plays a meaningful mediating role in linking CCC to ULGUE. In practice, CCC promotes industrial upgrading by guiding central cities to take the lead in restructuring traditional manufacturing and enhancing industrial competitiveness. By strengthening technological research and development, expanding producer services, and fostering deeper integration between manufacturing and services, CCC facilitates a shift toward higher value-added and lower pollution industrial activities. These changes reduce the dependence on extensive land use, improve the intensity and quality of land output, and lower environmental pressures, thereby exerting a clear and positive influence on ULGUE. Overall, the results indicate that industrial upgrading constitutes an important channel through which CCC enhances green and efficient urban land utilization.

From the IAG perspective, Columns (5)–(6) show that CCC significantly accelerates the development of information agglomeration, and the interaction term between CCC and IAG is positive and highly significant, indicating a strong and economically meaningful linkage between the policy and this mechanism. These results suggest that CCC not only directly promotes the concentration and integration of information resources but also strengthens the extent to which IAG contributes to improvements in ULGUE. As important information integration and communication hubs, central cities under the CCC framework place greater emphasis on the research, development, and application of digital and information technologies. These technologies provide more efficient tools for transforming traditional industries, enhancing coordination among production factors, and improving the precision of land-related decision-making. Through improved information sharing and reduced transaction and coordination costs, IAG facilitates more efficient allocation and intensive use of land inputs while also lowering the environmental pressures associated with inefficient land use. Consequently, the significant interaction effect indicates that the expansion of IAG under CCC conditions amplifies the policy's positive impact on ULGUE, highlighting information agglomeration as a key channel through which CCC translates digital advantages into greener and more efficient urban land utilization.

With respect to the URB mechanism, Columns (7)–(8) show that CCC has a positive and statistically significant effect on URB, with an estimated coefficient of 0.012, indicating that the policy effectively enhances both the quality and structural configuration of urbanization. When URB is introduced into the ULGUE specification, the interaction term between CCC and URB remains positive and significant at the 1% level, providing strong evidence that CCC improves urban land green utilization efficiency through an urbanization-mediated pathway. This finding underscores that URB is not simply an incidental outcome of CCC but a substantive transmission channel through which policy interventions translate into land use efficiency gains. As a core instrument guiding national urbanization, CCC reshapes urban spatial organization by optimizing population distribution, strengthening functional linkages across cities, and restraining disorderly expansion. These adjustments foster more compact and coordinated urban forms, thereby mitigating land fragmentation and reducing environmental pressure per unit of land. Concurrently, improvements in URB enhance the alignment between urban expansion and green spatial planning, offering critical structural support for greener and more efficient land use. Collectively, the coherence between empirical evidence across all mechanism variables and theoretical expectations validates the proposed transmission pathways and provides robust support for Hypothesis 2.

Table 12

Mechanism test

	(1) GIV	(2) ULGUE	(3) AIS	(4) ULGUE	(5) IAG	(6) ULGUE	(7) URB	(8) ULGUE
CCC	0.340^{***}		0.024^{***}		0.043^{***}		0.012^{***}	
	(0.051)		(0.002)		(0.006)		(0.002)	
GIV×CCC		0.033^{***}						
		(0.005)						

AIS×CCC				0.021***				
				(0.007)				
IAG×CCC						0.178***		
						(0.036)		
URB×CCC								0.077***
								(0.029)
Controls	YES	YES	YES	YES	YES	YES	YES	YES
_cons	16.305***	-3.660***	1.971***	-3.044***	1.841***	-3.453***	-0.312***	-3.132***
	(1.388)	(0.467)	(0.066)	(0.466)	(0.172)	(0.466)	(0.062)	(0.465)
Year/City fixed effect	YES	YES	YES	YES	YES	YES	YES	YES
N	3408	3408	3408	3408	3408	3408	3408	3408
Adj. R^2	0.793	0.758	0.938	0.755	0.834	0.757	0.952	0.755

5 Discussion

The results show that CCC significantly improves urban land green utilization efficiency within urban agglomerations through four interrelated channels: the promotion of green technological innovation, industrial structure upgrading, the expansion of internet penetration, and the optimization of the urbanization process. Heterogeneity analysis further reveals that these effects are substantially more pronounced in nonresource-based cities, coastal regions, and medium-sized cities but remain relatively limited in resource-dependent cities. Taken together, these findings indicate that the effectiveness of CCC is strongly conditioned by local structural characteristics rather than being spatially uniform. Cities located in coastal areas and embedded within mature urban agglomerations typically benefit from more efficient factor allocation, stronger innovation spillovers, and more advanced spatial governance frameworks, which jointly facilitate the translation of CCC-related policy incentives into tangible improvements in green land use efficiency (Wu, Wang, & Ren, 2025). In contrast, resource-based cities are often constrained by industrial path dependence and rigid land use structures, resulting in higher transformation costs and attenuated policy responsiveness. The particularly strong effects observed in medium-sized cities can be interpreted through a “scale regulation” perspective, whereby cities of intermediate sizes combine sufficient administrative and industrial capacity with greater flexibility in land reallocation and spatial restructuring (Li, Cai, & Jin, 2024). Overall, these findings underscore that CCC operates through context-dependent mechanisms, highlighting the importance of differentiated and place-sensitive policy design to maximize its effectiveness in advancing greener and more efficient urban land use.

The temporal evolution of the CCC effect further indicates that improvements in urban land green utilization efficiency materialize in a cumulative and path-dependent manner rather than as an immediate policy response. The initially weak or even insignificant effects observed in the early stages of implementation suggest the presence of adjustment costs associated with institutional coordination, land market regulation, and the reallocation of production factors. As CCC implementation deepens, the progressively strengthening effects reflect the gradual maturation of policy-induced mechanisms, including the diffusion of green technologies, the consolidation of industrial upgrading, and the reconfiguration of urban functional spaces. This dynamic pattern implies that CCC operates through long-term structural transformation rather than short-term administrative intervention. Land use efficiency gains tend to unfold as cities internalize new governance frameworks, align land development with environmental objectives, and adapt to broader institutional and economic transformations over time (Guo & Jin, 2025).

From a mechanistic standpoint, the findings indicate that CCC enhances urban land green utilization efficiency through an integrated transmission framework comprising functional innovation, structural upgrading, and urban–rural integration. Functional innovation is manifested in the combined effects of green technological innovation and internet penetration, suggesting that CCC not only stimulates the development of cleaner, land-saving technologies but also strengthens digital connectivity, thereby reducing information friction and accelerating the diffusion and effective adoption of green practices across urban systems. Structural upgrading operates primarily through industrial transformation, whereby CCC facilitates the reallocation of land and production factors away from land-intensive and high-emission activities toward higher value-added and environmentally compatible sectors, resulting in more efficient and sustainable land use configurations. Urban–rural integration, proxied by the level of urbanization, reflects the role of CCC in improving the coordination of population mobility, infrastructure provision, and public services, which supports more compact spatial organization and curbs inefficient land expansion. Overall, these mechanisms suggest that CCC should be understood not only as a spatial planning instrument but also as a comprehensive development-oriented policy framework. By reconfiguring technological capabilities, economic structures, and the spatial organization of urban territories, CCC facilitates a coordinated trajectory of development. This finding further substantiates that improvements in land use efficiency arise from the simultaneous evolution of innovation dynamics, structural transformation, and spatial integration and are fully consistent with conclusions drawn in studies conducted by scholars from Ethiopia (Koroso & Zevenbergen, 2024).

While this study offers meaningful insights into the effects and mechanisms of CCC on urban land green utilization efficiency, several limitations need further consideration. The reliance on aggregate city-level data may mask substantial intraurban heterogeneity in land use patterns and environmental performance, limiting the ability to capture variations across districts or neighborhoods within the same city; future research drawing on finer spatial units or high-resolution spatial data could therefore yield a more nuanced understanding of localized dynamics and policy impacts. Moreover, although this study identifies multiple transmission channels through which CCC operates, other important institutional dimensions, such as land governance capacity, intergovernmental coordination, and fiscal management practices, are not explicitly incorporated into the analysis. Integrating these governance-related factors in subsequent research would help clarify how CCC interacts with local institutional contexts and would contribute to a more comprehensive assessment of its role in shaping green and efficient urban land use outcomes.

6 Conclusions and policy recommendations

This study employs panel data from 213 prefecture-level cities across 19 Chinese UAs for the period from 2006 to 2021. A super-efficiency SBM model is used to assess ULGUE, while a DID model is applied to evaluate the impact of CCC on ULGUE and explore the underlying mechanisms. The empirical findings can be summarized as follows. (1) CCC has a significant positive effect on ULGUE, and this conclusion remains stable after addressing key concerns related to sample selection, policy exogeneity, and time-varying confounding factors through a series of robustness checks. (2) The magnitude of this effect exhibits pronounced heterogeneity, with stronger impacts observed in regional UAs, coastal UAs, nonresource-based cities, medium-sized cities, and cities included in the first batch of CCC implementation. (3) The mechanism analysis indicates that CC construction improves ULGUE through multiple, mutually reinforcing channels, including strengthening GIV, advancing AIS, accelerating IAG, and improving URB. Through the joint operation of these mechanisms, CCC promotes more efficient and environmentally sustainable land use, thereby generating a “win–win” outcome in which economic development and environmental performance are simultaneously enhanced.

Drawing on the foregoing empirical evidence, this study derives the following policy implications. First, governments should move beyond a uniform development logic and advance a more functionally differentiated development pattern within UAs by consolidating CCs as strategic cores. The spatial planning of CCs should explicitly reflect their role as carriers of green transformation and high-quality development rather than merely as centers of scale expansion. By strengthening structured upstream–downstream linkages and functional coordination between CCs and surrounding cities, CCC can facilitate the formation of stable regional production networks and coordinated land use systems. Importantly, policymakers need to carefully manage the balance between radiation and siphon effects, as excessive factor concentration in CCs may weaken the development capacity of peripheral cities. A well-calibrated CCC strategy can therefore enhance regional competitiveness while maintaining spatial equilibrium within UAs.

Second, achieving sustained improvements in ULGUE necessitates a fundamental shift in land factor governance away from expansion-oriented development toward efficiency gains rooted in innovation, with CCC construction continuing to function as a key institutional anchor. In practice, this transformation should be advanced through the coordinated operation of multiple interrelated channels rather than isolated or single-purpose policy instruments. Enhancing green innovation capacity allows CCs to more effectively translate concentrated scientific and technological resources into cleaner production technologies and higher-efficiency land use practices, thereby improving both economic returns and environmental performance per unit of land. Concurrently, industrial upgrading should be steered toward the progressive reallocation of land from low value-added and pollution-intensive activities to higher value-added, technology-intensive, and service-oriented sectors, which increases land output quality while alleviating environmental pressure. The expansion of digital and information infrastructure further underpins this process by reducing coordination and transaction costs and enabling more precise matching among land, capital, and labor. In parallel, improvements in urbanization quality provide essential spatial support, as more compact urban forms and closer alignment between population distribution and industrial structure help restrain inefficient land expansion. When these channels operate in an integrated and mutually reinforcing manner, they generate endogenous momentum for long-term improvements in ULGUE, diminishing the reliance on short-term, administratively driven interventions.

Third, given the pronounced heterogeneity in location, scale, and development stages across cities and UAs, the implementation of CCC should follow a differentiated and place-based approach. The nonuniform policy effects identified in the empirical analysis underscore that CCC effectiveness depends critically on initial development conditions and local constraints. Accordingly, UAs should align CCC objectives with their comparative advantages and structural characteristics, while policymakers should emphasize top-level design when formulating differentiated urban development pathways. Tailoring land-related green transformation policies to local contexts can better unlock the green land use dividends of CCC and support a coordinated transition toward sustainable land use and long-term economic growth.

Data availability

The datasets used and analyzed in the current study, together with the analytical code supporting the results of this study, are available from the corresponding author upon reasonable request.

References

Chen, K. Q., Wang, Y. X., Li, N. H., Xu, Y. L., Zheng, Y. H., Zhan, X. L., & Li, Q. X. (2023). The impact of farmland use transition on rural livelihood transformation in China. Habitat International, 135. doi:10.1016/j.habitatint.2023.102784

Chen, W., Chen, W. J., Ning, S. Y., Liu, E. N., Zhou, X., Wang, Y. A., & Zhao, M. J. (2019). Exploring the industrial land use efficiency of China's resource-based cities. Cities, 93, 215-223. doi:10.1016/j.cities.2019.05.009

Ding, Z. W., Dai, Y. Y., Zhou, L., Chen, S., & Wan, S. W. (2026). How regional integration accelerates urban energy transition: A quasi-experimental study from China's city clusters.

Energy, 342. doi:10.1016/j.energy.2025.139618

Dong, F., Wang, Y., Zheng, L., Li, J. Y., & Xie, S. X. (2020). Can industrial agglomeration promote pollution agglomeration? Evidence from China. Journal of Cleaner Production, 246. doi:10.1016/j.jclepro.2019.118960

Fei, R. L., Lin, Z. Y., & Chunga, J. (2021). How land transfer affects agricultural land use efficiency: Evidence from China's agricultural sector. Land Use Policy, 103. doi:10.1016/j.landusepol.2021.105300

Feng, Y. D., Yuan, H. X., & Liu, Y. B. (2023). The energy-saving effect in the new transformation of urbanization. Economic Analysis and Policy, 78, 41-59. doi:10.1016/j.eap.2023.02.008

Feng, Y., Li, Y., & Nie, C. F. (2023). The Effect of Place-Based Policy on Urban Land Green Use Efficiency: Evidence from the Pilot Free-Trade Zone Establishment in China. Land, 12(3). doi:10.3390/land12030701

Guan, Y., Qiang, Y., Qu, Y. Y., Lu, W. T., Xiao, Y., Chu, C. J., . . . Shao, C. F. (2024). Environmental sustainability and Beautiful China: A study of indicator identification and provincial evaluation. Environmental Impact Assessment Review, 105. doi:10.1016/j.eiar.2024.107452

Guo, B. S., & Jin, G. (2025). Heterogeneity of urban-rural responses to multigoal policy from an efficiency perspective: An empirical study in China. Habitat International, 158. doi:10.1016/j.habitatint.2025.103341

Guo, X. Y., Zhang, Y. X., Guo, D. F., Lu, W. T., & Xu, H. (2023). How does ecological protection redline policy affect regional land use and ecosystem services? Environmental Impact

Assessment Review, 100. doi:10.1016/j.eiar.2023.107062

Hu, R. F., Xu, W. Q., Liu, L. F., Cui, Z. Y., & Zhao, C. Y. (2023). The impact of urban agglomerations on carbon emissions in China: Spatial scope and mechanism. Journal of Cleaner Production, 419. doi:10.1016/j.jclepro.2023.138250

Huang, J., Han, W. J., Zhang, Z. F., Ning, S. S., & Zhang, X. L. (2024). The decoupling relationship between land use efficiency and carbon emissions in China: An analysis using the Socio-Ecological Systems (SES) framework. Land Use Policy, 138. doi:10.1016/j.landusepol.2024.107055

Huang, T. Y., Quan, Y. Y., & Li, N. (2024). Reallocate to the right place: The heterogeneous effect of internet use on factor allocation of rural households in China. Economic Analysis and Policy, 84, 1328-1346. doi:10.1016/j.eap.2024.10.026

Jiang, Y. F., Long, H. L., Ives, C. D., Deng, W., Chen, K. Q., & Zhang, Y. N. (2022). Modes and practices of rural vitalisation promoted by land consolidation in a rapidly urbanising China: A perspective of multifunctionality. Habitat International, 121. doi:10.1016/j.habitatint.2022.102514

Jiang, Y., Yang, L., Wei, X. K., & Zhang, X. D. (2024). The Impact of Government Digital Transformation on Land Use Efficiency: Evidence from China. Land, 13(12). doi:10.3390/land13122080

Koroso, N. H., & Zevenbergen, J. A. (2024). Urban land management under rapid urbanization: Exploring the link between urban land policies and urban land use efficiency in Ethiopia. Cities, 153. doi:10.1016/j.cities.2024.105269

Li, J. M., Dong, K. Y., & Dong, X. C. (2022). Green energy as a new determinant of green growth in China: The role of green technological innovation. Energy Economics, 114. doi:10.1016/j.eneco.2022.106260

Li, L., Huang, X. J., Wu, D. F., & Yang, H. (2023). Construction of ecological security pattern adapting to future land use change in Pearl River Delta, China. Applied Geography, 154. doi:10.1016/j.apgeog.2023.102946

Li, T. N., Liu, Y. B., Ouyang, X., Zhou, Y. J., Bi, M., & Wei, G. E. (2024). Sustainable development of urban agglomerations around lakes in China: Achieving SDGs by regulating Ecosystem Service Supply and Demand through New-type Urbanization. Habitat International, 153. doi:10.1016/j.habitatint.2024.103206

Li, W. M., Cai, Z. Y., & Jin, L. S. (2024). Urban green land use efficiency of resource-based cities in China: Multidimensional measurements, spatial-temporal changes, and driving factors. Sustainable Cities and Society, 104. doi:10.1016/j.scs.2024.105299

Lin, B. Q., & Zhang, A. X. (2023). Can government environmental regulation promote low-carbon development in heavy polluting industries? Evidence from China's new environmental protection law. Environmental Impact Assessment Review, 99. doi:10.1016/j.eiar.2022.106991

Lu, D., Wang, Z. P., Su, K. C., Zhou, Y. J., Li, X. X., & Lin, A. W. (2024). Understanding the impact of cultivated land-use changes on China's grain production potential and policy implications: A perspective of non-agriculturalization, non-grainization, and marginalization. Journal of Cleaner Production, 436. doi:10.1016/j.jclepro.2024.140647

Lu, X. H., & Ke, S. G. (2018). Evaluating the effectiveness of sustainable urban land use in China from the perspective of sustainable urbanization. Habitat International, 77, 90-98. doi:10.1016/j.habitatint.2017.10.007

Lu, X. H., & Tao, X. Q. (2024). Local Government Environmental Attention and Urban Land Green Use Efficiency in China: The Intermediary Role of Industrial Restructuring. Land, 13(1). doi:10.3390/land13010021

Ma, J. H., Shang, Y. J., & Liang, Z. H. (2024). National central cities, technological innovation, and economic growth. Finance Research Letters, 67. doi:10.1016/j.frl.2024.105890

Niu, W. H., Luo, L., Shi, Y., Chai, C. Q., Wang, H. Y., Tian, Q., . . . Zhang, B. B. (2025). Impacts of "One Household One Plot" and "One Village Group One Plot" fragmentation consolidation models on cultivated land use transition from perspective of human-land system. Habitat International, 156. doi:10.1016/j.habitatint.2024.103252

Shi, R. X., Yi, P. T., Li, W. W., & Wang, L. (2022). Sustainability self-determination evaluation based on the possibility ranking method: A case study of cities in ethnic minority autonomous areas of China. Sustainable Cities and Society, 87. doi:10.1016/j.scs.2022.104188

Song, X. Q., Feng, Q., Xia, F. Z., Li, X. Y., & Scheffran, J. (2021). Impacts of changing urban land-use structure on sustainable city growth in China: A population-density dynamics perspective. Habitat International, 107. doi:10.1016/j.habitatint.2020.102296

Song, Y., Yeung, G., Zhu, D. L., Xu, Y., & Zhang, L. X. (2022). Efficiency of urban land use in China's resource-based cities, 2000-2018. Land Use Policy, 115. doi:10.1016/j.landusepol.2022.106009

Tan, S. K., Hu, B. X., Kuang, B., & Zhou, M. (2021). Regional differences and dynamic evolution of urban land green use efficiency within the Yangtze River Delta, China. Land Use Policy, 106. doi:10.1016/j.landusepol.2021.105449

Wang, A. P., Lin, W. F., Liu, B., Wang, H., & Xu, H. (2021). Does Smart City Construction Improve the Green Utilization Efficiency of Urban Land? Land, 10(6). doi:10.3390/land10060657

Wang, C., Wang, J. Q., & Ai, W. W. (2024). Do urbanization, environmental regulation and GDP affect agricultural land use efficiency? Implications for just transition. Environmental Impact Assessment Review, 105. doi:10.1016/j.eiar.2024.107421

Wang, Q. X., Ren, J., Su, H. Y., Chen, Z. R., & Diao, M. (2026). Unraveling the impacts of free trade zones on urban innovation intensity: Evidence from China. Land Use Policy, 162. doi:10.1016/j.landusepol.2025.107901

Wang, Y. F., Shi, M., Liu, J. N., Zhong, M., & Ran, R. (2025). The impact of digital-real integration on energy productivity under a multi-governance framework: The mediating role of AI and embodied technological progress. Energy Economics, 142. doi:10.1016/j.eneco.2024.108167

Wu, Z. F., Wang, Y., & Ren, Y. (2025). Optimizing green space-building landscape characteristics of key urban functional zones for comprehensive thermal environment mitigation. Landscape and Urban Planning, 257. doi:10.1016/j.landurbplan.2025.105314

Xu, A. T., Song, M. Y., Wu, Y. G., Luo, Y. F., Zhu, Y. H., & Qiu, K. Y. (2024). Effects of new urbanization on China's carbon emissions: A quasi-natural experiment based on the improved PSM-DID model. Technological Forecasting and Social Change, 200. doi:10.1016/j.techfore.2023.123164

Yang, X., Yang, Y., Wang, F., Zhou, M. Y., & Wang, Y. (2024). Evaluation and convergence analysis of science and technology innovation efficiency in China's national central cities based on the super-efficiency SBM-ML model. Technology Analysis & Strategic Management. doi:10.1080/09537325.2024.2408732

Yang, Y. Y., Ren, X. Z., & Yan, J. M. (2023). Trade-offs or synergies? Identifying dynamic land use functions and their interrelations at the grid scale in urban agglomeration. Cities, 140. doi:10.1016/j.cities.2023.104384

Yu, H. J., & Yuan, C. L. (2025). The impact of land conservation and intensification policy on green land use efficiency: The role of factor agglomeration. Journal of Cleaner Production, 501. doi:10.1016/j.jclepro.2025.145297

Zhang, J. M., Wang, T., Goh, Y. M., He, P. M., & Hua, L. (2024). The effects of long-term policies on urban resilience: A dynamic assessment framework. Cities, 153. doi:10.1016/j.cities.2024.105294

Zhang, N., Sun, F. C., & Hu, Y. L. (2024). Carbon emission efficiency of land use in urban agglomerations of Yangtze River Economic Belt, China: Based on three-stage SBM-DEA model. Ecological Indicators, 160. doi:10.1016/j.ecolind.2024.111922

Zhang, W. X., Wang, B., Wang, J., Wu, Q., & Wei, Y. D. (2022). How does industrial agglomeration affect urban land use efficiency? A spatial analysis of Chinese cities. Land Use Policy, 119. doi:10.1016/j.landusepol.2022.106178

Zhang, W., Li, J., Li, G. X., & Guo, S. C. (2020). Emission reduction effect and carbon market efficiency of carbon emissions trading policy in China. Energy, 196. doi:10.1016/j.energy.2020.117117

Zheng, R. J., Wu, G., Cheng, Y., Liu, H. M., Wang, Y. P., & Wang, X. Y. (2023). How does digitalization drive carbon emissions? The inverted U-shaped effect in China. Environmental Impact Assessment Review, 102. doi:10.1016/j.eiar.2023.107203

Zhou, Y. X., & Lu, Y. (2023). Spatiotemporal evolution and determinants of urban land use efficiency under green development orientation: Insights from 284 cities and eight economic zones in China, 2005-2019. Applied Geography, 161. doi:10.1016/j.apgeog.2023.103117

Zhu, R. M., Xia, Z. Y., Liang, F. C., Yuan, C. C., & Liu, L. M. (2025). Non-linear responses and critical thresholds of human well-being to ecosystem services across land-use intensities in urbanizing areas. Environmental Impact Assessment Review, 114. doi:10.1016/j.eiar.2025.107921

Zhu, X. H., Zhang, P. F., Wei, Y. G., Li, Y., & Zhao, H. R. (2019). Measuring the efficiency and driving factors of urban land use based on the DEA method and the PLS-SEM model-A case study of 35 large and medium-sized cities in China. Sustainable Cities and Society, 50. doi:10.1016/j.scs.2019.101646

Zuo, Z. L., Guo, H. X., Li, Y. L., & Cheng, J. H. (2022). A two-stage DEA evaluation of Chinese mining industry technological innovation efficiency and eco-efficiency. Environmental Impact Assessment Review, 94. doi:10.1016/j.eiar.2022.106762

Competing interests

The authors declare that they have no competing interests.

Ethical approval

This study does not involve human participants or their data so no informed consent and other forms of ethical approve is needed.

Informed consent

No informed consent was needed for this paper. This article does not contain any studies with human participants performed by any of the authors.