frontiers | Frontiers in Earth Science

TYPE Original Research
PUBLISHED 19 September 2025
DOI 10.3389/feart.2025.1630832

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OPEN ACCESS

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RECEIVED 18 May 2025
ACCEPTED 25 August 2025
PUBLISHED 19 September 2025

CITATION
Li B, Liu S, Song Y and Cui Z (2025) The coordination effects of low-carbon city pilot and smart city pilot on urban land green use efficiency: evidence from a quasi-natural experiment in China.
Front. Earth Sci. 13:1630832.
doi: 10.3389/feart.2025.1630832

The coordination effects of low-carbon city pilot and smart city pilot on urban land green use efficiency: evidence from a quasi-natural experiment in China

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Low-carbon city pilot and smart city pilot are two main measures which could improve urban land green use efficiency (ULGUE). In this study, we take two pilot policies as a quasi-natural experiment. Using the difference-in-differences (DID) method, we designate “dual-policy” cities as the treatment group to examine the combined effect of the policies on ULGUE. To our knowledge, this is the first attempt to integrate these two policies into a unified analytical framework. This framework allows us to investigate both their coordination effects and the magnitude of differences between dual and single policies. We find that (1) both the low-carbon pilot and the smart city pilot can improve the ULGUE. (2) Dual-pilot cities show a stronger enhancement of ULGUE than the cities with a single policy. (3) The policy sequence demonstrates varying effect magnitudes, suggesting that ecological regulation provides a solid foundation for subsequent technological upgrading.

KEYWORDS

low-carbon city, smart city pilot, urban land green use efficiency, dual-pilot, DID

1 Introduction

Land is the most important element of human economic life. As cities are the spatial carriers for the exchange and interaction of various elements, the importance of land has long been widely recognized and supported by various sectors of society (Marshall, 2007). In 2018, approximately 55.2% of the global population resided in urban areas. It is projected that by 2050, the proportion of the global population residing in urban areas will reach 68% (Szabo, 2018). With the continuous growth of urban populations, the tension between human demands and land resources in cities has become increasingly acute (Seto and Shepherd, 2009). Urban land-use efficiency remains relatively low and has significant regional disparities, characterized by high resource consumption, pollution emissions, and carbon footprints that contribute to global warming; elevated *per capita* greenhouse gas emissions; and inefficient natural resource utilization (Grimm et al., 2008; Edenhofer, 2015; Güneralp and Seto, 2013). Within this context, urban land green use efficiency (ULGUE) has emerged as a key point for academic research and policy-making. Improving ULGUE is crucial for optimizing urban land allocation and utilization, which is also essential for driving a green transformation in socioeconomic development.

As the largest developing country, China's reform and opening-up over the past 47 years has driven unprecedented urbanization and rapid urban land expansion (Liu et al., 2018). By 2024, China's urbanization had reached 67%. The green utilization of urban land reflects the principles of sustainable development in land-use processes, aiming to minimize environmental pollution while maximizing economic returns and social welfare (Auzins et al., 2013). Accordingly, urban land use should not be guided solely by economic objectives; rather, environmental benefits derived from land utilization must be incorporated into evaluation frameworks, thereby improving ULGUE. For China, enhancing ULGUE constitutes a crucial strategy for advancing low-carbon economic transition and alleviating ecological constraints. Moreover, China's practices provide replicable pathways for other developing countries to reconcile urbanization with ecological conservation. These initiatives not only accelerate the global transition toward low-carbon cities but also contribute tangible momentum to international climate change mitigation efforts.

China has implemented multiple initiatives to advance the green transition of its economy. Among them, the low-carbon city pilot policy and the smart city pilot policy are two critical instruments for promoting the green transition and sustainable development of urban areas. By establishing low-carbon city pilot policies, the government has prioritized energy supply in key high-energy-consumption regions. Low-carbon city pilot policies have been launched since 2010, designating Guangdong, Liaoning, Chongqing, and other provinces and municipalities as the first batch of pilot areas. The second and third batches of pilot projects were introduced in 2012 and 2017, respectively, to further explore appropriate pathways for low-carbon and green development. Green development is closely linked to technological innovation, with cities serving as the spatial carriers of innovation (Heiskanen et al., 2017). In 2013, the introduction of the smart city pilot policy provided a new model of urban development that integrates innovation with green development. As a practical embodiment of China's commitment to green innovative development, the construction of low-carbon cities and smart cities has contributed to urban green development, thereby enhancing the urban land green utilization efficiency.

Green and intelligent development, as an important trend of new urbanization, has created new opportunities for the green development of urban economy (Song et al., 2020; Jiang et al., 2021). Previous studies consistently showed that both low-carbon and smart city pilot programs promote urban green growth (Cheng et al., 2019; Song et al., 2023), improve ecological and energy efficiency (Wang et al., 2023), and strengthen innovation capacity (Yigitcanlar and Kamruzzaman, 2018), particularly in large or high-tech urban areas (Caragliu and Del Bo, 2019). Additionally, regarding research on the dual-pilot policies, scholars have found that the low-carbon city and innovative city pilot policies can promote the adoption of green lifestyles among urban residents (Zhang and Zheng, 2023). These policies also contribute to high-quality economic development in cities (Wu et al., 2024). Although the effects of single pilot policies, such as low-carbon cities or smart cities, have been widely examined, and some studies have explored other dual-pilot policy combinations, research on the synergistic effects of low-carbon and smart city dual-pilot policies remains insufficient. Against this backdrop, in this paper, we address several important but unanswered questions: do the combined low-carbon and smart city dual-pilot policies enhance land green use efficiency? Is the impact of the dual-pilot policy better than that of a single pilot? Answering these questions is essential for consolidating China's efforts to build smart low-carbon cities.

This study contributes to the literature in the following ways: first, unlike existing studies that focus on single pilot policies, we examine the synergistic effects of combining the low-carbon city and smart city pilot policies on ULGUE. Second, we employ a multi-period difference-in-differences (DID) approach to systematically compare the effects of these dual-pilot policies on ULGUE based on their implementation timelines, thereby providing a more accurate assessment of policy effectiveness. Third, we investigate the mechanisms and pathways through which the dual policies enhance ULGUE. Together, these contributions provide practical implications for improving urban land sustainability.

The remainder of this study is organized as follows: Section 2 presents the literature review. Section 3 develops the theoretical framework. Section 4 describes the methodology and data. Section 5 discusses the empirical results and the analysis of the dual-pilot policies' impact on ULGUE. Section 6 introduces further discussion. Section 7 provides conclusions.

2 Literature review

2.1 ULGUE

ULGUE is a core indicator of urban sustainable development. Its improvement requires efficient resource allocation, ecological environmental protection, and social equity. Enhancing ULGUE can significantly improve urban ecological environments, meet residents' increasing demands for higher living standards, strengthen urban competitiveness, and facilitate sustainable urban development (Su and Yang, 2022).

Previous studies have identified multiple factors that influence ULGUE. Economic development, industrial structure optimization, environmental regulation, and land urbanization have generally been found to promote efficiency, whereas higher population density, excessive investment in science and technology, and financial development may exert negative effects (Ma et al., 2024). Larger cities, benefiting from advanced economic conditions and infrastructure, tend to achieve higher ULGUE (Wang et al., 2021). The role of technological innovation, however, remains contested. Whereas some studies suggest that it may generate short-term inefficiencies, others emphasize the positive contributions of innovation investment, internet penetration, and digital applications in land management (Wang et al., 2021; Cardone et al., 2023). In addition, industrial structure upgrading has been shown to improve land-use allocation, whereas stringent environmental regulations have been shown to foster low-carbon practices and stimulate technological advancement, thereby improving ULGUE (Zhang et al., 2025; Fu et al., 2022).

In terms of measurement methods, in existing research, ULGUE is divided into three dimensions—inputs, desirable outputs, and undesirable outputs—aiming to maximize resource efficiency while minimizing environmental costs. Approaches that are commonly employed include GIS-based models for evaluating ecological benefits in densely populated cities (Cardone et al., 2023) and super-efficiency SBM models for assessing the industrial output, emissions, and land use (Wang et al., 2021). In addition, some studies incorporate financial support systems to enrich the measurement framework (Fu et al., 2022).

In summary, the improvement of ULGUE is a complex, multifactorial process that requires the integrated consideration of economic, social, and environmental dimensions. Continuous optimization and adjustment of these factors are essential to effectively enhance ULGUE and advance the broader goals of urban sustainable development.

2.2 Low-carbon and smart city pilot policies

In this paper, we focus on two key urban pilot policies: the low-carbon city pilot policy and the smart city pilot policy.

The low-carbon city pilot policy aims to embed carbon reduction targets into local governance and planning, with the objective of building clean, energy-efficient, and environmentally friendly cities. It establishes explicit carbon emission constraints and green land-use standards, compelling local governments and enterprises to restructure development patterns. Existing research has examined its impacts from multiple perspectives. Studies show that the policy has significantly improved ULGUE (Liu and Xu, 2022), reduced enterprise pollution emissions (Yang et al., 2023), fostered urban green innovation by increasing green patent applications (Chen et al., 2022), and enhanced intelligent manufacturing capabilities (Wu et al., 2023). Positive spillover effects have also been observed, with green development diffusing from technology-intensive and coastal cities to inland regions (Chen et al., 2023). Nonetheless, limitations remain, including vague policy definitions and insufficient support (Khanna et al., 2014), neglect of social dimensions (Hunter et al., 2019), and constraints from traditional urbanization patterns and energy pressures (Sarker et al., 2018), which hinder the scalability and effectiveness.

The smart city pilot policy, in contrast, seeks to improve urban governance and efficiency through digital technologies, focusing on information infrastructure, data-driven decision-making, public service optimization, innovation ecosystems, and resource allocation. Existing studies emphasize three aspects: first is the conceptualization and implementation of the smart city pilot policy, with theoretical frameworks developed from governance, social, and economic perspectives, and comparative analyses highlighting different international approaches (Mora et al., 2023). Second, their economic and environmental impacts, as smart city construction has been found to enhance urban innovation and green total factor productivity, particularly in high-tech sectors, large cities, and the eastern coastal regions of China (Caragliu and Del Bo, 2019; Chen et al., 2024), while improving urban land-use efficiency through innovation investment, informatization, and optimized land allocation (Zhuo et al., 2025). Third, debates persist regarding carbon emissions. Although smart city initiatives generally promote energy conservation and efficiency through technological innovation and industrial upgrading (Pasolini et al., 2018; Shu et al., 2023), concerns over possible adverse effects still remain, such as intensified data monopolies (Yigitcanlar and Kamruzzaman, 2018).

Currently, increasing scholarly attention has been devoted to examining the synergistic effects of dual-pilot policies. For example, studies have investigated the combined impacts of low-carbon city pilots and innovative city pilots on urban carbon emissions, along with the integrated effects of low-carbon city pilots and new energy demonstration cities on the carbon emission intensity (Li and Zhang, 2024). These investigations demonstrate that dual-policy frameworks exhibit significantly stronger emission reduction effects than single-policy approaches.

The synergy between the low-carbon city and smart city policies represents a significant innovation in China's ongoing pursuit of new urbanization and sustainable development. As previously noted, scholars have conducted comprehensive assessments of the effectiveness of both the smart city pilot policy and low-carbon city pilot policy, encompassing multidimensional benefit analyses across economic, environmental, and social dimensions. Both policies have been demonstrated to influence ULGUE. However, research examining the synergistic effects between these two policies remains limited, particularly research on how the implementation sequence influences their differential impacts, despite methodological advances and accumulated policy implementation experience. Therefore, in this study, we analyze the differential impacts arising from the implementation order and intensity of these policies. The long-term coordination mechanisms of dual-pilot policies are further elucidated, exploring approaches to enhance policy synergies and clarifying the optimal implementation pathways and mechanisms for sustained impact.

3 Theoretical analysis

The low-carbon city pilot policy is designed to foster clean, low-carbon, and environmentally sustainable urban development, thereby enhancing ULGUE through institutional reform, technological innovation, and industrial restructuring. The policy establishes binding carbon emission targets and green land-use standards, which compel local governments and enterprises to optimize spatial planning, prioritize ecological protection, and expand green space and forest coverage. These measures collectively strengthen urban ecosystems, increase the ecological value of land, and promote intensive and sustainable land utilization patterns. The policy framework incorporates complementary instruments, including dedicated funds, subsidies, and tax incentives, which encourage the adoption of green technologies, the establishment of low-carbon industrial parks, and the retrofitting of the infrastructure. These initiatives effectively reduce emissions, improve energy structures, and lower land-based energy intensity. Furthermore, the policy drives industrial transformation by supporting high-tech and service sectors while imposing restrictions on energy-intensive and high-polluting industries, thereby conserving land resources and mitigating environmental degradation (Qiu et al., 2021). Through the demonstration of its effect, the policy facilitates broader diffusion of green land-use practices, thus advancing the sustainable urban development scale (Cheng et al., 2019).

In summary, the low-carbon city pilot policy exerts multidimensional synergistic effects, effectively enhancing ULGUE and providing robust support for urban sustainable development. Thus, we propose the following hypothesis:

Hypothesis 1: the low-carbon city pilot can improve the ULGUE.

Smart cities leverage information technology agglomeration to overcome spatial and institutional barriers, thus facilitating efficient resource allocation and promoting sustainable urban development (Vanolo, 2014). The pilot policy advances industries such as the Internet of Things (IoT) and big data, attracting knowledge-intensive, low-energy, and high-value-added sectors while driving industrial upgrading. Digitalization expedites production factor mobility, which enhances land-use efficiency, whereas green technologies minimize resource consumption and pollution while improving energy efficiency (Yu and Zhang, 2019), thus creating synergies between economic output and ecological benefits to improve the ULGUE. In contrast with conventional approaches, smart cities utilize geographic information systems, remote sensing, and algorithms for real-time land monitoring and precise management, integrating multidimensional data to detect inefficiencies, reduce waste, and optimize resource allocation. Scientifically, grounded planning is often linked to green building standards and directs development toward low-carbon, sustainable pathways. International practices validate these interventions' effectiveness, whereas public participation strengthens accountability, encouraging greener practices by both enterprises and governments. Collectively, these frameworks enhance ULGUE while integrating sustainability principles into urban development processes.

In conclusion, the smart city pilot policy, through its multidimensional integration, can effectively enhance ULGUE, thereby advancing urban sustainable development. Based on this mechanistic understanding, we propose the following hypothesis:

Hypothesis 2: the smart city pilot policy can improve the ULGUE.

Policy synergy has emerged as a critical research area of significant scholarly interest, manifesting as the coordination and collaboration among policies that generate synergistic effects driving societal progress (Kwon, 2018). Following years of policy implementation, China's low-carbon city and smart city pilot initiatives have generated synergistic effects in enhancing the ULGUE. Low-carbon pilot policies facilitate industrial transformation toward high-value-added, low-environmental-impact sectors through carbon emission constraints and green development incentives (Wang et al., 2021). Simultaneously, smart city construction leverages IoT and big data technologies to optimize land resource allocation and prevent inefficient land expansion.

This "dual-pilot" synergy promotes deep integration of digitalization and environmental sustainability in urban land use, fostering sustainable development pathways. Low-carbon policies provide fiscal incentives and carbon trading mechanisms that enhance green land-use viability, whereas smart cities' "digital twin" technology accurately simulates carbon footprints across various land-use scenarios. These combined policies effectively reduce land resource consumption and carbon emission intensity per GDP unit.

Dual-pilot policies integrating low-carbon city and smart city initiatives can improve urban digital innovation, market-oriented innovation, and industrial innovation (Zhang and Zhang, 2023). The dual-pilot framework has reallocated land resources from high-carbon industries to low-carbon services and high-tech sectors by eliminating information asymmetries and mobility barriers. Additionally, the smart cities' information infrastructure complements renewable energy deployment in low-carbon cities through smart grid integration and distributed photovoltaics, improving both energy efficiency and long-term sustainability.

These policies establish dual technology–institutional innovation mechanisms, creating robust environmental regulatory frameworks that accelerate societal low-carbon transitions while enhancing public awareness and participation in green development initiatives. Based on these findings, we propose the following hypothesis:

Hypothesis 3: dual-pilot policies significantly enhance regional ULGUE, demonstrating stronger synergistic effects than single policies.

4 Methodology

4.1 Difference-in-differences (DID) design

In this study, we employ a multi-period DID approach to estimate the effects of the dual implementation of low-carbon and smart city pilot policies on ULGUE. By incorporating appropriate control variables, the multi-period DID framework enables a rigorous identification of whether significant differences in ULGUE arise between the pilot and non-pilot regions before and after the introduction of these policies. The empirical specification of the DID model is presented in Equation 1.

$$\mathrm{ULGUE} = \beta_0 + \beta_1 \mathrm{CarbonSmart} + \mathrm{Control}_{i,t} + \eta_i + \gamma_t + \varepsilon_{i,t}. \quad (1)$$

Here, subscripts *i* and *t* denote the city and year, respectively; ULGUE represents urban land green use efficiency; CarbonSmart is the core explanatory variable, which is defined as a multi-period DID indicator capturing the joint policy intervention of simultaneously implementing the low-carbon city and smart city pilot policies; and $\mathrm{Control}_{i,t}$ denotes time-varying covariates influencing ULGUE. City-specific fixed effects (ηi), year-specific fixed effects (γ_t), and a stochastic error term ($\varepsilon_{i,t}$) are included in the equation. Specifically, CarbonSmart has the value of 1 for cities that are simultaneously designated as both low-carbon and smart city pilots from the year of policy implementation onward, and the value is 0 otherwise.

4.2 Variables

4.2.1 Dependent variable

The dependent variable in this study is ULGUE. Building on the conventional slacks-based measure (SBM) model, Tone (2001) proposed a super-efficiency SBM model with undesirable

TABLE 1 ULGUE evaluation indicator system.

Primary indicators	Secondary indicators	Third-level indicators	Connotation of indicators
Urban	Inputs	Land	Urban construction land area in urban districts
Land		Capital	Urban fixed asset investment
Green		Labor	Employment in secondary and tertiary industries
Use	Desired outputs	Economy	Real added value of the secondary and tertiary industries
Efficiency		Green	Green coverage rate of built-up areas
	Undesired outputs	Environment	CO_2 emissions

outputs, which integrates the strengths of both super-efficiency and SBM frameworks. The formal specification of this model is expressed as follows:

$$\rho = min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}_i}{x_{i0}}}{\frac{1}{S_1+S_2}\left(\sum_{r=1}^{S_1}\frac{\bar{y}_r^g}{y_{r0}^g}+\sum_{r=1}^{S_2}\frac{\bar{y}_r^b}{y_{r0}^b}\right)}. \quad (2)$$

$$s.t.\begin{cases}\bar{x} \geq \sum_{j=1,\neq k}^{n}\theta_j x_j \\ \bar{y}^g \leq \sum_{j=1,\neq k}^{n}\theta_j y_j^g \\ \bar{y}^b \geq \sum_{j=1,\neq k}^{n}\theta_j y_j^b \\ \bar{x} \geq x_0, \bar{y}^g \leq y_0^g, \bar{y}^b \geq y_0^b, \bar{y}^g \geq 0, \theta \geq 0\end{cases}. \quad (3)$$

In Equations 2, 3, ρ is the ULGUE. There are n decision-making units (DMUs). Each DMU consists of three input–output vectors: inputs, desirable outputs, and undesirable outputs, using m units of input to produce s_1 desirable outputs and s_2 undesirable outputs. The three input–output vectors can be expressed as x, y^g, and y^b.

Drawing upon the conceptual definition of ULGUE and previous relevant studies (Dong et al., 2020; Jiang et al., 2021; Wu et al., 2022), in this study, three input indicators were selected: the built-up area, fixed asset investment, and the number of employees in secondary and tertiary industries. Desired outputs include the added value of secondary and tertiary industries and the green coverage rate in built-up areas, whereas carbon dioxide emissions are treated as an undesirable output. The detailed descriptions and units of these selected indicators are summarized in Table 1.

4.2.2 Core explanatory variables

The core explanatory variable is the multi-period DID variable, *CarbonSmart*. We treat the dual-pilot policies as a quasi-natural experiment. *CarbonSmart* is constructed as the interaction between two dummy variables: *Treat* and *Post*. *Treat* indicates the treatment group. Cities implementing both low-carbon and smart city pilots are assigned *Treat* = 1. Non-dual-pilot cities form the control group (*Treat* = 0). *Post* marks the implementation timeline. For dual-pilot cities, *Post*= 1 starting from the year when both pilots are established. Prior years are coded as *Post* = 0. In additional analyses, we construct similar multi-period DID variables: *Carbon* (low-carbon city pilot only), *Smart* (smart city pilot only), *One* (single-pilot cities), *Intensity* (intensity DID measure), *PreCarbon* (low-carbon pilot precedes smart city), and *PreSmart* (smart city pilot precedes low-carbon). All these variables follow the same coding rule: 1 from the pilot implementation year onward, and 0 otherwise.

4.2.3 Control variables

The control variables in this paper include the following: (1) industrial structure (*Ind*), which is expressed as the proportion of added value of the secondary industry to GDP; (2) the level of openness to the outside world (*Open*), which is calculated based on the actual utilization of foreign capital as a percentage of GDP; (3) urban technology investment intensity (*Tech*), which is expressed as the ratio of technology expenditure; (4) infrastructure level (*Infra*), which is expressed in terms of *per capita* urban road area; (5) education level (*Edu*), which is expressed as the number of college students per 10,000 people.

4.3 Data

The dataset used in this study is primarily drawn from the *China Urban Statistical Yearbook*, *China Urban Construction Statistical Yearbook*, municipal statistical bulletins on national economic and social development, and carbon emission data obtained from the Emission Database for Global Atmospheric Research. To ensure data comparability, pilot cities designated as province-level units, municipalities directly under the central government, county-level districts, or those with substantial missing data were excluded. The final panel dataset comprises 170 prefecture-level cities in China over the period 2008 to 2019.

Table 2 presents the essential statistical characteristics of the main variables.

5 Results

5.1 Baseline results

The baseline regression results are presented in Table 3. Columns (1)–(3) report the estimated effects of various pilot policies on

TABLE 2 Descriptive statistics.

Variables	Obs	Mean	Std. dev.	Min	Max
Carbon	1989	0.29	0.46	0.00	1.00
Smart	1989	0.17	0.37	0.00	1.00
CarbonSmart	1989	0.04	0.20	0.00	1.00
Ind	1989	47.50	10.87	14.74	80.70
Open	1989	1.47	1.74	0.00	19.78
Tech	1989	1.20	1.30	0.07	20.68
Infra	1989	15.75	7.09	1.55	60.07
Edu	1989	123.50	147.60	0.31	1508.00

ULGUE without controls, whereas columns (4)–(6) present the results with control variables. Specifically, columns (1) and (4) show the impacts of the low-carbon city pilot policy on ULGUE before and after incorporating control variables, respectively. Columns (2) and (5) report similar results for the smart city pilot policy, and columns (3) and (6) illustrate the outcomes for the dual-pilot policy.

As shown in columns (1) and (4), the low-carbon city pilot policy significantly improved ULGUE (coefficient = 0.049, $p < 0.01$) before incorporating control variables. After including the control variables, the effect remained positive (coefficient = 0.020), though at a reduced significance level ($p < 0.10$). Columns (2) and (5) indicate that the smart city pilot policy also significantly increases the ULGUE (coefficient = 0.034, $p < 0.01$) without controls, and it remained statistically significant (coefficient = 0.011, $p < 0.05$) after including controls. Furthermore, columns (3) and (6) reveal that the dual-pilot policy significantly enhances ULGUE both without (coefficient = 0.069, $p < 0.01$) and with (coefficient = 0.029, $p < 0.01$) controls.

After controlling for covariates, the dual-pilot policy (coefficient = 0.029) demonstrated a stronger positive impact on ULGUE than either the low-carbon city (coefficient = 0.020) or smart city (coefficient = 0.011) policies individually. This suggested that the dual-pilot policy generated a greater synergistic enhancement in ULGUE relative to single-policy approaches.

5.2 Parallel trends test

To ensure the accuracy of the DID basic results, the treatment and control groups should show no significant difference in ULGUE prior to the pilot implementation. The results of the parallel trend test are illustrated in Figure 1. Current (0) denoted the year of implementation of the dual-pilot policies; −4 to −1 denoted four to one years before policy implementation; and 1–4 denoted one to four years after policy implementation. As shown, the regression coefficients were not significant before current (0) became significantly positive, beginning in current (0). This indicated that there was no significant difference in ULGUE between the treatment and control groups before the implementation of the dual-pilot policies, whereas significant differences emerged thereafter, thereby satisfying the prerequisites of the DID model. Furthermore, after current (0), the regression coefficients of ULGUE were significantly different from 0 and exhibited a gradual decline, suggesting that the ULGUE of the treatment cities continued to increase.

5.3 Placebo test

A placebo test in DID was employed to validate the robustness and credibility of the DID estimation results, ensuring that these findings were attributable to the treatment effect rather than other confounding factors. The placebo test used fake treatment groups, in which some control units were randomly assigned as if they had received the treatment. Specifically, a pseudo-treatment group was generated by randomly selecting 79 observations from the full sample of 1,989 observations, matching the size of the actual treatment group. These observations were then assumed to be cities under the dual-pilot policies. This procedure was repeated 500 times to obtain 500 sets of regression results. The estimated coefficients and corresponding p-values from the pseudo-policy dummy variables were plotted to visualize the distribution.

As shown in Figure 2, the blue dots representing placebo test coefficients were concentrated around 0 and approximated a normal distribution. The red curve depicted the expected distribution under no true effect, whereas the red vertical dashed line at $x = 0.03$ indicated the actual treatment coefficient from the main study. The horizontal dashed line denoted the 1% significance threshold ($p = 0.01$). The placebo test results strongly confirm the robustness of our findings. Most placebo coefficients were distributed between −0.02 and 0.02, which is consistent with the "no effect" expectation. The actual treatment coefficient, located far from the placebo distribution center, suggested that the true treatment effect was unlikely to have been randomly generated. This placebo test supports the main results, indicating that the treatment effect is genuine and unlikely to be caused by chance or other confounding factors.

5.4 Further studies

To further validate the superior effectiveness of dual-pilot policies on ULGUE, we conducted comprehensive subgroup analyses across different city classifications (Table 4).

Single-policy analysis: we first examined each pilot policy independently. Column (1) retains cities that implemented only the low-carbon city pilot policies (treatment group) and those without any pilot policies (control group), with *Carbon* serving as the DID dummy. Column (2) adopts the same framework for smart city pilots. Both coefficients were significantly positive, confirming that either policy alone effectively enhanced ULGUE.

Comparative policy effectiveness: to evaluate whether dual policies outperformed single approaches, we created a "single-pilot policy" group that encompassed cities with either the low-carbon or

TABLE 3 Baseline results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	ULGUE	ULGUE	ULGUE	ULGUE	ULGUE	ULGUE
Carbon	0.049*** (4.386)			0.020* (1.746)		
Smart		0.034*** (3.361)			0.011** (1.976)	
CarbonSmart			0.069*** (3.324)			0.029*** (2.596)
Ind				−0.003*** (−5.758)	−0.003*** (−5.831)	−0.003*** (−5.707)
Open				−0.366 (−1.304)	−0.430 (−1.548)	−0.424 (−1.528)
Tech				−0.237 (−0.647)	−0.172 (−0.468)	−0.190 (−0.520)
Infra				0.003*** (3.284)	0.003*** (3.695)	0.003*** (3.441)
Edu				0.000*** (4.731)	0.000*** (5.185)	0.000*** (4.881)
N	1989	1989	1989	1989	1989	1989
adj. R^2	0.461	0.459	0.459	0.496	0.495	0.496

t statistics in parentheses.
$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

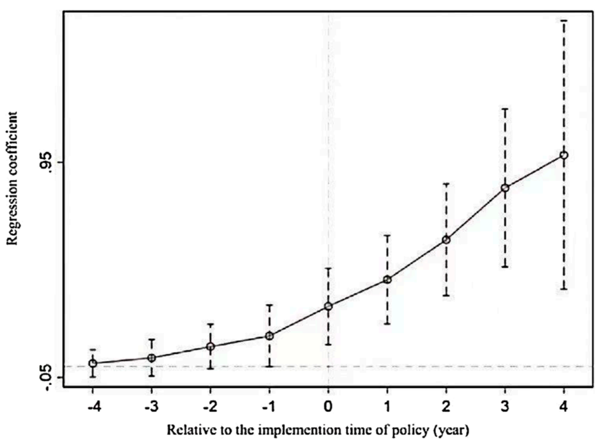

FIGURE 1
Parallel trend test.

smart city designation. Results in column (3) show that the single policy improved ULGUE compared to non-pilot cities (significant at 10% level), although the effect magnitude was smaller than that of dual policies.

Intensity-based analysis: we further implemented an intensity DID model by assigning values of 1 for single-pilot cities and 2 for dual-pilot cities. Column (4) indicates that each additional pilot policy increased ULGUE by 0.012 units (significant at 5% level). This gradient effect supported the hypothesis that policy intensity positively correlated with improvements in ULGUE, providing robust evidence for synergistic benefits of coordinated policy implementation.

Comparison of the pilot policy implementation sequences: based on the approval timeline, cities with dual-pilot policies were divided into two groups: those that first implemented the low-carbon city pilot policy and later the smart city pilot policy, and those that adopted the reverse sequence. To examine whether the order of policy implementation affected ULGUE, we investigated the differential effects arising from the order of the dual-policy adoption.

We first compared cities that initially implemented the low-carbon city pilot policy (followed by the smart city pilot policy) with cities without any pilot policies to measure the net effect of adopting the low-carbon policy first. The results, reported in column (1) of Table 5, show that the policy had a coefficient of 0.021, which was significant at the 10% level. For cities that first implemented the smart city pilot policy followed by the low-carbon city pilot policy, the coefficient in column (2) was 0.016, which was also significant at the 10% level. These findings suggested that implementing the low-carbon city pilot policy prior to the smart city pilot policy generated a stronger positive effect on ULGUE than the opposite sequence.

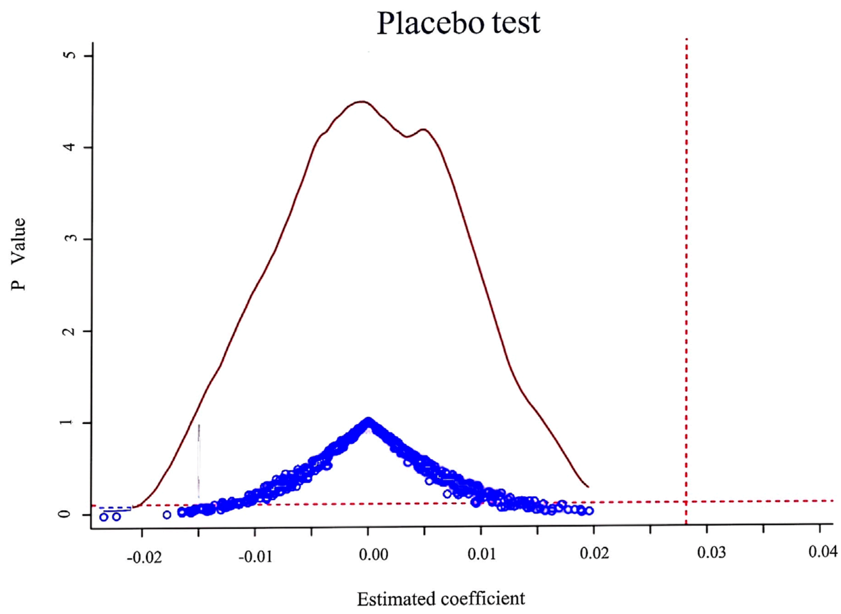

FIGURE 2
Placebo test.

TABLE 4 Results of the discussions.

Variables	(1)	(2)	(3)	(4)
	ULGUE	ULGUE	ULGUE	ULGUE
Carbon	0.017** (2.436)			
Smart		0.025** (2.406)		
One			0.014* (1.947)	
Intensity				0.012** (2.481)
Ind	−0.003*** (−4.418)	−0.002*** (−3.300)	−0.003*** (−5.724)	−0.003*** (−5.673)
Open	−0.457 (−1.511)	−0.277 (−0.815)	−0.445 (−1.604)	−0.435 (−1.566)
Tech	−0.013 (−0.031)	−0.020 (−0.043)	−0.195 (−0.530)	−0.213 (−0.580)
Infra	0.004*** (4.542)	0.002*** (2.601)	0.003*** (3.436)	0.003*** (3.299)
Edu	0.0001 (1.239)	0.0001*** (3.211)	0.0001*** (5.011)	0.0001*** (4.878)
N	1662	1414	1989	1989
adj. R^2	0.499	0.572	0.495	0.495

t statistics in parentheses.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

TABLE 5 Results of sequence comparison.

Variables	(1)	(2)
	ULGUE	ULGUE
PreCarbon	0.021* (1.743)	
PreSmart		0.016* (1.947)
Ind	−0.003*** (−5.289)	−0.003*** (−5.442)
Open	−0.445 (−1.565)	−0.430 (−1.510)
Tech	−0.251 (−0.684)	−0.200 (−0.549)
Infra	0.003*** (3.899)	0.003*** (4.308)
Edu	0.000* (1.772)	0.000** (2.014)
N	1919	1919
adj. R^2	0.502	0.502

t statistics in parentheses.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

6 Discussion

In this study, we provide novel evidence on the synergistic effects of dual-pilot policies on ULGUE. The results showed that both low-carbon city and smart city pilots independently improved ULGUE, with coefficients of 0.020 and 0.011, respectively. More importantly, the dual-pilot policy exhibited superior effectiveness (coefficient = 0.029), confirming stronger coordination effects than single policies.

The intensity analysis further validated our hypothesis, showing that each additional pilot policy increased ULGUE by 0.012 units. This suggested diminishing but positive marginal returns from policy stacking. Notably, the implementation sequence mattered: cities that adopted low-carbon pilots before smart city initiatives achieved greater benefits (coefficient = 0.021 vs 0.016).

Subgroup analyses further demonstrated that both policy intensity and the implementation sequence influenced effectiveness. Specifically, implementing low-carbon policies prior to smart city policies generated greater improvements, suggesting that ecological regulation provided a foundation upon which technological upgrading exerted more substantial impacts.

However, several limitations require attention. First, the analysis is limited by the availability of data and the exclusive focus on Chinese cities, which may restrict the generalizability of the findings. Second, potential endogeneity issues cannot be fully excluded. Finally, future research should consider long-term impacts, regional heterogeneity, and international comparisons to validate and extend these results.

7 Conclusion

In this study, we investigated the coordination effects of low-carbon city and smart city pilot policies on ULGUE in China, employing a quasi-natural experimental framework with a multi-period DID model. The findings provided clear evidence that both policies individually promoted ULGUE, whereas their joint implementation generated significantly stronger effects. This demonstrated the existence of policy synergies that enhanced the sustainability of ULGUE more effectively than single-policy approaches.

The results further revealed important nuances. The intensity analysis showed that the benefits of policy implementation increase with the number of pilots, underscoring the cumulative effect of coordinated interventions. Moreover, the sequence analysis indicated that cities implementing low-carbon pilots prior to smart city pilots achieved relatively higher improvements in ULGUE, suggesting that ecological regulation provided a solid foundation for subsequent technological upgrading. These insights extended the literature by highlighting the dynamic interplay between technological innovation and environmental governance in shaping urban land sustainability.

From a policy perspective, the evidence underscored the necessity of integrated urban governance strategies. Policymakers are advised to avoid fragmented approaches and instead adopt coordinated, sequenced, and multidimensional pilot designs that combined digital transformation with environmental objectives. Such an approach could accelerate the green transition of urban development while strengthening the resilience of cities to ecological and resource pressures.

Overall, this study contributed new empirical evidence to the field of sustainable urban development, while also pointing toward future research avenues, including cross-country comparisons, long-term evaluation of policy effectiveness, and the integration of additional policy dimensions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

BL: Supervision, Conceptualization, Writing – review and editing, Funding acquisition. SL: Conceptualization, Writing – review and editing, Investigation. YS: Resources, Writing – original draft. ZC: Data curation, Writing – original draft, Visualization.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by the Beijing Social Science Foundation Youth Project “Research on Digital Economy Driving Beijing’s Enhanced Regional Radiative and Leading Effects” (No: 22JJC023).

Acknowledgments

The authors thank the reviewers for their constructive comments on the earlier version of the manuscript.

Conflict of interest

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

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