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The effects of low-carbon city pilot policy on urban land green use efficiency: evidence from 284 cities in China

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Abstract
China's low-carbon city pilot (LCCP) initiative aims at devising and implementing a holistic strategy for fostering environmentally sustainable economic progress. This ambitious and multidimensional transition towards a green economy carries implications across economic, social, and environmental domains. This study explores whether the LCCP policy effectively contributes to enhancing urban land green use efficiency (ULGUE). Harnessing data collected from a sample of 284 Chinese cities between 2004 and 2019, we employ the super-efficiency SBM model to gauge ULGUE and utilize a time-varying Difference-in-Differences (DID) method along with a quasi-experimental design to scrutinize the specific influence of the LCCP policy. The empirical results reveal that the LCCP policy significantly boosts ULGUE in pilot cities, yielding a marked increment of 3.23%. This facilitative impact materializes as the policy drives industrial restructuring and fosters technological innovation within these cities. Notably, however, the effectiveness of the LCCP policy on ULGUE varies considerably across different Chinese regions. It exerts a particularly supportive effect in eastern areas, leading to an average ULGUE increase of 7.68%, whereas it fails to register any statistically significant influence on ULGUE in the central and western parts of China. Furthermore, the analysis indicates that the LCCP policy's impact on ULGUE demonstrates a more substantial improvement in non-old industrial base (NOIB) cities and non-resource-based (NRB) cities relative to other city types. These findings enrich the scholarly discourse around the LCCP policy and provide useful experiences for other developing nations, thereby broadening the comprehension of viable strategies for sustainable urban development worldwide.

Keywords Urban land green use efficiency · Low-carbon city pilot · Difference-in-differences model · China

Extended author information available on the last page of the article

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1 Introduction

Since the introduction of the reform and opening-up policy in 1978, China has undergone a profound socio-economic transformation, which has not only produced an unprecedented economic growth miracle, but also a large-scale urbanization drive. Compared to the 17.9% recorded in 1978, the urbanization rate increased significantly to 60.6% in 2019 (Liu et al., 2022). The China Statistical Yearbook reported a substantial increase in the urbanized land area of China, which had expanded to 60,312.5 km^2 by the end of 2019. This expansion represents a substantial increase of approximately 8.3 times compared to the 7,300 km^2 recorded in 1978. While rapid urbanization has brought about social and economic benefits by enhancing convenience and efficiency for Chinese people's production and daily life activities, it has also resulted in long-term ecological and social challenges. Countries face significant challenges in meeting Sustainable Development Goal number 7 by addressing energy poverty, enhancing energy efficiency, and reaching net-zero emissions (Dagher & Yacoubian, 2012; Zakari et al., 2022; Dagher et al., 2023). Human activity is a major contributor to CO_2 emissions, which are up 50% since the start of the industrial revolution (Lamb et al., 2021). Urban regions worldwide cover just 2% of the Earth's total land area, yet they use 75% of the energy generated and produce 78% of the CO_2 emissions (Lu et al., 2022). China's urban areas are largely to blame for the nation's overall carbon emissions, making up approximately 85% of the country's energy consumption and carbon footprint (Shan et al. 2018). All governments, particularly the Chinese government, have a vital responsibility to decrease greenhouse gas emissions. After overtaking the US in 2005, China emerged as the global leader in CO_2 emissions. This trend is continuing, with China maintaining its position as the largest emitter. In 2022, China contributed a staggering 11,550.2 million tons of CO_2 to the global tally, constituting a substantial 30.7% share of worldwide emissions, as documented in BP's 2023 report. As a responsible global actor, China has committed itself to significantly curbing its carbon intensity, with a target of reducing emissions by 60–65% relative to 2005 levels per GDP unit by 2030. This commitment is part of the national strategy to achieve its peak carbon emissions, as outlined by Mi et al. (2017). China has made significant efforts to achieve this goal, with the most decisive initiative being the low-carbon city pilot (LCCP) policy. Evaluating how well the LCCP policy promotes sustainable urban development is the primary goal of this article.

Land is a vital resource for economic and social progress, playing a vital part in enabling a shift to low-carbon practices through sustainable use (Zhang & Dilanchiev, 2022). Land use is one of the anthropogenic sources, based on the five identified greenhouse gases producing economic sectors (Ribeiro et al., 2019). Additionally, urban land resources serve as spatial carriers for socioeconomic development, and their development and utilization are significant sources of greenhouse gases (Lamb et al., 2021). The primary source of new urban areas is agricultural land. If this resource is not employed judiciously, it can exacerbate greenhouse gas emissions while simultaneously weakening the land's potential to absorb carbon. Hence, the eco-friendly and efficient deployment of urban land is not merely advantageous for propelling urbanization and fostering regional economic progress, but also constitutes a pivotal measure for nations to confront the global climate crisis (Feng et al., 2023). The rationale behind the efficient use of urban land serves as a foundational strategy to mitigate resource limitations, sustain economic vibrancy, and achieve the sustainable development of urban land (Niu et al., 2023b). China is currently in a transition towards high-quality economic development, emphasizing ecological and environmental management to replace outdated growth drivers and advance sustainable economic growth (Song et al., 2022). In order to efficiently manage emissions of greenhouse gases and investigate methods for low-carbon development, the National Development and Reform Commission (NDRC) of China initiated three sets of LCCP policy initiatives in the years 2010, 2012, and 2017. The goal of this policy is to encourage the growth of eco-friendly cities through restructuring sectors and enhancing the application of renewable energy sources along with energy conservation strategies (Yang et al., 2023c).

The LCCP policy constitutes a pivotal initiative by the Chinese government geared toward ameliorating environmental conditions, and confronting the pressing issues of promoting sustainable growth (Tan et al., 2017). The pilot program provides a special “quasi-natural experiment” (QNE) for policy evaluation. Most studies focus on a single analysis of its economic effect (Qiu et al., 2021), social consequence (Yang et al., 2023a), or environmental effect (He et al., 2023). However, there are few comprehensive assessments of LCCP policy that consider its effects from all three perspectives.

It is, therefore, crucial to evaluate the effectiveness of LCCP policy from an integrated “economic-social-environmental” perspective, and the urban land green use efficiency (ULGUE) provides us with such an integrated tool (Zeng et al., 2023). This research, which is new from this angle, aims to study the mechanisms underlying the LCCP policy’s impact on ULGUE. The question we need to address is how to comprehensively measure the ULGUE. Is it possible for the ULGUE to be effectively promoted by the LCCP policy? If the promotion effect is valid, what are the mechanisms and transmission pathways? What is the heterogeneity of such impacts? As China navigates its critical juncture of achieving carbon peaking, compounded by mounting economic challenges, generating robust scientific evidence regarding the LCCP policy’s influence on ULGUE assumes paramount importance for unraveling the intricacies of the policy’s operative mechanisms and their implications for sustainable urban development. This has significant theoretical value and practical consequences for China’s green transition. This research could also provide direction for other emerging nations in achieving a balance between sustainable development and environmentally friendly utilization of urban.

This work makes the following main contributions: (1) By taking into account the nature of ULGUE, the impacts on the economy, society, and environment are thoroughly examined, and a super-efficiency SBM model is employed for measurement, thus broadening the scope of previous studies in this area. (2) The study employs data from three groups of pilot cities to conduct a thorough analysis of the effect of LCCP policy on ULGUE using the DID model. (3) The study investigates the theoretical mechanisms through which LCCP policies affect ULGUE and empirically analyzes their structural and technological effects. (4) It explores how LCCP policy affects ULGUE in cities with different industrial features, resource endowments, and regional characteristics, offering a more nuanced view of the complexities involved.

The paper’s structure is as follows: The literature review is presented in Sect. 2. The background information on the policy and theoretical mechanisms by which the LCCP policy influences ULGUE are analyzed in Sect. 3. The design of the study is explained in Sect. 4. The findings and empirical analyses are presented in Sect. 5. We analyze heterogeneity in Sect. 6. A summary of the study’s findings and their implications for policy are provided in Sect. 7.

2 Literature review

2.1 Literature on the ULGUE

Maximizing the efficiency of urban land usage via eco-friendly methods is vital for attaining sustainable urban progress in China (Hu et al., 2024). ULGUE is a concept that has evolved from the extension of conventional land use efficiency. Its theoretical foundation has expanded and evolved, moving beyond just measuring economic output per land area to now incorporating green land utilization efficiency, which considers economic, social, and environmental advantages (Pellegrini & Fernández, 2018). The measurement of ULGUE has undergone advancements in line with the enhanced comprehension of its theoretical implications (Zhou & Lu, 2023). In terms of the construction of measurement indexes, a straightforward approach involves utilizing a single input-output ratio for measurement (Chen et al., 2016). Nevertheless, that method does not completely grasp the intricate relationship among various input factors and multiple outcomes in the urban land use setting (Wang et al., 2023c). Subsequent scholars have addressed this limitation by devising a multi-indicator comprehensive assessment system, which incorporated the factors of structure, scale, and agglomeration to provide a comprehensive measurement of land use efficiency (Lambin & Meyfroidt, 2010). The methods used for multi-indicator comprehensive assessment might vary depending on the specific study emphasis (Wu et al., 2017). Currently, there is no established uniform indicator evaluation system, and these methods tend to be very subjective (Ouyang et al., 2023). Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA) are two commonly used models for measuring and evaluating performance (Tan et al., 2021). The use of SFA necessitates a thorough understanding of the error distribution in the distribution situation, which can be challenging to establish with precision (Haider & Mishra, 2021). Conversely, the identification of a particular production function model is not required by DEA, which adopts a goal-driven optimization methodology to ascertain the significance of various input elements (Liu et al., 2020). This approach helps to avoid bias towards certain factors and allows for a more objective assessment of decision units involving multiple input factors and output indicators (Tone, 2002). Presently, studies on ULGUE tend to focus on assessing and examining its spatial and temporal development, primarily from a geographic standpoint (Tan et al., 2021; Zhou & Lu, 2023). A few scholars have conducted causal inference studies using ULGUE as the dependent variable. Ge et al. (2021) examined the effects of urban agglomeration, while Feng et al. (2023) analyzed the causal impact of establishing pilot free trade zones on ULGUE. Overall, there is a lack of literature on causal inference of ULGUE.

2.2 Literature on policy evaluation of LCCP

The LCCP policy has been trialed in China for over 10 years. Researchers have extensively analyzed the impacts of the policy, with a primary emphasis on assessing a single effect of the policy like economic, social, or environmental consequences. Several researchers have analyzed how LCCP policy has influenced total factor productivity at urban and enterprise levels in terms of economic impact (Chen et al., 2021). At the industrial level, the LCCP policy positively affects industrial structure optimization, yet has minimal influence on industrial structure rationalization according to Zheng et al. (2021). Scholars analyzing the societal impacts of the LCCP policy have noted that in test cities, the policy notably boosts the need for labor in businesses (Wang et al., 2023a), encourages entrepreneurship (Wang et al., 2023b), supports the shift towards eco-friendly lifestyles among residents (Liu & Xu, 2022), and effectively lowers electricity consumption rates (Yang et al., 2023b). The assessment of the LCCP policy focuses more on its environmental effects. The primary objective of constructing low-carbon cities is the mitigation of carbon emissions. Most scholars have concluded that the LCCP policy has effectively decreased carbon emissions (Huo et al., 2022) and enhanced carbon emission efficiency (Zhang et al., 2022). However, according to a study conducted by Lyu et al. (2023), the LCCP policy has minimal effect on decreasing carbon emissions relative to GDP. Certain works of literature have also examined how LCCP initiatives affect energy efficiency. Enhancing energy efficiency is essential to address the increasing energy needs in various regions and lower worldwide carbon emissions (Dagher, 2012; Khan et al., 2022). It was found that the LCCP policy of China has driven energy efficiency improvements (Niu et al., 2023a).

The current research on the theory and measurement methods of ULGUE has been enriched by reviewing the literature (Fig. 1). These findings lay the groundwork for further exploration in this paper. Nevertheless, when considering these bodies of literature collectively, there remains a potential for further enhancement in the research conducted within these domains. Regarding the substance of LCCP policy research, the majority of current studies focus primarily on singular assessments of economic, social, or environmental consequences. Nonetheless, a dearth of thorough evaluations exists that incorporate the combined consequences of all three aspects. The connotation of ULGUE effectively encompasses the multifaceted advantages related to urban land use, including economic, social, and environmental aspects, which offers a comprehensive assessment factor for LCCP policy effect studies. Thus, it is crucial to look into how LCCP policy has affected ULGUE since it provides insight into the overall effects of environmental laws on cities. Moreover, concerning the selection of indicators, the majority of previous scholarly works have examined cities on a broader scale, encompassing the entire urban area. In contrast,

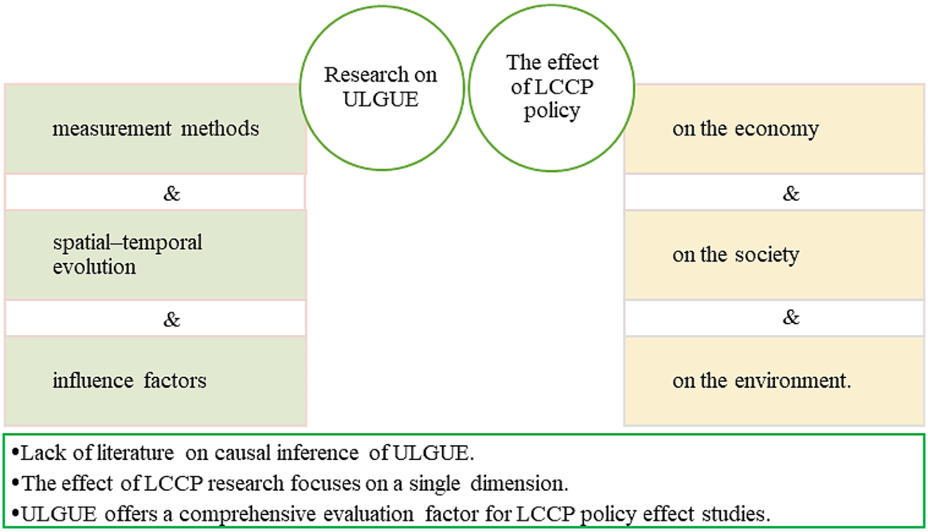

Fig. 1 Literature review analysis chart

this study specifically concentrates on municipal districts characterized by more frequent human activities, as well as higher population and economic densities. This approach allows for a fairer assessment of the impact of the policy.

3 Policy background and research hypothesis

3.1 Policy background

The Chinese government first committed to reducing carbon emission intensity by 40–45% by 2020 compared to 2005 levels, as part of a larger global framework for mitigating carbon emissions, at the 2009 Copenhagen Climate Conference. To meet this target of reducing carbon emissions by 2020, the NDRC initiated the first set of LCCP projects in July 2010. The initial phase was rolled out in 5 provinces and 8 cities, aiming to establish a framework for industry and consumption that reduces carbon emissions. In November 2012, 3 provinces and 26 prefecture-level cities were selected to join the second group. The second pilot batch aims to broaden the range of pilot initiatives, leverage the distinct advantages of various regions, promote constructive inter-regional dynamics, and explore viable strategies for managing greenhouse gas emissions and achieving environmentally sustainable and low-carbon growth in diverse regional contexts. Subsequently, in January 2017, the NDRC expanded the pilot program's reach by designating 45 cities as the third cohort of experimental zones. The number of LCCP cities in China is now 71, distributed in 29 provinces. There are 70 LCCP cities total in this paper, excluding Lhasa, when data availability is taken into account. (Fig. 2).

3.2 Hypothesis development

Local authorities are required to carry out various actions outlined by the government as part of the LCCP policy, aimed at decreasing carbon emissions and encouraging sustainable urban growth. These measures include conserving energy, reducing emissions, promoting alternative energy sources, and optimizing urban planning (Millimet et al., 2009; Ryan, 2012). The final aim is a significant reduction in carbon emissions and an advancement in the overall extent of sustainable urban development (Zhang et al., 2017). Effectively reducing CO_2 emissions in urban areas requires a focus on structural and efficiency-oriented measures (Niu et al., 2023a), encompassing the refinement of the energy mix and downsizing the footprint of carbon-intensive activities. To accomplish the objective of carbon footprint reduction, one strategy involves governments instituting measures to bar certain heavily polluting industries from entering the market and limiting land transactions involving such pollution-intensive sectors (Lin & Zhang, 2023). Meanwhile, they actively strive to reshape the regional industrial landscape by incentivizing firms to adopt low-carbon technologies, thereby facilitating the greening of existing industries. Optimizing industrial activities related to land, in terms of increasing output capacity and reducing pollution, is expected to significantly enhance the ULGUE. Herein lies the presentation of the first hypothesis:

Hypothesis 1 Implementation of the LCCP policy contributes to the promotion of ULGUE.

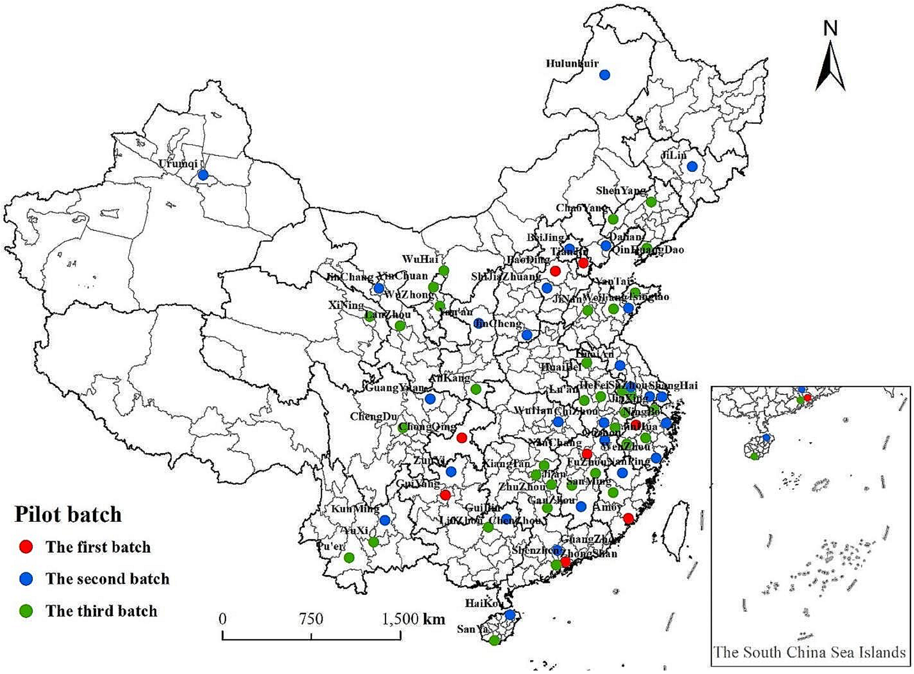

Fig. 2 The distribution of the LCCP

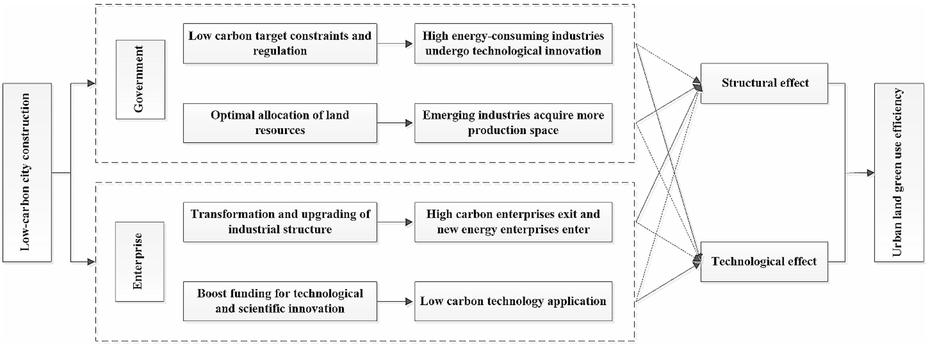

Fig. 3 The theoretical explanation of how the LCCP policy impacts ULGUE

At the heart of the LCCP policy lies the quest for a harmonious convergence between low-carbon practices and economic progress, a synergy that would propel environmentally sound and sustainable urban growth (Lan et al., 2023). Recognizing that carbon emissions exert profound influences on the external environment, predominantly through structural and technological levers (Lu et al., 2022), this paper posits that the LCCP policy will exert dual influences on ULGUE: firstly, by optimizing the industrial structure, and secondly, by stimulating technological innovation (Fig. 3).

The LCCP policy, implemented by both government and enterprises, has the potential to enhance ULGUE by effectively optimizing the industrial structure via structural effects. As far as the government is concerned, the governments of pilot cities will comprehensively use various policy tools such as finance, taxation, and land allocation to adjust the industrial structure of their jurisdiction (Liu et al., 2020). Some high-polluting and high energy-consuming industries facing transformation difficulties will be limited by costs and environmental standards to relocate from the region, to provide production space for the introduction of other emerging industries. The method of promoting industrial upgrading through land resource allocation is very effective in China because the Chinese government is in charge of the primary land market (Liu et al., 2018). Concerning enterprises, the LCCP policy imposes constraints requiring production enterprises to transform and upgrade. Meanwhile, conventional farming, manufacturing, and service sectors are making a shift towards sustainable agriculture, environmentally friendly industry, and updated services. Stricter environmental regulations may lead surplus enterprises and those with high energy, pollution, and emission levels to relocate to places with laxer laws (Zhang et al., 2023). Conversely, businesses known for innovative energy sources, cutting-edge materials, and emerging technologies are set to expand into experimental urban areas (Qiu et al., 2021). Consequently, this phenomenon would result in a transformation of the industrial structure within the designated pilot areas. Moreover, the LCCP policy's technological impetus has steered regional industries towards transitioning into low-carbon segments. The shift has resulted in reduced energy usage and pollution in the manufacturing process. The specified pilot area is anticipated to attract more eco-friendly businesses, thereby aiding in the improvement and modernization of the local industrial layout. Therefore, the second hypothesis introduced in this context:

Hypothesis 2 The LCCP policy enhances ULGUE by optimizing the industrial structure.

Starting from the government and enterprises, LCCP policy can improve ULGUE by optimizing technological innovation through technological effects. The hypothesis put forth by Porter suggests that environmental regulations can exert a beneficial influence on technological innovation. Essentially, properly crafted environmental regulations can incentivize companies to innovate, improve their production capacities, and offset the expenses of implementing environmental protection measures (Porter & van der Linde, 1995). On the one hand, governments will encourage businesses to innovate technologically and enhance their production efficiency by phasing out outdated production capacity. Conversely, enterprises are motivated to participate in technological innovation when faced with regulatory pressure. Otherwise, these enterprises will face huge costs for violating the law. This, in turn, improves the production efficiency per unit area and reduces the emission of pollutants from the production process. Ultimately, this results in a mutually beneficial partnership between the government and enterprises. Moreover, the introduction of low-carbon regulations bears a technical impact that will facilitate the transition of industries in the region towards low-carbon practices. Consequently, this transformation will result in lower in energy usage and pollution throughout the manufacturing process (Ramanathan et al., 2017). The promotion of ULGUE can be achieved by the upgrading of capital invested in urban land and the decrease of pollutant emissions resulting from low-carbon technology advancement and industrial transformation. Therefore, the third hypothesis is proposed here:

Hypothesis 3 The LCCP policy enhances ULGUE by upgrading technological innovation.

4 Research design

4.1 Benchmark model

The DID framework facilitates the analysis of discrepancies among cities that have implemented experimental policies and those that have not (Zeng et al., 2023). It also enables an evaluation of changes in the utilization of green spaces before and after these policies are introduced, effectively delineating the impact of the policies (Athey & Imbens, 2017; Cheng et al., 2023). Another pivotal benefit of the DID framework is that it can significantly mitigate endogeneity problems (Zhang et al., 2023). This research treats the rollout of LCCP policy as a QNE, utilizing a time-varying DID approach to establish policy experimental groups in batches to assess whether the LCCP policy has improved ULGUE. Referring to Athey and Imbens (2017), the benchmark model is as follows:

$$ulgue_{it} = \alpha_o + \alpha_1 lccppost_{it} + \alpha_2 X_{it} + \phi_i + \gamma_t + \epsilon_{it} \tag{1}$$

where i symbolizes a specific city while t denotes the year. The term $ulgue_{it}$ signifies the ULGUE of the city i during year t. If city i is a pilot city in year t, then $lccppost_{it}$ equal to 1, otherwise 0 will be returned. The focus of this research is α_1 and its significance. X_{it} are the control variables. ϕ_i and γ_t denote the city-fixed and the time-fixed effect variables, respectively. ϵ_{it} is the term of the random error. Figure 4 displays a schematic representation of the DID model.

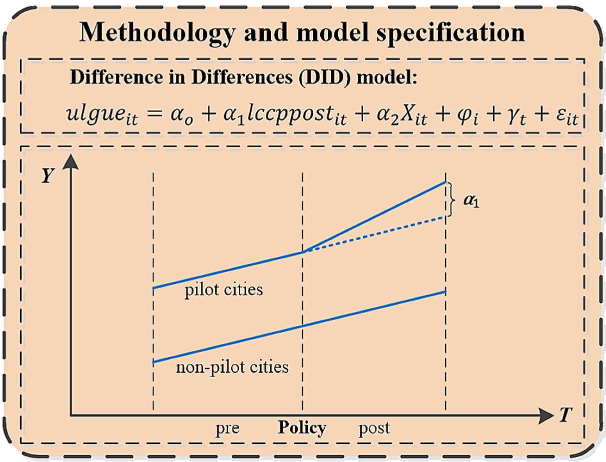

Fig. 4 Schematic diagram of DID model

4.2 Variables and data description

4.2.1 Dependent variable

Charnes et al. (1978) initially presented DEA model for evaluating relative effectiveness between identical sectors. To overcome the disadvantages of the classical radial model, Tone (2002) proposed SBM model that contains relaxation variables, is dimensionless, and non-angular. This refined model accounts for both slack variables and undesired outputs, allowing for a more precise assessment of decision unit efficiency when multiple effective decision units exist simultaneously. ULGUE involves transforming inputs like capital and labor in urban land use activities to generate diverse output benefits, encompassing economic, social, and environmental dimensions. This concept differs from traditional land-use efficiency in that it emphasizes maximizing the economic output of land and social well-being while minimizing environmental pollution. The super-efficiency SBM model effectively tackles the challenge presented by the multifaceted output of urban land use. Hence, this model is adopted in this paper to assess ULGUE, which is formulated in the following manner.

$$ulgue = min\frac{\frac{1}{m}\sum_{i=1}^{m}\bar{x}/x_{ik}}{\frac{1}{r_1+r_2}\left(\sum_{s=1}^{r1}\bar{y^d}/y_{sk}^d+\sum_{q=1}^{r2}\bar{y^u}/y_{qk}^g\right)} \tag{2}$$

$$s.t\begin{cases} \bar{x} \geqslant \sum\limits_{j=1,\neq k}^{n} x_{ij}\lambda_j; \overline{y^d} \leqslant \sum\limits_{j=1,\neq k}^{L} y_{sj}^d\lambda_j \\ \overline{y^d} \geqslant \sum\limits_{j=1,\neq k}^{L} y_{qj}^d\lambda_j; \bar{x} \geqslant x_k \\ \overline{y^d} \leqslant y_k^d; \overline{y^u} \geqslant y_k^u \\ \lambda_j \geqslant 0, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \\ s = 1, 2, \cdots, r_1; q = 1, 2, \cdots, r_2 \end{cases} \tag{3}$$

in Eqs. (2) and (3), n indicates the overall count of decision-making units, in which every decision unit consists of inputs m, desired outputs r_1, and undesired outputs r_2. $x?y^d?y^u$ denote the constituents of the input matrix, the desirable output matrix, and the undesirable outputs matrix sinks, respectively. λ_j represents the weighting factor. $s?q?k?u$ as decision-making units.

This research focuses more on defining inputs and outputs per land unit, to distinguish between land green utilization efficiency and green total factor productivity accurately. The measurement indexes utilized in this study are derived from the production theory of neoclassical economics. Specifically, the input indicators include the investment in fixed assets per unit of land, as well as the total labor force quantity in the secondary and tertiary industries per unit of land. The target output indicators include value added per unit of land generated by the secondary and tertiary sectors, the mean salary of employed workers, and the percentage of green space in developed regions. Undesirable outputs include emissions of industrial wastewater, sulfur dioxide and industrial dust per unit of land.

4.2.2 Core explanatory variable

Independent variable: The variable $lccppost$ is a set of dummy variables for the interaction of city and year, the meaning of which is explained in Eq. (1) as well. The second cohort of pilot cities was officially established in November 2012. Taking into account the inherent latency often associated with policy enactment, it is logically inferred that the implementation phase for this second group would have commenced in the year 2013. The other two batches of policies will be set according to their enactment time.

Mechanism variables: Based on the previous hypothesis development, in this paper, the proportion of value-added within the tertiary sector relative to that of the secondary sector serves as an indicator of the prevailing industrial composition ($stru$). And then uses the city innovation index as a measure of technological innovation ($cityinno$), the calculation of which can be found at the Industrial Development Research Centre of Fudan University. Considering heteroscedasticity, we calculated a natural logarithm of the city innovation index after it plus 1 to reflect the technological innovation level.

4.2.3 Control variables

Control variables: Referring to existing studies (Gozgor & Can, 2017; Gu et al., 2021; Fang et al., 2022; Zhang & Wang, 2022), in our study, we employed several key metrics to gauge the multifaceted aspects of regional development. Specifically, we utilized GDP per capita (ln_rgdp) as a proxy for the overall economic prosperity, the population density (ln_den) to illuminate the degree of urbanization, the per capita availability of urban road infrastructure ($infras$) as an indicator of the sophistication of the transportation network, and the ratio of the combined year-end deposit and loan balances held by financial institutions to the GDP $fina$) as a measure of the financial depth and maturity. To mitigate the impact of heteroscedasticity, we took logarithmic transformations on economic and urbanization levels.

4.2.4 Data source and description

In this study, 284 Chinese cities are included in the dataset that covers the years 2004 through 2019. The sampling mainly revolves around municipal districts, whereas data for undesirable outputs are aggregated at the city level. To handle any individual-level data gaps, the moving average technique is employed for supplementation. The data for the various indicators are meticulously gathered from esteemed publications like the China Statistical Yearbook, China Urban Statistical Yearbook, and each city's National Economic and Social Development Statistical Bulletin. Table 1 displays the statistical analysis of the variables discussed in the study.

5 Results and empirical analyses

5.1 ULGUE measurement results

We measured the ULGUE of 284 Chinese cities between 2004 and 2019 using the SBM model and MATLAB software. The spatial distribution features of ULGUE in 284 cities

Table 1 Descriptive statistics

Variables set	Variables	Obs	Mean	Sd	Min	Max
Dependent variable	*ulgue*	4,544	0.450	0.251	0.044	1.997
Independent variable	*lccppost*	4,544	0.082	0.275	0.000	1.000
Control variables	*ln_rgdp*	4,544	9.916	0.680	7.518	12.410
	ln_den	4,544	6.443	0.945	2.523	9.551
	infras	4,544	11.340	8.120	0.308	108.300
	fina	4,544	1.202	0.667	0.043	8.894
Mechanism variables	*stru*	4,544	1.050	0.640	0.094	6.533
	cityinno	4,544	1.155	1.244	0.000	7.583

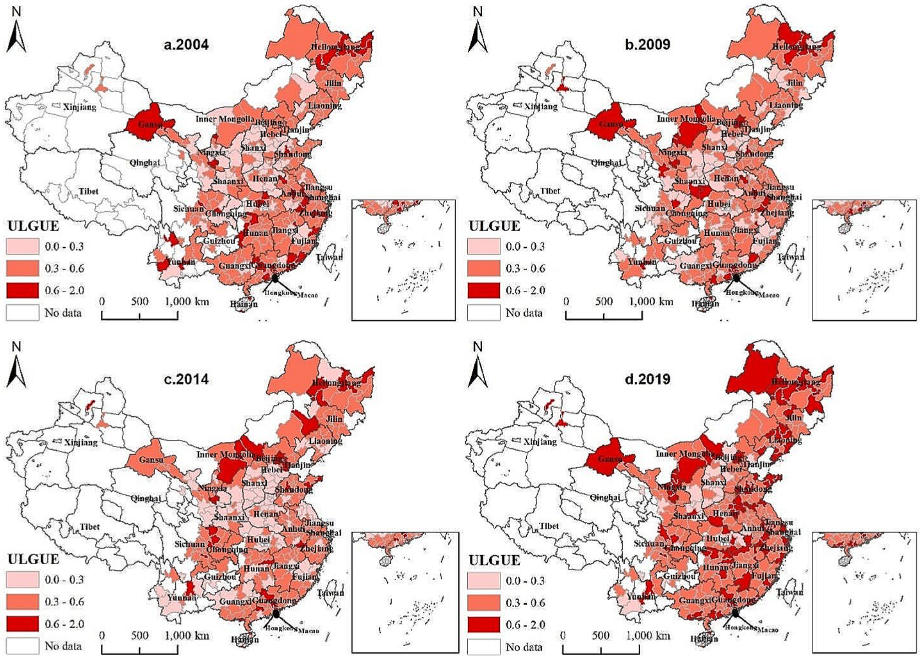

Fig. 5 The spatial distributions of ULGUE in 2004, 2009, 2014 and 2019

are illustrated for the years 2004, 2009, 2014, and 2019 in Fig. 5. A comprehensive overview indicates a nationwide uplift in ULGUE by 2019 compared to 2004, accompanied by a substantial rise in municipalities boasting high and moderate ULGUE levels. In 2004, 2009, and 2014, the number of high ULGUE was lower than that of medium-high ULGUE cities, which were primarily located in the eastern and central regions. The number of cities with medium-high ULGUE increased significantly in the western region in 2019, while there were noticeable agglomeration effects in the high ULGUE cities. The tally of cities with ULGUE scores of 0.6 or higher escalated from 42 in 2004 to 93 by 2019, marking a significant progression.

5.2 Benchmark regression result

The regression outcomes based on Eq. (1), which investigates the influence of the LCCP policy on ULGUE, are presented in Table 2. Across columns (1) through (6), the estimates incorporate city-fixed and time-fixed effects, whereas column (6) further incorporates a comprehensive set of control variables. The findings indicate that the policy intervention variable has a statistically significant positive impact at the 1% significance level, even when controlling for the effects of other variables. Hence, it can be inferred that the adoption of the LCCP strategy greatly enhances the sustainability of the pilot cities. After taking into account several additional parameters, the ULGUE of the pilot cities exhibited an average rise of 3.23%. Therefore, the first hypothesis is confirmed.

5.3 Parallel trend test

The fundamental tenet of the DID methodology rests upon the Parallel Trends Assumption (Bertrand et al., 2004), positing that in the absence of the policy intervention, the temporal evolution of ULGUE in the pilot cities should closely mirror that observed in their non-pilot counterparts. To rigorously assess the validity of this assumption, we adopt the analytical framework devised by Jacobson et al. (1993) for event studies, a sophisticated approach encapsulated mathematically as follows.

$$ulgue_{it} = \alpha_3 + \sum_{l=-5}^{7} \delta_{it} D_{it}^{l} + \alpha_4 X_{it} + \phi_i + \gamma_t + \epsilon_{it} \tag{4}$$

in which D_{it}^{l} is the dummy variable. Assuming city i was enlisted as a LCCP city in year p ($p = 2010, 2013$,2017), we define l as $t - p$. For $l < 0$, signifying a time before the LCCP's inception, D_{it}^{l} is set to 1, otherwise, it is 0. Conversely $l \geq 0$, denoting times after the policy's start, D_{it}^{l} equals 1, and 0 otherwise. The other variables are the same as those

Table 2 The effect of the LCCP policy on ULGUE

	ulgue	ulgue	ulgue	ulgue	ulgue	ulgue
	(1)	(2)	(3)	(4)	(5)	(6)
lccpost	0.0329***	0.0324***	0.0328***	0.0327***	0.0330***	0.0323***
	(0.0122)	(0.0122)	(0.0122)	(0.0123)	(0.0122)	(0.0124)
ln_rgdp		0.0314*				0.0127
		(0.0180)				(0.0195)
ln_den			-0.0104			-0.0188
			(0.0113)			(0.0123)
infras				0.0038***		0.0039***
				(0.0011)		(0.0011)
fina					-0.0111	-0.0115
					(0.0072)	(0.0075)
Cons	0.4468***	0.1353	0.5138***	0.4038***	0.4602***	0.4121**
	(0.0024)	(0.1782)	(0.0732)	(0.0124)	(0.0090)	(0.1825)
City FE	√	√	√	√	√	√
Year FE	√	√	√	√	√	√
Obs	4544	4544	4544	4544	4544	4544
adj. R^2	0.6268	0.6272	0.6267	0.6299	0.6269	0.6268

Notes Robust standard errors in parentheses, *p<0.1, **p<0.05, ***p<0.01. (Same below) used in Eq. (1). Central to this analysis is the estimated coefficient δ_{it}, which quantifies the disparity in ULGUE between pilot and non-pilot cities in year t, post the LCCP policy's implementation, thus encapsulating the policy's differential impact.

To enhance the visual representation of parallel trends and the changing effect of LCCP policies on ULGUE, we present the estimated coefficients δ_{it} along with their respective 95% confidence intervals in Fig. 6. According to the analysis, statistical significance is not attained by the coefficient estimates for the periods prior to the execution of LCCP policy. This finding implies an absence of any discernible, statistically meaningful difference in ULGUE between cities with and without pilot status before the policy's inception. In other words, the assumption of parallel trends is satisfied. These findings imply that the institution of the LCCP significantly contributes to boosting ULGUE. A conspicuous improvement in ULGUE becomes evident in the third year post the LCCP's rollout, indicative of a latency period in the policy's effects. This delay is likely due to the time necessary for the holistic objectives of urban development—including economic prosperity, societal advancements, and environmental sustainability—to fully manifest.

5.4 Placebo test

According to Cai et al. (2016), a placebo test is performed to reduce the possibility that unobserved missing variables could distort the results of the benchmark regression, with different cities serving as the treatment groups. To form the treatment group for this study, 70 cities were randomly selected from a larger group of cities, the remaining for the con-

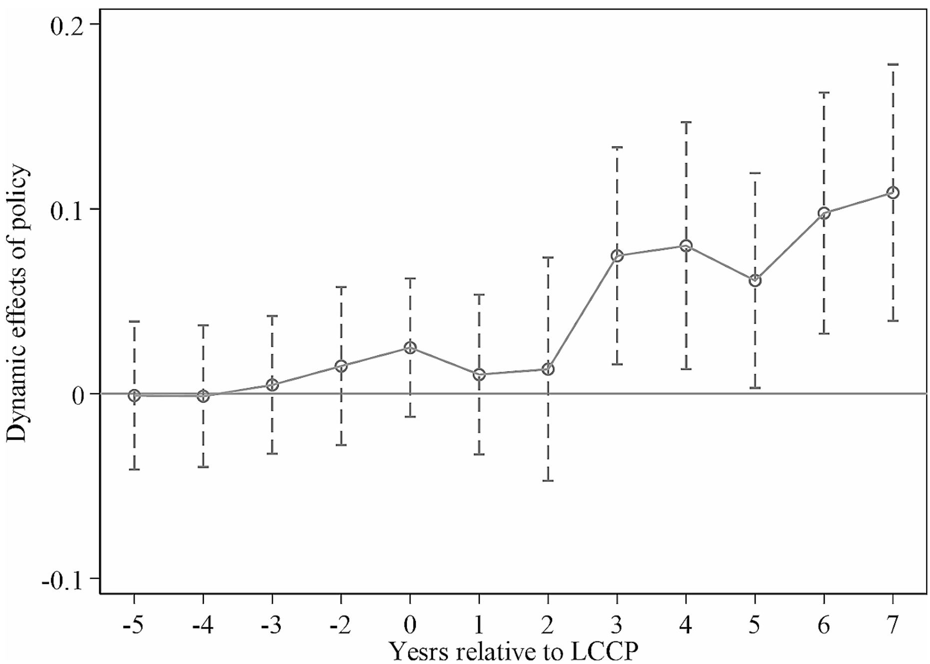

Fig. 6 Dynamic effect of the LCCP policy on ULGUE. *Notes* Open circles denote the estimated coefficient δ_{it} of Eq. (4), with the brief vertical bars representing the upper and lower boundaries of the 95% confidence intervals, calculated using robust standard errors

trol group. An accurate assessment of the LCCP policy's effect on ULGUE can be derived thanks to this methodology. 500 iterations of the procedure were performed to ensure comprehensiveness, yielding 500 unique regression coefficients and corresponding p-values. A plot of the 500 coefficient estimates' p-values and kernel density distributions was used to analyze the regression coefficient distribution (Fig. 7). The analysis revealed that the majority of regression coefficients were centered around zero and followed a normal distribution. Furthermore, a large proportion of the regressions were found to be statistically insignificant at a 10% significance level. Consequently, it can be concluded that unobservable influences have no effect on the benchmark estimations reported in this study.

5.5 Robustness analysis

5.5.1 Impact of the inclusion of a benchmark variable to mitigate selection

A random selection of cities within the treatment group is the best scenario for the DID model. A bias in the ULGUE estimate could be introduced if changes in the LCCP cities' geographic location, historical significance, and rate of economic growth affect the selection process. To mitigate biases in the selection of LCCP, it is advisable to adopt the approach put forth by Edmonds et al. (2010), which involves integrating an interplay term between the urban benchmark characteristic and a linear temporal progression into the model. This modification, as embodied in Eq. (1), leads to the formulation of Eq. (5):

$$ulgue_{it} = \alpha_o + \alpha_1 lccppost_{it} + \alpha_2 X_{it} + Z_i * trend_t + \phi_i + \gamma_t + \epsilon_{it} \tag{5}$$

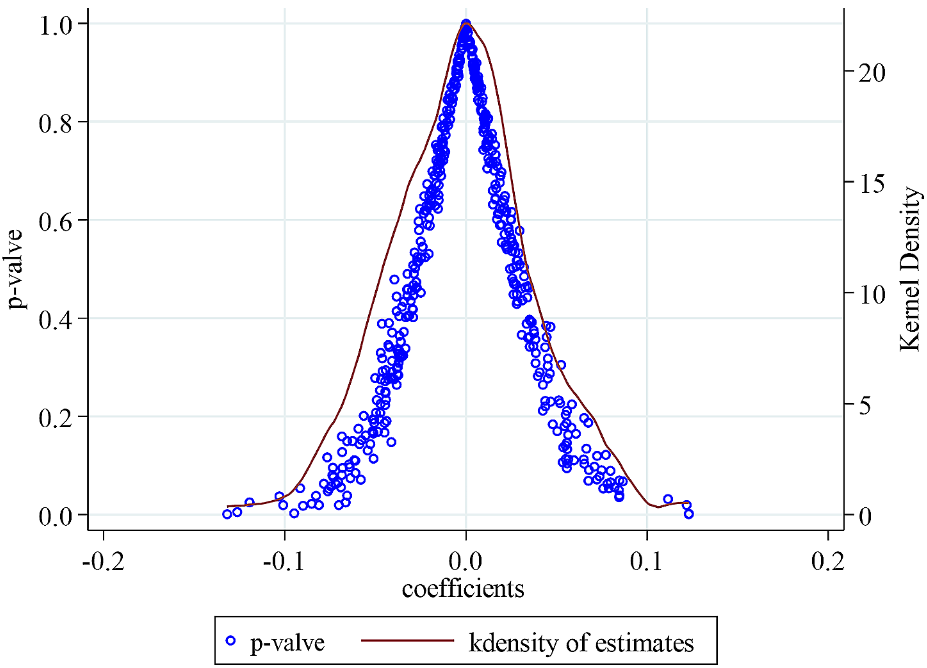

Fig. 7 City placebo test

where Z_i is a dummy variable capturing fundamental attributes, such as whether the city lies east of the Hu Huanyong Line (Hu Line, a demographic divide in China), whether it belongs to Special Economic Zone (SEZ), and whether it falls within Acid Rain or Sulphur Dioxide Pollution Control Zones (TCZ). $trend$ is the time trend term. The findings of columns (1)-(4) in Table 3 are presented after adding an interaction term. The coefficient estimates of the $lccpost$ variable demonstrate statistical significance when the interaction term is included in the analysis. This underscores the robust effect of LCCP policy on ULGUE, confirming the initial benchmark results. Whether the interaction term is introduced incrementally or concurrently, this conclusion remains consistent, affirming the policy's substantial role in enhancing ULGUE.

5.5.2 Eliminating the impact of other policies

In order to isolate LCCP policy's impact on ULGUE from potential influences of concurrent measures, this study meticulously examined pertinent documentation to pinpoint two pilot policies that might have exerted an effect on ULGUE across the entire study period. Among the referenced materials are the 2010 NDRC notification regarding the Promotion of the National Innovative Cities Pilot Scheme and the 2013 Ministry of Ecology and Environment of China Announcement concerning the Enforcement of Specific Emission Standards for Air Pollutants. To account for these interventions, the variable $innopost$ is introduced to denote a city's involvement in the national innovative city pilot program, while the variable $kcapost$ denotes the membership status of a city in the key control area, which is associated with particular emission limitations for air pollutants in a given year. To mitigate any potential confounding effects of these identified policies, dummy variables representing them were incorporated into Eq. (1). The ensuing results, displayed in Table 4, show that, whether each policy is controlled for separately or jointly, the coefficient of $lccppost$ maintains its statistical significance.

5.5.3 PSM-DID test

Despite the existence of standardized approval procedures and criteria for the LCCP cities, the final selection process can be impacted by factors like administrative level and economic scale, thereby introducing a degree of non-random selection bias. This non-randomness may create endogeneity problems that can lead to biased estimation results. Propensity Score

Table 3 Results of adding the interaction variables

	ulgue	ulgue	ulgue	ulgue
	(1)	(2)	(3)	(4)
lccpost	0.0322***	0.0329***	0.0298**	0.0304***
	(0.0124)	(0.0118)	(0.0123)	(0.0117)
Hu Line**trend*	√	×	×	√
SEZ**trend*	×	√	×	√
TCZ**trend*	×	×	√	√
Control Vars.	√	√	√	√
City FE	√	√	√	√
Year FE	√	√	√	√
N	4544	4544	4544	4544
adj. R^2	0.6303	0.6303	0.6308	0.6307

Table 4 Results of eliminating relevant policies

Variables	ulgue	ulgue	ulgue
	(1)	(2)	(3)
lccppost	0.0262**	0.0295**	0.0249*
	(0.0127)	(0.0124)	(0.0127)
kcapost	√	×	√
innopost	×	√	√
Control Vars.	√	√	√
City FE	√	√	√
Year FE	√	√	√
N	4544	4544	4544
adj. R^2	0.6306	0.6304	0.6306

Table 5 The estimation results of the PSM-DID test

	Neighbor	Radius	Kernel
	ulgue	*ulgue*	*ulgue*
lccppost	0.0326**	0.0284**	0.0229*
	(0.0134)	(0.0132)	(0.0134)
Control Vars.	√	√	√
City FE	√	√	√
Year FE	√	√	√
N	3095	3297	3284
adj. R^2	0.6334	0.6296	0.6208

Matching (PSM) is used in this study to pair treatment and control groups in order to solve endogeneity issues. The three different matching techniques covered in this paper were kernel, radius, and nearest neighbor matching. Tests for sexual robustness came after each of these techniques. The findings, as summarized in Table 5, revealed that the coefficient estimates of $lccpost$ past the significance tests at the 5%, 5%, and 10% levels respectively under these differing approaches. This is a further indication that the LCCP policy does promote ULGUE.

5.6 Mechanism analysis

The aforementioned empirical findings have established that the LCCP policy holds promise in improving the ULGUE of cities designated as pilots. However, the underlying mechanism by which this policy operates has yet to be disclosed and validated. As previously stated, pilot cities have observed a rise in ULGUE by the implementation of low-carbon development planning. This has been achieved by progressively optimizing the industrial structure, upgrading technological innovation, and promoting the development of technologies to reduce carbon emissions. Taken together, the intrinsic mechanism can be attributed to both industrial restructuring and technological innovation capacity enhancement. The full explanation of the mechanism variables stu and $cityinno$ have already been covered. Proceeding forward, we seek to validate these mechanisms by applying Eq. (6) and Eq. (7) in our analysis.

$$mechanism_{it} = \alpha_5 + \alpha_6 lccppost_{it} + \alpha_7 X_{it} + \phi_i + \gamma_t + \epsilon_{it} \tag{6}$$

$$ulgue_{it} = \alpha_8 + \alpha_9 mechanism_{it} + \alpha_{10} X_{it} + \phi_i + \gamma_t + \epsilon_{it} \tag{7}$$

where $mechanism_{it}$ denotes each variable representing the mechanism under examination. The remaining variables maintain their definitions as previously outlined in Eq. (1).

5.6.1 Test of the structural effects

Building upon the theoretical discourse from Sect. 3, it is posited that the LCCP policy impacts ULGUE through structural effects. To empirically substantiate this mechanism, this section utilizes the industrial structure indicator ($stru$) previously defined to investigate the policy's effect on ULGUE through structural adjustments. The estimated effect of the LCCP policy on the industrial structure is shown in Table 6, column (1). The empirical results yield a statistically significant coefficient of 0.0753 for the $lccppost$ variable, attaining the stringent 1% level of significance. This robust statistical evidence powerfully substantiates the proposition that the LCCP policy indeed triggers a substantial and meaningful improvement in the industrial structure. Our findings align harmoniously with the conceptual edifice advanced by Wang et al. (2023b), which suggests that the LCCP policy drives industrial structure upgrading through mechanisms such as fiscal decentralization, technological innovation, and the promotion of green consumption. Column (2) of Table 6 showcases the discernible influence exerted by the industrial structure indicator on ULGUE, serving as a dedicated platform to probe the inherent, direct association between these two pivotal constructs. For $stru$, the coefficient estimate is 0.0403, satisfying the 1% level requirement for statistical significance. This demonstrates how the LCCP policy optimizes the industrial structure to support ULGUE. Thus, the "structural dividend" engendered by the transformative and elevating effects of the LCCP policy on the industrial landscape proves instrumental in amplifying resource utilization efficiency, refining the spatial organization of industries, and, crucially, dismantling the environmental pollution-induced constraints impeding economic advancement. This, in turn, elevates environmental standards and achieves a holistic enhancement of ULGUE alongside economic expansion.

5.6.2 Test of technological effects

This study also investigates how LCCP policy can improve ULGUE by promoting technological innovation. To gauge technological effects, we utilize the city innovation index ($cityinno$). Table 6, in its column (3), presents the estimated effect of the LCCP policy on the domain of innovation capacity. At the 1% significance level, the coefficient estimate for *lccpost* is 0.5086, underscoring the profound and statistically robust influence of the LCCP policy on fostering technological innovation. This result echoes the conclusion reached by Zhu and Lee (2022), who argue that LCCP policy can promote local technological innovation as well as surrounding technological innovation through spatial spillovers. Progressing to Column (4), the coefficient estimate for $cityinno$ stands at 0.0115, successfully clearing the threshold of statistical significance. This result confirms the fact that the catalytic effect of LCCP policy on technological innovation actively contributes to increasing ULGUE performance. Thus, the policy not only fosters innovation but also translates this into tangible improvements on ULGUE, validating its dual impact on innovation and environmental efficiency.

Table 6 Results of mechanism tests

	stru	ulgue	ln_inno	ulgue
	(1)	(2)	(3)	(4)
lccppost	0.0753***		0.5086***	
	(0.0225)		(0.0341)	
stru		0.0403***		
		(0.0113)		
ln_inno				0.0115*
				(0.0069)
Control Vars.	√	√	√	√
City FE	√	√	√	√
Year FE	√	√	√	√
N	4544	4544	4544	4544
adj. R^2	0.7958	0.6318	0.9056	0.6300

Thus, hypotheses 2 and 3 are supported.

6 Heterogeneity analysis

China is a geographically expansive nation with cities that exhibit significant variations in terms of geographic position, economic magnitude, environmental consciousness, and policy execution. Therefore, these differences might result in divergent reactions to LCCP initiatives across different cities. Consequently, this study delves deeper into the variations in how the LCCP policy affects ULGUE across different locales. In this paper, the study of heterogeneity is developed from three different perspectives, i.e., different sub-samples are divided according to geographic location, industrial attributes of the city, and type of urban development in order to examine heterogeneity.

6.1 Testing for heterogeneity in geographical locations

Cities throughout various regions display differences in their industrial structures and development stages due to disparate resource endowments and economic foundations. The paper evaluates the impact of the LCCP policy on ULGUE in all sample cities, which are divided into three main economic regions—East, Central and West—aligning with the zoning framework outlined in China's Seventh Five-Year Plan.

Table 7 reports geographical heterogeneity in policy effects in columns (1) through (3). The analysis shows that the LCCP policy coefficient has a statistically significant positive association with ULGUE at the 1% significance level for cities situated in the eastern region. Conversely, the coefficients corresponding to the LCCP policy do not demonstrate statistical significance for urban centers in the central and western regions. Several factors account for the conclusions mentioned above. Firstly, it is crucial to note that eastern region cities boast a higher level of economic maturity, possess more sophisticated industrial frameworks, and harbor greater potential for urban innovation. Therefore, these cities are better equipped to swiftly conform to the policy requirements during the initial stages of implementing the LCCP policy. Moreover, they can strategically adjust their industrial composition to mitigate the presence of enterprises that contribute to high pollution, excessive energy consumption, and substantial emissions, while simultaneously maintaining stability

Table 7 Testing for heterogeneity based on city location and industrial attributes

Variables	Eastern	Central	Western	OIB cities	NOIB cities
	(1)	(2)	(3)	(4)	(5)
lccppost	0.0768***	-0.0057	0.0010	-0.0363*	0.0519***
	(0.0202)	(0.0193)	(0.0236)	(0.0204)	(0.0145)
Control Vars.	√	√	√	√	√
City FE	√	√	√	√	√
Year FE	√	√	√	√	√
N	1680	1888	976	1520	3024
adj. R^2	0.7020	0.5942	0.4996	0.5656	0.6509

in economic development objectives. Additionally, these municipalities vigorously foster green technological innovations as a pivotal strategy for nurturing environmentally sustainable urban development. The flourishing of a green economy will be accelerated in particular by the introduction and application of new technologies. Cities in the west and center, however, are particularly dependent on labor- and resource-intensive industries for their economic growth. Given the fragility of local ecosystems and the relative backwardness of industrial processes, these urban areas confront challenges in fostering innovation as they transition toward a low-carbon model, all in pursuit of reducing greenhouse gas emissions. This situation indirectly leads to a decline in the ULGUE.

6.2 Testing for heterogeneity in industrial attributes

The unique industrial attributes of different cities determine their development methods, pollutant emission patterns, and the degree of intensive and economical utilization of land use. Cities with an old industrial (OIB) usually have strong heavy industries and their industrial development methods show more roughness. In this paper, 284 cities are divided into 95 OIB and 189 non-old industrial base (NOIB) cities according to the National Plan for Transforming OIB (2013–2022) published by the NDRC.

Estimates for the subsample are presented in columns (4) and (5) of Table 7, with the $lccppost$ coefficients significant at the 10% and 1% levels for OIB and NOIB cities, respectively. The coefficient is noteworthy as it shows a negative significance in OIB cities and a positive significance in NOIB cities. Furthermore, when considering the actual impact values, the influence of the LCCP regulations on ULGUE is more significant in NOIB urban areas. This indicates that the ULGUE level in the NOIB cities is raised by the LCCP policy., while on the contrary, it reduces it in the OIB cities. There are two potential explanations. The first characteristic of OIB cities is their rough development mode and low industrial level. To be more precise, the percentage of raw materials and primary products in OIB cities' total industrial output value is 19% higher than the national average, and the percentage of energy consumed is 1.3 times higher, with more than 60% of OIB cities having energy intensities above the national average. ULGUE's potential for advancement is constrained by the illogical internal spatial layout and antiquated infrastructure of OIB cities. Hence, focusing on the LCCP policy in OIB cities is crucial, as its implementation can greatly improve ULGUE levels in these areas.

6.3 Testing for heterogeneity in urban resource endowments

The conditions of the city's resource endowment will determine the way the city's land is utilized. Acknowledging that the practical effects of the LCCP policy might depend on local resource endowments, this study delves deeper to examine ULGUE improvement responses to the LCCP policy across cities with differing degrees of resource dependence. Guided by the State Council's Circular on the Release of the National Sustainable Development Plan for Resource-Based Cities (2013–2020), the 284 sampled cities are bifurcated into 169 non-resource-based (NRB) cities and 115 resource-based (RB) cities. Further, RB cities are subclassified into four categories—growth, mature, recession, and regeneration—based on their urban resource endowments. Given the absence of LCCP within the regeneration category, heterogeneity among regeneration cities is not considered in this analysis.

The regression findings based on urban resource reliance are presented in Table 8. Based on the projected outcomes shown in columns (1) and (2), it becomes observed that the adoption of the LCCP policy by NRB cities yields a statistically significant beneficial effect on ULGUE, with confidence reaching a 1% significance. However, the improvement is not discernible within our subset of RB cities. Furthermore, it is observed that, at a significance level of 10%, the LCCP policy has a statistically significant positive effect on ULGUE of growth cities, while this improvement is not evident in other samples of cities classified as RB cities. These results echo the conclusions reached by Wang et al. (2022), which also suggested stringent environmental policies tend to facilitate green transitions in NRB locales but can inadvertently impede such transformations in RB locales. RB cities, typified by their reliance on the exploitation of indigenous fossil energy i.e., coal, petroleum, and gas for economic prosperity, face unique challenges in adapting to green policies. RB cities frequently encounter the resource curse dilemma when endeavoring to construct low-carbon cities, mostly due to their poor resource usage rate and significant environmental damage. However, when compared with other RB cities, the LCCP policy benefits ULGUE in growing cities. This is because they serve as vital energy reserve bases of China, which have lower levels of energy extraction, and lesser environmental pressures, and the factors of production are more likely to move towards them. As the LCCP policy is implemented, it can lure companies with advanced production technologies, promoting the growth of ULGUE in growing cities. However, in other RB cities, particularly those experiencing economic decline, the exhaustion of energy reserves not only escalates manufacturing costs but also

Table 8 Testing for heterogeneity based on urban resource endowment

Variables	NRB cities	RB cities	Growth	Mature	Recession
		All samples			
	(1)	(2)	(3)	(4)	(5)
lccpost	0.0447***	-0.0111	0.1042*	-0.0207	-0.0416
	(0.0157)	(0.0170)	(0.0562)	(0.0206)	(0.0511)
Control Vars.	√	√	√	√	√
City FE	√	√	√	√	√
Year FE	√	√	√	√	√
Cons	0.5491**	0.2210	-0.5748	0.0789	1.4453**
	(0.2565)	(0.2655)	(0.7500)	(0.4032)	(0.6718)
N	2704	1840	224	992	368
adj. R^2	0.6614	0.5335	0.5791	0.5085	0.6152

triggers the translocation of production constituents. This migration hinders the advancement of urban local government economic development in these cities while implementing the LCCP policy.

7 Conclusions and policy implications

7.1 Conclusions

The LCCP policy stands as a pivotal strategy in facilitating the metamorphosis of urban into environmentally sustainable, low-carbon ecosystems, and it is an important cornerstone for coordinating the ULGUE. This study employs a panel dataset encompassing 284 Chinese prefectural cities spanning from 2004 to 2019, adopting the super-efficiency SBM model to quantify ULGUE. Adopting the rollout of the LCCP as a quasi-experimental setting, the research initially delves into the theoretical underpinnings that govern the policy's influence on ULGUE. Subsequently, a DID model, sensitive to temporal variations, is employed to rigorously assess the policy's repercussions on ULGUE, thereby contributing to a nuanced understanding of its effectiveness. In addition, multiple robustness and heterogeneity tests are performed. The implementation benchmarking results are verified through several placebo and robustness tests for credibility. The aforementioned research yields the following primary conclusions in this paper:

(1) The LCCP policy drives ULGUE development, even when regional, temporal characteristics and other factors are considered. This conclusion remains true even after the PSM-DID test, the removal of additional policy interferences, the inclusion of the benchmark variable, and robustness tests.
(2) The LCCP policy promotes ULGUE upgrading through structural and technological effects. The LCCP policy proves instrumental in driving the optimization of industrial structures and fostering advancements in urban technological innovation.
(3) The impact of the LCCP policy on the ULGUE is highly heterogeneous, with divergent outcomes observed across distinct geographical zones, industrial attributes, and resource endowments. Specifically, in eastern region, the policy has exerted a discernible positive influence, boosting ULGUE by an average margin of 7.68%. However, such a statistically significant effect is conspicuously absent in both the central and western regions. Across different industrial attributes, the LCCP policy enhanced ULGUE by an average of 5.19% in NOIB cities. Yet there was no significant impact on ULGUE in OIB cities. The promotional effect of the policy resulted in an average improvement of 4.47% on ULGUE in NRB cities. However, there was not a significant impact observed on ULGUE in RB cities.

7.2 Policy implications

To propel the evolution of low-carbon cities and secure sustainable prosperity within China, while simultaneously providing a tangible reference point for other emerging economies striving to strike a balance between low-carbon measures and economic advancement, the following policy recommendations, grounded in the study's findings, are proffered:

(1) It is recommended that the lessons learned from the LCCP be condensed and applied to other regions of the nation. This article shows that the LCCP policy makes an advantageous contribution to ULGUE, demonstrating that the policy has an integrated impact and is coming into effect over time. Local characteristics and development experience of pilot cities should be considered, with strict control of carbon emissions goals, the reinforcement of low-carbon development capacity, and assuming a leading as well as exemplary role. Hence, by systematically consolidating and diffusing the lessons learned from LCCP initiatives, it becomes feasible to progressively magnify the breadth of these pilots and judiciously identify the opportune moment to generalize the urban low-carbon transition across the entire nation. Without a doubt, this endeavor will significantly aid China's efforts to achieve carbon neutrality and carbon peaking. Other developing countries have the opportunity to draw valuable lessons from China's successful application of the LCCP policy and subsequently replicate it in their own domestic contexts.
(2) The influence of the LCCP policy on industrial upgrading, in terms of the influence mechanism of structural effect, is a constitutive factor in promoting the improvement of ULGUE. Thus, in the future, industrial transformation strategies and paths should be tailored to the unique traits of each city's industrial development to support LCCP policy. One approach is to use the target constraints of the LCCP policy and technology improvement strategy to support the facilitation of metamorphosis and upgrading of urban industrial sectors. Additionally, it is imperative for cities to adopt proactive strategies in adjusting and optimizing their industrial configurations. This requires gradually increasing the contribution of the third sector and reducing the proportion of the second sector, especially in high energy consumption. The development of the LCCP policy in conjunction with industry optimization and transformation may lead to the improvement of ULGUE.
(3) The LCCP policy exerts a statistically significant, positive influence on the intensity of urban technological innovation, ultimately bolstering the levels of ULGUE, thereby affirming the pivotal role of innovation-driven progress in optimizing ULGUE. Therefore, the LCCP should guide technological innovation to formulate a medium- and long-term guiding program for technological transformation. There should be a concerted effort to augment financial support for scientific research and technological innovation, encompassing increased investment and more substantial subsidies in these domains. Efforts should be made to introduce foreign advanced technologies and encourage internal innovation of enterprises as promotion of efficacious and eco-friendly utilization of land resources. Improving the innovation capacity of low-carbon cities and encouraging innovation within enterprises is an effective approach to enhancing the efficient and sustainable exploitation of land resources.

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Data availability The datasets generated or analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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