scientific reports

OPEN

The impact of national land supervision system on urban low-carbon transformation: evidence from China

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The land system is a crucial factor influencing urban low-carbon sustainable development. However, previous research has paid little attention to the effects and mechanisms of the national land supervision system (NLSS) on urban low-carbon transformation (ULCT). This study uses China's routine land inspection as a quasi-natural experiment and examines the impact of NLSS on ULCT using panel data from 283 Chinese cities between 2005 and 2016. The study finds that NLSS significantly promotes ULCT, with a series of robustness checks supporting this conclusion, showing a 1.95% improvement in carbon emission performance in cities under supervision. NLSS mainly facilitates ULCT by improving land use efficiency, upgrading the structural of the service sector, and promoting technological progress. Compared to eastern cities, southern cities, large cities, and non-resource-based cities, NLSS more effectively promotes low-carbon transformation in central and western, northern, small- and medium-sized, and resource-based cities. Additionally, in contrast to cities with high environmental awareness, high marketization levels, high financial development levels, and high fiscal pressure, NLSS more strongly promotes ULCT in cities with lower levels of these factors. Furthermore, NLSS exhibits a significant positive spatial spillover effect in promoting ULCT. In advancing ULCT, NLSS can be synergized with smart city pilot policies and innovative city pilot policies but has not shown synergies with low-carbon city pilot policies.

Keywords National land supervision system, Urban low-carbon transformation, Quasi-natural experiment, Spatial spillover effect

Climate warming caused by human activities is primarily attributed to greenhouse gas emissions resulting from fossil fuel combustion and land use[1], posing a severe threat to human survival. As a major global carbon emitter, China's carbon emissions issue is particularly prominent[2,3]. According to the *BP Statistical Review of World Energy 2021*, China accounted for 30.70% of global carbon emissions in 2020. Between 2001 and 2019, carbon emissions from land use in China continuously increased, rising from 5.13×10^9 tons to 17×10^9 tons. As a land supplier and a principal entity responsible for carbon reduction, the Chinese government has actively intervened in carbon emissions through multidimensional land policies[1]. According to the *Outline of the National Land Use Plan of China (2005–2020)*, optimizing land use practices since 2005 contributed 27.6% toward achieving the target of reducing carbon emissions per unit of GDP by 40-45% by 2020[4]. However, under China's decentralized governance system, the institutional flaws of the "development through land" model are the root cause of local governments' failure to effectively implement central objectives for farmland protection and intensive land use. These flaws have led to illegal land use, inadequate farmland protection, and ineffective enforcement of land control policies, with illegal land activities spreading across China[5]. If not promptly addressed, these issues will have far-reaching negative impacts on China's economic development, social stability, and environmental benefits[5,6]. Therefore, the Chinese government urgently needs to establish high-intensity, high-standard institutional arrangements to optimize land use and ensure the achievement of carbon reduction targets.

In 2004, the Chinese government issued the *Decision on Deepening Reform and Strictly Managing Land*, which for the first time proposed the establishment of the NLSS to oversee illegal land occupation and unauthorized approvals of land for construction, while also formulating policies to encourage the revitalization of existing land stock. The document clearly stipulated that, apart from land that must be auctioned, bid for, or listed as per current regulations, industrial land should also gradually follow these methods. This measure effectively curbed

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local governments from selling industrial land at low prices to high-tax-base, high-pollution, high-emission heavy industries, thereby weakening the incentive for local governments to pursue development through land and helping to reduce carbon emissions[7]. To further implement this system, in 2006, the *Notice on Issues Concerning the Establishment of the National Land Supervision System*was issued, formally launching the NLSS. The Ministry of Land and Resources set up nine national land supervision bureaus across the country to monitor land use and management nationwide. The document also shifted the focus of land supervision from "land violations" to "land use" oversight, strengthening supervision over farmland protection, efficient land use, and spatial planning. This policy adjustment aimed to regulate local governments' land transfer practices, promote efficient and intensive land development, and prevent disorderly land transfers and unchecked expansion, thereby positively influencing urban low-carbon sustainable development[4,8]. In 2019, the newly revised *Land Administration Law* formally incorporated the land supervision system into legal statute, further ensuring its legal recognition and protection. The law called for improving the efficiency of land use, protecting and enhancing the ecological environment, and implementing national spatial development and protection requirements. The *Regulations for the Implementation of the Land Administration Law* issued in 2021 further clarified the scope of supervision and the responsibilities of the supervisory institutions, making the land supervision system more specific and operational. Thus, the NLSS, as a high-standard institutional innovation in land supervision and management, plays a vital role not only in optimizing land use patterns but also in environmental governance, with a profound impact on urban low-carbon sustainable development.

In the past, the institutional flaws of the "development through land" model were the primary causes of illegal land use, inadequate farmland protection, and ineffective implementation of land control policies in China[9,10]. As land is a scarce resource and spatial carrier for urban production and living, addressing these institutional flaws and achieving efficient land use are crucial for promoting urban low-carbon transformation (ULCT)[1]. The National Land Supervision System (NLSS) was designed to address the institutional shortcomings that emerged in urban economic development under the "development through land" model[10]. As an important land supervision and management tool of the Chinese government, NLSS aims to curb illegal land use[11,12], enforce farmland protection[13], and oversee the implementation of land control policies[10], thereby restraining excessive development and irrational land use. These measures are expected to significantly impact ULCT. But does NLSS truly influence ULCT? If so, through what mechanisms does it operate? Are there heterogeneous effects and spatial impacts? Exploring these questions can provide developing countries with Chinese experience and empirical evidence on how land systems can promote urban low-carbon sustainable development.

Related work

Influencing factors of ULCT

Existing literature primarily examines the factors influencing ULCT from three key perspectives. First, some studies investigate ULCT using a multi-factor framework. One line of research suggests that GDP, energy intensity, and carbon intensity have a greater impact on CO_2 emissions in the transportation sector than urbanization[14]. Additionally, other studies find that industrial carbon emissions are positively correlated with factors such as urban industrial structure, the level of industrial agglomeration, the size of industrial enterprises, and the level of urban economic development, while they are negatively correlated with industrial structure and ownership structure[15].

Second, some studies explore the factors influencing ULCT from a single-factor framework, mainly focusing on the digital economy, urbanization, and industrial agglomeration. The digital economy primarily reduces CO_2emissions at the provincial level through effects related to industrial structure optimization and resource allocation[16,17]. The relationship between the digital economy and urban carbon emissions follows an inverted U-shape[18]. Additionally, the digital economy enhances carbon emission performance by reducing energy intensity, regulating energy consumption scale, and promoting urban greening[19]. Its influence on carbon emission performance also exhibits spatial spillover effects[20]. The relationship between urbanization and carbon emissions is debated across three perspectives: the promotion theory[21], which posits that urbanization increases carbon emissions; the inhibition theory[22], which argues that urbanization reduces emissions; and the non-linear theory[23], which suggests a complex relationship that varies with stages of urbanization. Industrial agglomeration helps reduce carbon emissions by promoting technological progress[24]. Similar to the digital economy, there is an inverted U-shaped relationship between industrial agglomeration and carbon productivity, with technological innovation playing a crucial role in determining the "turning point"[25]. Moreover, specialized industrial agglomeration tends to exacerbate CO_2emissions, while diversified agglomeration helps curb the reduction of carbon emissions[26].

Finally, some studies examine the factors influencing ULCT from a policy perspective, focusing on various pilot policies, such as the national big data comprehensive pilot policy[27], low-carbon city pilot policy[28], smart city pilot policy[29], civilized city pilot policy[30], and information consumption pilot policy[31]. These pilot policies promote ULCT through different mechanisms, and their effectiveness shows regional heterogeneity effects. For instance, certain policies may be more effective in specific regions due to varying levels of economic development, industrial structure, and local governance, which influence how the policies are implemented and their impact on low-carbon transformation.

Environmental impacts of land use

The environmental effects of land use have become a major focus of academic research[32–35]. In terms of intensive land use, it primarily reduces carbon emissions by advancing industrial structure[4], and it significantly promotes low-carbon transformation in neighboring cities[36]. Regarding land transfer interventions, green technological innovation plays a partial mediating role in the relationship between the structure of industrial land transfers and carbon emission efficiency. Industrial land transfers biased towards low-end technology industries have a significant negative impact on carbon emission efficiency[37]. Marketization of land transfers has curbed carbon emissions by promoting the rationalization, upgrading, and high-quality development of industrial structures[1].

In terms of land resource allocation, land resource misallocation hinders industrial upgrading and technological innovation, thereby exacerbating carbon emissions[38]. Misallocation of land resources not only significantly increases local carbon emissions but also affects neighboring areas. Environmental regulations have a significant negative moderating effect on local carbon emissions caused by land resource misallocation[39]. Market-oriented industrial land allocation can effectively reduce carbon emissions in both local and neighboring regions[7].

Economic and environmental impacts of the NLSS

In terms of economic impacts, land supervision has been shown to significantly reduce the amount of farmland occupied by construction, with routine land inspections having a stronger effect on farmland protection compared to special inspections[13]. Additionally, land supervision has actively promoted the marketization of land, with routine inspections having a greater positive impact than special inspections[40]. For every 1% increase in the coverage rate of routine land inspections, 92 fewer illegal land cases may occur[12]. Moreover, land inspections have effectively curbed urban expansion, with supervised cities experiencing an approximate 5.3% reduction in expansion speed[10].

In terms of environmental impacts, one study focused on the establishment of national land supervision bureaus in 9 provinces in China in 2006, using panel data from 30 provinces to evaluate the environmental effects of land supervision. The findings indicate that the establishment of these bureaus did not significantly worsen environmental pollution levels, but as the scale of the economy expanded, the positive effects of land supervision on environmental pollution became more significant[41].

Literature summary

This study explores the effects and mechanisms of the NLSS on urban ULCT from the perspective of routine land inspections, and its potential marginal contributions are as follows: (1) Unlike existing studies that examine the impact of land use on ULCT or analyze the factors influencing ULCT, this research is the first to explore ULCT factors from the perspective of NLSS. As a high-intensity, high-standard institutional arrangement in China's land supervision system, NLSS expands the understanding of ULCT influence factors and enriches the scope of relevant literature. (2) In contrast to studies evaluating the environmental effects of NLSS[41], this research treats routine land inspections as a quasi-natural experiment. Using panel data from 283 Chinese cities between 2005 and 2016, it investigates the impact of NLSS on ULCT, extending the research on NLSS environmental effects to the more granular urban level. (3) A systematic examination of mechanisms such as improving land use efficiency, upgrading the structure of the service sector, and promoting technological progress, this study reveals the mechanisms through which NLSS influences ULCT. It opens the "black box" of how NLSS operates in relation to ULCT and provides a clearer explanatory framework for understanding its specific pathways of influence. (4) The study also explores the heterogeneous effects of NLSS on ULCT by considering aspects such as city geography, government environmental awareness, marketization level, financial development, and fiscal pressure. Furthermore, it examines the spatial spillover effects of NLSS on ULCT. These findings offer valuable insights and empirical evidence from China, providing developing countries with a reference for optimizing land systems to promote low-carbon sustainable development.

Theoretical analysis

Direct impact of NLSS on ULCT

The NLSS can directly influence ULCT by curbing illegal land use, enforcing farmland protection, and implementing land control policies. First, illegal land use not only generates negative externalities such as environmental pollution, noise pollution, and land fragmentation, but also encourages irrational investment behavior. This tends to attract businesses into low-threshold, high-pollution, and high-emission industries[6], exacerbating environmental pollution and other related issues[42]. Second, the conversion of agricultural land to non-agricultural use in China is largely facilitated by the government through low-cost compulsory land acquisition, which provides institutional support for local governments to pursue "development through land"[43]. Under China's dual land management system, local governments can only transfer land for development after converting agricultural land into construction land[9]. This model has led to a rapid expansion of land transfers, with large amounts of fertile farmland being encroached upon, resulting in irreversible changes in land use. This shift also undermines the role of farmland as a carbon sink[44], exacerbating the imbalance between carbon emissions and carbon sequestration. Additionally, effective land control policies can promote more intensive and environmentally-friendly land use patterns[1]. However, land development that lacks strict regulatory oversight often prioritizes short-term economic gains while neglecting green, low-carbon development. This leads to disorderly urban expansion and irrational land use, driving high-energy-consumption and high-emission economic activities, which ultimately hinders urban low-carbon sustainable development[4,8].

Through a strong political mechanism, significant pressure is exerted on local governments, forcing them to strictly enforce central policy objectives. The regional land supervision bureaus, empowered by the central authority, have fundamentally transformed the previously lax oversight of land use. They no longer turn a blind eye to violations but decisively implement central policy mandates. This shift has had a significant deterrent effect on local governments' land transfer practices. Local governments have come to realize that any illegal land use will face severe accountability measures and public scrutiny, with the costs of violations far outweighing potential gains[9]. The NLSS has gradually corrected illegal land use practices and broken the previous "development through land" model, where economic growth was driven by land development. Under this high-pressure regulatory environment, local governments are forced to reassess and adjust their land-use policies, adopting more rational and sustainable strategies to avoid the risks of violations and the high costs of penalties[10].

To further strengthen this regulatory mechanism, the Ministry of Land and Resources issued the Land Routine Inspection Work Standards (Trial) in 2009, specifying that the results of routine land inspections would be an important basis for assessing local governments' responsibilities in farmland protection. These results were also tied to rewards and penalties in the annual land-use planning process. This policy created a strong political incentive by linking inspection outcomes to officials' performance evaluations. Many provinces have implemented a "one-vote veto" system and lifetime accountability, ensuring that officials bear greater responsibility for farmland protection and land management. Any failure to effectively implement central policies could have a direct impact on local officials' career trajectories. This motivates local governments to be more proactive in land management, ensuring the realization of land transfer and farmland protection goals in line with central directives.

Indirect effects of NLSS on ULCT

Improving land-use efficiency is crucial for reducing carbon emissions[45]. Numerous studies have shown that intensive land use and efficient allocation of land resources can effectively promote ULCT[4,38]. There is a negative correlation between land-use efficiency and carbon intensity, and both can work together with industrial structural adjustments to reduce carbon intensity[46]. On one hand, the NLSS establishes a strict land supervision and accountability mechanism to ensure that local governments strictly enforce central policies in land use, preventing disorderly development and inefficient use. For illegal land occupation, idle land, and inefficient development, the NLSS promptly takes corrective action. Through intensive supervision, the NLSS effectively reduces land waste, ensuring that land resources are used more rationally and efficiently. On the other hand, the NLSS strengthens strict control over land use, preventing arbitrary and inefficient land utilization. Governments at all levels are required to use land according to predetermined land-use plans, avoiding the extensive growth model of "development through land." The processes of land planning, approval, and transfer are all strictly regulated to ensure that land resources are allocated appropriately, preventing resource waste caused by blind expansion and excessive land supply. Through these mechanisms, the NLSS significantly improves land-use efficiency, providing critical support for achieving carbon reduction and promoting ULCT.

The NLSS also mandates that local governments strictly follow central planning in land transfers and usage, prioritizing the allocation of land resources to efficient industries and sustainable development projects. By restricting the excessive supply of low-cost industrial land, the NLSS effectively curbs the disorderly expansion of high-pollution, high-energy-consuming industries. Under the traditional "development through land" model, local governments attracted businesses by offering low-cost industrial land, which led to high-pollution, low-end industries occupying a large portion of land resources[47]. This stifled the growth of efficient, low-pollution service sectors[48,49], hindering ULCT. With NLSS supervision, local governments are now more proactive in implementing the "emptying the cage for new birds" policy, phasing out inefficient, outdated industries and enterprises. The land freed up through this process is reallocated for the cultivation and development of high-tech industries and modern service sectors, in line with policy directives. This shift promotes industrial upgrading and supports ULCT, fostering a more sustainable and low-carbon urban economy.

The "development through land" model entrenched a short-term profit orientation for both governments and enterprises, leading them to focus on immediate returns while neglecting long-term, high-risk technological innovation activities. This, in turn, resulted in slow technological progress and ineffective environmental governance[50]. By strictly controlling land supply and usage, the NLSS effectively curtails this short-sighted behavior, reducing the demand for land[10]. In promoting high-quality economic development, this may pressure governments and businesses to place greater emphasis on long-term technological innovation. For example, local governments may intentionally lower economic growth targets to mitigate the negative impacts on technological progress and carbon emission efficiency[51]. Additionally, the NLSS prioritizes allocating land resources to technology-intensive and environmentally friendly enterprises, creating a strong incentive for technological innovation. In order to secure more resources and development opportunities, businesses are compelled to increase R&D investments, focusing on long-term technological advancements and environmental protection. This dynamic promotes both technological progress and ULCT. Moreover, by linking land use with environmental protection, the NLSS enforces stricter environmental standards for businesses in the process of land development and use. This compels companies to adopt energy-saving and emission-reducing technologies, as well as green production methods, further driving the synergistic development of technological innovation and low-carbon transformation.

Spatial spillover effect of NLSS to ULCT

The NLSS effectively promotes low-carbon transformation in surrounding cities through multiple mechanisms. First, the strict land management and environmental policies implemented in cities under supervision often influence neighboring cities through policy diffusion effects. These neighboring cities, in an effort to remain competitive, tend to imitate the low-carbon development measures of the supervised cities by proactively strengthening land control and optimizing their industrial structures, thereby advancing low-carbon transformation across a broader region. Additionally, the green technological innovation and industrial upgrading driven by the NLSS also spread to surrounding cities through regional economic and industrial chain linkages. Through technological cooperation and market partnerships, enterprises and governments gain access to and apply energy-saving and emission-reduction technologies, further promoting the adoption of green technologies and low-carbon development throughout the region. The environmental spillover effects generated by the NLSS are another crucial pathway for promoting low-carbon transformation in neighboring cities. As supervised cities reduce high-pollution industries, improvements in shared regional air quality and water resources benefit neighboring cities as well. These environmental benefits are transmitted through interconnected ecosystems, leading to enhanced environmental quality in adjacent cities. The market and resource linkages are similarly significant. As supervised cities improve land-use efficiency and phase out high-pollution industries, surrounding cities adjust their industrial structures by introducing more green industries and high-tech sectors, thereby driving overall regional industrial upgrading and low-carbon transformation. Moreover, the NLSS curbs the "race to the bottom" phenomenon, in which local governments compete to attract investment by lowering land prices and environmental standards. By raising land management and environmental standards across supervised cities, the NLSS encourages neighboring cities to follow suit, reducing disorderly competition and fostering coordinated regional development.

Research design

Model specification

In 2008, China's National Land Supervision Bureau launched routine inspection pilot programs in 16 administrative regions, including Cangzhou in Hebei Province, Fushun in Liaoning Province, Yuxi in Yunnan Province, and Xi'an in Shaanxi Province. By 2017, this supervision had expanded nationwide, covering all 31 provincial-level administrative regions. To ensure a comprehensive analysis of the policy's impact before and after its implementation, this study selected a time span from 2000 to 2016, providing sufficient control group samples among the cities in the experimental group. The research sample includes 283 prefecture-level and above cities across the country. This extensive temporal and spatial coverage allows for a more precise evaluation of the impact of NLSS on ULCT.

The study employs a difference-in-differences (DID) model, which compares the changes in ULCT between two groups of cities—those subject to NLSS supervision and those not—before and after the implementation of land inspections. The DID model specifically constructed for this analysis is as follows:

$$ULCT_{it} = \alpha_0 + \alpha_1 NLSS_{it} + \alpha_2 Controls_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (1)$$

In this equation, $ULCT_{it}$ denotes urban low-carbon transformation in city *i* at time *t*. $NLSS_{it}$ is a dummy variable representing the National Land Supervision System. $Controls_{it}$ is a series of control variables. λ_i and μ_t represent individual fixed effects and time-fixed effects. ε_{it} is the random error term.

Variable definitions

(1) Dependent variable.

Referring to the existing literature[52], this study employs a hybrid model that incorporates both radial and slack-based measure (SBM) distance functions, namely the epsilon-based measure (EBM) model, to calculate the urban carbon emission efficiency index, which serves as the key indicator for measuring ULCT. Following previous research[53], the indicator system for urban carbon emission efficiency is constructed based on three aspects: inputs, desirable outputs, and undesirable outputs.

In terms of input indicators, land input is measured by the area of urban construction land; capital input is assessed by the capital stock estimated using the perpetual inventory method with a depreciation rate of 9.6%; labor input is represented by the total number of urban employees at the end of the year; and energy input is reflected by the total urban energy consumption, converted into tons of standard coal. For desired output indicators, we considered three dimensions: economic, environmental, and social benefits. Specifically, GDP is used as the indicator for economic benefits; the green coverage rate of built-up areas is chosen to measure environmental benefits; and the average wage of employees is used to represent social benefits. In terms of undesired output indicators, to more accurately measure carbon emission efficiency, this study incorporates both pollutant emissions and carbon emissions into the undesired output system. The calculation of carbon emissions follows the IPCC 2006 method, using a bottom-up approach, covering the carbon emissions from natural gas, liquefied petroleum gas, electricity, and thermal energy consumption across urban society. For pollutant emissions, the study selects three major pollutants to represent urban pollution emissions: industrial wastewater discharge, industrial sulfur dioxide (SO_2) emissions, and industrial soot (dust) emissions.

(2) Independent variable.

The NLSS includes three forms of inspections: audit inspections, special inspections, and routine inspections, with routine inspections being the most central, representative, and effective form[10]. Although the national land routine inspections are a regular policy, their implementation varies significantly across space and time. This means that not all cities are subject to inspections at the same time, frequency, or intensity. Different cities become targets of inspection in different years, and this gradual, phased implementation of the policy creates conditions for a quasi-natural experiment. As a result, we treat the implementation of NLSS as a quasi-random policy "shock," assuming that cities not yet inspected can serve as a control group for evaluating the impact of NLSS on ULCT. Furthermore, although NLSS is a routine activity, its effects have varied across regions and years, adding an element of exogeneity. For instance, the implementation of NLSS is not entirely determined by the will of local governments but is largely shaped by central government planning and regulation, thus providing a certain degree of externality in the intervention. Consequently, this study selects routine land inspections as the core indicator for measuring NLSS. Specifically, if a city undergoes a routine inspection in a given year (including counties under its jurisdiction), the NLSS value for that city is assigned a 1 for that year and subsequent years; otherwise, the NLSS value is assigned a 0.

(3) Control variables.

To more accurately assess the impact of the NLSS on ULCT, this study also includes the following control variables that influence ULCT. Industrial agglomeration (AGG) can have either a positive or negative impact on ULCT, and in this study, AGG is measured by the location quotient of the manufacturing sector. Investment in green infrastructure (INVSET) can drive economic growth and promote the development of environmental technologies and innovations, thereby facilitating the transformation and upgrading of urban economies. This study sums four types of investments—sewage treatment, sludge disposal, urban landscaping, and urban sanitation—and uses the logarithm of the total investment to measure INVSET.

The ratio of the tertiary sector to the secondary sector (RITO) represents an increase in the proportion of the tertiary sector (services) in the economic structure, which relatively weakens the dominance of the secondary sector (industry). The tertiary sector is typically characterized by lower energy consumption and lower pollution, with significantly lower energy consumption and carbon emissions compared to traditional industries. As RITO increases, the overall carbon emission intensity of the city is expected to decrease, contributing to ULCT.

Environmental regulation (ER) typically includes standards and limits on pollutant emissions, particularly in the industrial and transportation sectors. The establishment and enforcement of these standards encourage businesses and individuals to adopt more environmentally friendly production and lifestyle choices, promoting the adoption of low-carbon technologies and energy sources. In this study, ER is measured by the sulfur dioxide removal rate.

Urbanization (URB) drives large-scale infrastructure construction and renewal, which directly impacts the city's carbon footprint. URB is measured by the proportion of the urban population relative to the year-end resident population.

Openness to the outside world (OPEN) fosters exchanges and cooperation between cities and the international community. Through international cooperation, cities can learn from and adopt successful low-carbon policies and practices from other countries, accelerating the process of low-carbon transformation. OPEN is measured by the ratio of total imports and exports to GDP.

Government intervention (GOV), such as economic measures to promote low-carbon transformation (e.g., tax adjustments, energy pricing), may increase the economic burden on businesses and residents. If the policies are poorly designed or ineffectively implemented, they could negatively impact economic development and social stability. This study measures GOV by the proportion of fiscal expenditure (excluding fiscal education and science and technology expenditures) relative to total fiscal expenditure.

Sample selection and data sources

The data for this study come from a variety of sources. The NLSS data were manually compiled from the official website of the Ministry of Natural Resources of the People's Republic of China. The raw data for other city-level variables were obtained from the *China Urban Statistical Yearbook* (2006–2017). For some missing data, we supplemented and completed the dataset using city statistical bulletins from the corresponding years. The study covers 283 cities nationwide. Since routine land inspections had achieved full national coverage by 2017, the difference-in-differences method is no longer applicable. Therefore, this study uses panel data from 2005 to 2016 for empirical analysis. The statistical descriptions of the variables are presented in Table 1.

Empirical analysis

Parallel trend test

Figure 1 shows the results of the parallel trend test for the impact of the NLSS on ULCT. It can be seen that before 2008, there was no significant difference in ULCT between pilot cities and non-pilot cities, indicating that during this period, the NLSS had no significant effect on ULCT. However, after 2008, the impact of the NLSS on ULCT became significantly positive, suggesting that the NLSS's effect on ULCT aligns with the parallel trend assumption. Specifically, the coefficient of the NLSS's impact on ULCT in 2008 was not significant, which could be attributed to local governments' inadequate enforcement of land inspection policies, possibly due to concerns about economic development and fiscal revenue. Some regions may have even engaged in policy evasion or

Variables	*N*	Mean	SD	Min	p25	p50	p75	p95	Max
ULCT	3396	0.620	0.180	0.000	0.490	0.600	0.730	1.000	1.070
NLSS	3396	0.380	0.490	0.000	0.000	0.000	1.000	1.000	1.000
AGG	3396	0.860	0.470	0.020	0.520	0.780	1.130	1.750	2.820
INVSET	3396	5.590	1.350	1.670	4.790	5.550	6.320	7.470	19.760
RITO	3396	0.820	0.410	0.090	0.580	0.750	0.950	1.490	4.170
ER	3396	0.570	0.210	0.060	0.380	0.610	0.740	0.860	0.990
UBR	3396	42.480	18.720	8.070	28.370	40.450	52.800	78.180	100.000
OPEN	3396	0.380	0.960	0.000	0.040	0.130	0.380	1.440	24.880
GOV	3396	0.800	0.050	0.610	0.770	0.800	0.830	0.870	0.980

Table 1. Statistical description of variables.

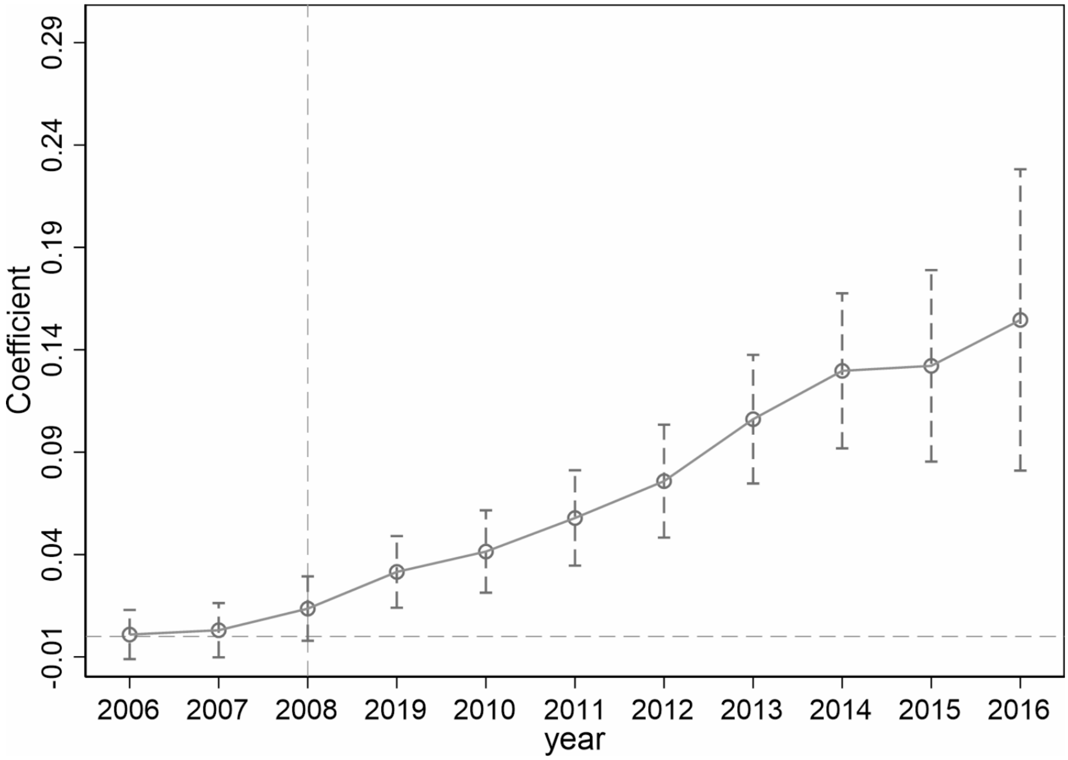

Fig. 1. Parallel trend test results.

violations. Additionally, land inspections require coordination across multiple departments and policies, and if effective communication and collaboration are lacking, the policy's implementation may be limited. After 2008, however, with the continuous development of the land market and the gradual strengthening of the national regulation and management of the land market, the impact of the NLSS steadily increased. Strict land supervision measures and inspection systems gradually took effect, curbing illegal activities and enhancing the incremental effects of the policy.

Baseline regression analysis

The multicollinearity test for the variables in this study shows that the average VIF value for all variables is less than 10, and the VIF value for each individual variable is also below 10, indicating that there is no multicollinearity problem in the regression model. Table 2 presents the baseline regression results of the impact of the NLSS on ULCT. The results indicate that, regardless of whether control variables are introduced or whether city fixed effects and time fixed effects are controlled for, the NLSS consistently shows a significant positive effect on ULCT.

For example, in column (4), compared to cities without routine land inspections, cities with inspections saw an average improvement of 1.95% in carbon emission performance. Although the 1.95% improvement in carbon emission performance may seem modest, it is still significant in the context of urban carbon reduction policies. Reducing carbon emissions is typically a long-term and complex process that involves the coordinated effort of multiple factors. Compared with other policy interventions, the NLSS indirectly promotes ULCT by optimizing land resource allocation, curbing unreasonable land development, and reducing the expansion of high-energy-consuming industries. This policy approach complements the industrial land bidding and auction system.

Additionally, this figure can be compared with the effects of similar policies. Some studies have found that the Low-Carbon City Pilot Policy improved cities' carbon emission performance by 1.7%[54], whereas the NLSS, through land resource management, led to a nearly 2% improvement in carbon emission performance. This suggests that the indirect impact of land policies on carbon emission reduction should not be underestimated.

Robustness analysis

Placebo test

To further exclude the possibility that other unobservable factors influenced ULCT and to ensure that the study's conclusions are indeed driven by the NLSS rather than random factors, a placebo test was conducted for verification. Specifically, this study randomized the treatment group, control group, and the timing of the routine land inspections, constructing dummy variables for pseudo-treatment groups and pseudo-policy implementation times. Interaction terms were then formed for the placebo test. This process was repeated 1,000 times, yielding 1,000 regression estimates for the interaction terms of the pseudo-treatment groups and pseudo-policy implementation times.

Figure 2 shows the distribution of the P-values and kernel density of these pseudo-regression coefficients. It can be observed that the randomly generated coefficients are mostly concentrated around 0, and the majority

	(1)	(2)	(3)	(4)
NLSS	0.0148**	0.0355***	0.0238***	0.0195***
	(2.345)	(7.954)	(4.272)	(3.551)
AGG		-0.0656***		-0.0510***
		(-6.262)		(-4.950)
INVSET		0.0019		-0.0018
		(1.077)		(-1.004)
RITO		-0.0012		0.0215**
		(-0.122)		(2.016)
ER		0.0837***		0.0237*
		(7.227)		(1.830)
UBR		0.0014***		0.0001
		(5.715)		(0.288)
OPEN		0.0079***		0.0136***
		(3.107)		(5.385)
GOV		-0.5824***		-0.5109***
		(-9.839)		(-7.804)
_cons	0.6156***	1.0126***	0.6122***	1.0378***
	(158.179)	(19.957)	(234.411)	(17.761)
City fixed effects	No	Yes	Yes	Yes
Year fixed effects	No	No	Yes	Yes
N	3396	3396	3396	3396
r2	0.0016	0.7716	0.7754	0.7845
r2_a	0.0013	0.7502	0.7541	0.7635
F	5.4998	72.0677	18.2493	18.7824

Table 2. Empirical results of baseline regression. Note: t-values in parentheses, *, **, and ***indicate significance at the 10%, 5%, and 1% levels, respectively.

of P-values are greater than 0.1. This indicates a significant difference between these random results and the actual estimated coefficient of 0.0195 from the baseline regression. These findings demonstrate that the baseline regression results are not driven by random factors but are influenced by the actual NLSS policy, thereby passing the verification of the placebo test.

Other robustness tests

(1) Two-stage did estimation.

This study uses the two-stage did method for robustness analysis. As shown in column (1) of Table 3, after accounting for the bias related to bidirectional fixed effects, the coefficient of the core explanatory variable is 0.0539, significantly higher than the baseline regression coefficient of 0.0195. This suggests that the results adjusted using the two-stage estimation method more accurately reflect the actual impact of the NLSS on ULCT.

(2) Changing the dependent variable.

This study uses carbon emissions per unit of GDP as the indicator for ULCT and re-runs the regression analysis of the baseline model. The regression results are shown in column (2) of Table 3. The results indicate that NLSS significantly reduces carbon emissions per unit of GDP, further confirming the positive role of NLSS in promoting the low-carbon transition of cities.

(3) Excluding other pilot policies.

To exclude the potential effects of the Smart City Pilot Policy (SCCPP), Low-Carbon City Pilot Policy (LCCPP), and Innovation City Pilot Policy (ICPP) on ULCT, this study incorporates these variables into the baseline regression model. The regression results are shown in column (3) of Table 3. The results indicate that even after controlling for these potential policy confounding factors, the impact coefficient of NLSS remains significantly positive. This suggests that the promoting effect of NLSS on ULCT is robust and not significantly influenced by other policy interventions, further enhancing the reliability of the study's conclusions.

(4) Propensity score matching did estimation.

Since cities subject to routine land inspections typically exhibit higher carbon emission performance levels, there may be a "selection bias" in the choice of cities for land inspections. To eliminate the impact of systematic

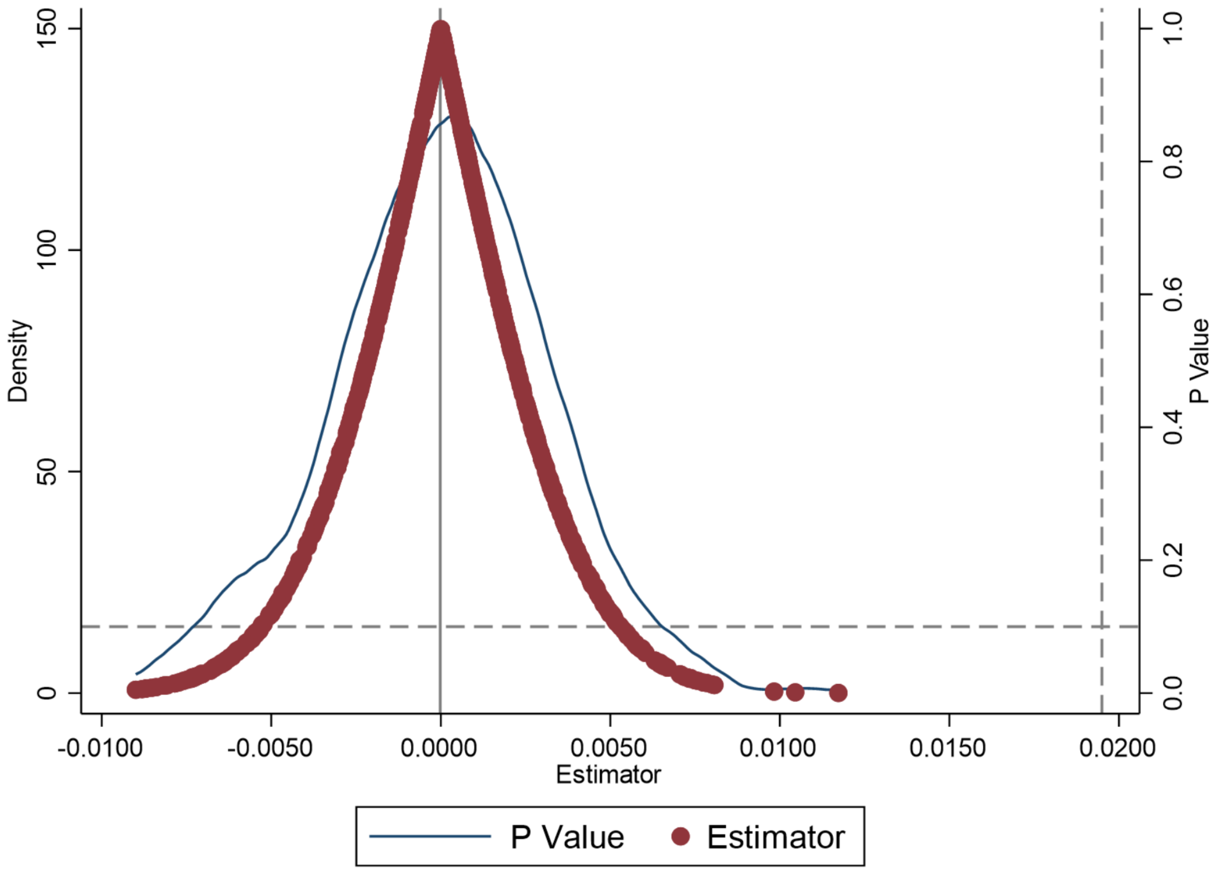

Fig. 2. Placebo test.

	(1) Two-stage did estimation	(2) Changing the dependent variable	(3) Excluding other pilot policies	(4) Propensity score matching did estimation	(5) Excluding special samples
NLSS	0.0539***	-0.0705***	0.0091*	0.0188***	0.0176***
	(3.304)	(-3.641)	(1.655)	(3.433)	(3.096)
LCCPP			0.0285***		
			(4.456)		
ICPP			0.0842***		
			(10.012)		
SCCPP			0.0096		
			(1.464)		
Controls	Yes	Yes	Yes	Yes	Yes
_cons	-	-0.0225	0.9532***	1.0297***	0.9436***
	-	(-0.109)	(16.503)	(17.254)	(15.898)
N	3396	3396	3396	3382	3168
r2	-	0.7834	0.7932	0.7847	0.7877
r2_a	-	0.7623	0.7729	0.7636	0.7669
F	-	9.5886	26.0708	14.8152	15.0559

Table 3. Results of other robustness tests. Note: t-values in parentheses, *, and *** indicate significance at the 10%, and 1% levels, respectively. We controlled the city-fixed effect and year-fixed effect.

differences between the experimental and control groups on the model, this study uses propensity score matching (PSM) to match the two groups of samples. Specifically, the study applies a 1:1 nearest-neighbor matching method to match the experimental and control group samples on a yearly basis, followed by baseline analysis of the matched samples. Table 3 presents the results of this empirical analysis, showing that NLSS still significantly promotes ULCT.

(5) Excluding special samples.

Since municipalities and sub-provincial cities have higher administrative levels, their advantages in economic development and policy implementation may affect the baseline regression results. To eliminate the interference of these factors, this study further excludes the samples of these cities and reanalyzes the data. The results, shown in column (5) of Table 3, indicate that even after removing municipalities and sub-provincial cities, NLSS still significantly promotes ULCT. This demonstrates that the positive effect of NLSS is robust and not influenced by the presence of cities with higher administrative levels.

(6) Endogeneity analysis.

The slope of urban terrain has a significant impact on the types of land transfer. Areas with slopes less than 15 degrees are generally suitable for industrial use, making such cities more likely to offer more industrial land. In these areas, extensive land supply through negotiated transfers is relatively common[55,56]. The "Vertical Planning Norms for Urban Land Use," issued by China's Ministry of Construction in 1999, also clearly stipulates that areas with slopes greater than 15 degrees are not suitable for industrial use. This makes the slope of urban terrain a suitable instrument variable, as it meets the two core requirements: exogeneity and relevance.

First, urban slope is highly correlated with NLSS. Cities with gentler slopes tend to have more industrial land available, making them likely targets for routine inspections. Second, as a natural geographic feature, terrain slope is not directly influenced by ULCT, thus satisfying the exogeneity requirement of instrument variables.

However, since the slope of urban terrain is a static variable and cannot change over time, it poses limitations in dynamic panel data analysis. To address this issue, this study introduces an interaction term between urban slope and a time dummy variable, using it as an instrument variable for NLSS to enhance the dynamic nature and explanatory power of the analysis. In addition to slope, other natural geographic features, such as urban relief and altitude, are also introduced as auxiliary instrument variables.

The results of the endogeneity tests, shown in Table 4, indicate that the selected instrument variables are appropriate. Specifically, the Kleibergen-Paap rk LM statistic rejects the null hypothesis of under-identification at the 1% significance level, demonstrating that these instrument variables are identifiable. Furthermore, the Cragg-Donald Wald F statistic is significantly higher than the critical value of 11.490, ruling out the possibility of weak instruments. These test results confirm that urban slope, relief, and altitude are effective instrument variables in addressing the endogeneity of NLSS's impact on ULCT. The re-estimated regression analysis shows that even after the introduction of these instrument variables, the positive effect of NLSS on ULCT remains significant, further reinforcing the robustness of the conclusions.

Transmission mechanism test

Building upon Model (1), this study further examines the mechanism through which NLSS affects ULCT. The model is constructed as follows:

$$M_{it} = \alpha_0 + \beta_1 NLSS_{it} + \beta_2 Controls_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{2}$$

$$ULCT_{it} = \delta_0 + \delta_1 NLSS_{it} + \delta_2 M_{it} + \delta_3 Controls_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{3}$$

	(1)	(2)	(3)
	Urban slope	**Urban relief**	**Urban altitude**
NLSS	0.2015***	0.2827***	0.4169***
	(3.053)	(3.868)	(4.120)
Controls	Yes	Yes	Yes
N	3384	3396	3396
F	32.6108	28.6838	28.5366
Kleibergen-Paap rk LM statistic	29.187***	30.561***	24.622***
	[0.000]	[0.000]	[0.000]
Cragg-Donald Wald F statistic	29.07	30.45	24.51
	{ 11.490}	{11.490}	{ 11.49}

Table 4. Endogeneity test results. Note: The Z-values are provided in parentheses next to the regression coefficients. *** indicate significance at the 1% levels, respectively. The values in [ ] represent the p-values, while those in { } denote the Stock-Yogo weak identification test critical values at the 10% level. Both city fixed effects and year fixed effects have been controlled.

	(1)	(2)	(3)	(4)	(5)	(6)
NLSS	0.0160*	0.0170***	0.0043*	0.0191***	0.0252**	0.0172***
	(1.755)	(3.207)	(1.885)	(3.482)	(2.507)	(3.177)
LUS		0.1533***				
		(14.688)				
SUSS				0.0877**		
				(2.025)		
TP						0.0900***
						(9.305)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
_cons	11.3074***	-0.6960***	0.3379***	1.0082***	2.2547***	0.8350***
	(116.206)	(-5.318)	(13.941)	(16.745)	(21.039)	(13.549)
N	3396	3396	3396	3396	3396	3396
r2	0.9466	0.7986	0.8293	0.7848	0.8193	0.7904
r2_a	0.9414	0.7789	0.8127	0.7638	0.8017	0.7699
F	46.8462	41.8234	3.9255	17.1680	23.4456	26.7779

Table 5. Mechanism test results. Note: t-values in parentheses, *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. We controlled the city-fixed effect and year-fixed effect.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Eastern region	Central and western regions	Southern region	Northern region	Large cities	Small and medium city	Resource-dependent cities	Non-resource cities
NLSS	0.0013	0.0290***	0.0054	0.0355***	0.0070	0.0152*	0.0313***	0.0035
	(0.157)	(3.982)	(0.914)	(3.262)	(0.983)	(1.846)	(3.270)	(0.543)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	1.1939***	0.9132***	0.7931***	1.0980***	0.9904***	0.8312***	0.9655***	0.9988***
	(12.662)	(12.127)	(12.344)	(8.707)	(13.043)	(9.273)	(9.668)	(14.363)
N	1428	1968	2244	1152	1680	1716	1368	2028
r2	0.7637	0.8030	0.8166	0.7677	0.8003	0.7660	0.7344	0.8310
r2_a	0.7386	0.7830	0.7981	0.7422	0.7796	0.7417	0.7060	0.8138
F	11.1279	12.6616	28.5765	11.0886	16.0920	7.9006	10.4711	15.4398

Table 6. Results of heterogeneity tests based on urban geographic location. Note: t-values in parentheses, *, and *** indicate significance at the 10%, and 1% levels, respectively. We controlled the city-fixed effect and year-fixed effect.

M is the conduction mechanism variable. β_1 represents the influence coefficient of NLSS on M, and δ_2 represent the influence coefficient of M on ULCT. Suppose NLSS affects ULCT through M, both β_1 and δ_2 should be significant.

M represents land use efficiency (LUS), structural upgrading of the service sector (SUSS), and technological progress (TP). Following existing literature[10], this study measures LUS using the ratio of the output of secondary and tertiary industries to the built-up area of the urban district. For SUSS, based on the literature[57], the share of productive services is used as a proxy variable. For TP, the technological progress index derived from the decomposition of total factor productivity is employed, as suggested by prior research[58].

Table 5 presents the results of the mechanism tests for the impact of NLSS on ULCT. From columns (1) and (2) in Table 5, it can be concluded that NLSS significantly enhances LUS, and the improvement in LUS also contributes to promoting ULCT, indicating that NLSS promotes ULCT by enhancing LUS. From columns (3) and (4), it can be inferred that NLSS significantly promotes SUSS, and SUSS is beneficial for ULCT, suggesting that NLSS promotes ULCT by facilitating SUSS. Additionally, from columns (5) and (6), it is clear that NLSS significantly promotes TP, and TP is conducive to ULCT, indicating that NLSS promotes ULCT by advancing TP.

Heterogeneity analysis

(1) Urban geographic location.

Table 6 shows the impact of NLSS on ULCT across different urban locations. The findings indicate that NLSS has a more significant effect in the central and western regions, northern cities, small to medium-sized cities, and resource-dependent cities, reflecting how differences in regional economic structures and stages of development influence the effectiveness of policy implementation.

Compared to the eastern regions, NLSS is more effective in promoting ULCT in the central and western regions. Cities in these regions, lagging behind the eastern regions in terms of economic development, infrastructure, and environmental protection, have weaker foundations. As a result, NLSS can more significantly improve land use efficiency and promote low-carbon development in the central and western regions. Through strict land regulation, cities in these regions can prevent disorderly expansion and inefficient land use, optimize urban planning, and thus increase land resource efficiency and reduce carbon emissions. In contrast, the eastern regions, with relatively mature urban development and higher levels of land management, can still benefit from NLSS in terms of optimizing land use and reducing emissions, but the marginal effects are smaller due to their already high operational levels.

NLSS also has a stronger impact on ULCT in northern cities compared to southern cities. The industrial structure in northern cities is dominated by heavy industries such as steel, chemicals, and coal, which are high-energy-consuming and high-emission sectors. Through strict land-use regulations and environmental assessments, NLSS limits the expansion of these polluting industries, driving industrial upgrading and the development of low-carbon industries. For example, land policies restrict land use by energy-intensive enterprises and encourage the development of high-tech industries and modern services, thereby reducing carbon emissions. In contrast, southern cities have a more diversified industrial structure, with a larger share of service and high-tech industries, leading to lower carbon intensity. Thus, NLSS has a more pronounced effect in northern cities, while in southern cities, with their already relatively low-carbon industrial structure, the marginal effects of the policy are smaller.

Compared to large cities, NLSS is more effective in promoting low-carbon transitions in small to medium-sized cities. Land use efficiency in small and medium-sized cities is generally lower than in large cities, with land use often being extensive and inefficient. NLSS, through strict land approval processes and scientific planning, encourages small and medium-sized cities to focus more on intensive land use. For example, optimizing land use and increasing land development density can reduce land wastage, improve land use efficiency, and consequently reduce carbon emissions. In contrast, large cities tend to have more mature land use and management systems. Although NLSS can still optimize land use in large cities, the higher starting point of these cities results in relatively limited marginal effects of the policy.

In resource-dependent cities, NLSS is more conducive to ULCT compared to non-resource-dependent cities. NLSS also has a more pronounced effect on the low-carbon transition of resource-based cities, which often face more severe environmental issues. Through strict land regulation, NLSS effectively prevents land degradation caused by resource extraction and promotes ecological restoration and the implementation of environmental protection measures. For instance, NLSS can foster ecological recovery, increase green spaces, and enhance carbon sequestration capacity, thereby improving environmental quality and reducing carbon emissions. In contrast, non-resource-based cities face less environmental pressure, and the impact of NLSS policies is less significant compared to resource-based cities.

(2) Government environmental attention and marketization.

Table 7 presents the results of heterogeneity tests based on government environmental attention and marketization. Following previous studies[59], this study measures local governments' attention to environmental protection by analyzing the frequency of environment-related terms in local government work reports. The results indicate that NLSS has a more significant effect on low-carbon transitions in cities with lower environmental attention compared to those with higher attention.

The likely reason is that cities with lower environmental attention often face issues like extensive land use and low resource efficiency. NLSS, through strict land-use approvals and supervision, helps prevent illegal land occupation and inefficient use, thereby improving land-use efficiency. For example, strengthened land-use management and increased development density enable these cities to plan and use land resources more rationally, reduce waste, and promote low-carbon transitions. In contrast, cities with higher environmental attention already have relatively mature environmental awareness and measures, with a solid foundation in

	(1)	(2)	(3)	(4)
	Low environmental attention	**High environmental attention**	**High marketization level**	**Low marketization level**
NLSS	0.0334***	0.0047	0.0017	0.0195***
	(4.444)	(0.553)	(0.224)	(3.551)
Controls	Yes	Yes	Yes	Yes
_cons	0.8848***	1.0536***	0.8849***	1.0378***
	(11.796)	(9.873)	(10.553)	(17.761)
N	1841	1528	1633	3396
r2	0.8444	0.7825	0.8185	0.7845
r2_a	0.8151	0.7351	0.7873	0.7635
F	13.1963	4.0089	12.9455	18.7824

Table 7. Results of heterogeneity tests based on government environmental attention and marketization. Note: t-values in parentheses, *** indicate significance at the 1% levels, respectively. We controlled the city-fixed effect and year-fixed effect.

land management and environmental protection. Although NLSS still optimizes land use and reduces carbon emissions in these cities, the marginal effects of the policy are smaller due to their already high environmental standards.

Additionally, this study uses the proportion of individual and private-sector employment relative to total employment as an indicator of marketization to further examine NLSS's impact on ULCT under different levels of marketization. The results show that NLSS has a more pronounced effect on low-carbon transitions in cities with lower levels of marketization. In such cities, land management and policy enforcement often rely on strong government intervention, with market mechanisms being relatively underdeveloped. Through strict land regulation and policy implementation, NLSS prompts these cities to strengthen land management and environmental protection. For instance, by enforcing stringent land-use regulations, these cities improve land-use efficiency and enhance environmental protection, effectively driving low-carbon transitions. In contrast, cities with higher levels of marketization rely more on market mechanisms and self-improvement initiatives and have already made progress in low-carbon transitions. Although NLSS still plays a positive role in these cities, their stronger self-regulatory capabilities and market-driven improvement mechanisms result in relatively smaller marginal effects of NLSS.

(3) Financial development and fiscal pressure.

Table 8 presents the results of heterogeneity tests based on financial development and fiscal pressure. This study uses the ratio of financial deposits and loans to GDP to measure the level of financial development and further examines the impact of NLSS on ULCT in cities with high and low levels of financial development. The results show that NLSS is more effective in promoting low-carbon transitions in cities with low financial development compared to those with high financial development. This may be because cities with low financial development often lack sufficient funds and financial instruments, making it difficult for them to invest in large-scale environmental and low-carbon projects on their own. In such cases, routine land inspections, through strict land approvals and regulation, compel these cities to improve land-use efficiency and promote environmental protection and carbon emission reduction. For instance, restricting land use for high-pollution projects and promoting ecological restoration and environmental protection measures help drive low-carbon transitions.

Additionally, the study measures fiscal pressure by the ratio of the difference between local fiscal expenditures and revenues to local fiscal revenues, exploring the impact of NLSS on ULCT under high and low fiscal pressure. The results indicate that NLSS is more effective in cities with low fiscal pressure compared to those with high fiscal pressure. These cities typically have more abundant fiscal resources, enabling them to implement routine land inspections more effectively. For example, cities with low fiscal pressure can optimize land use, increase development density, and enforce stricter land approval processes, ensuring that land resources are used efficiently and scientifically, thus reducing land waste and carbon emissions.

In contrast, cities with high fiscal pressure may face more challenges in enforcing land inspection policies due to limited fiscal resources. Insufficient funding may hinder their ability to effectively regulate land use or implement environmental protection projects, affecting the efficiency of land resource utilization. Although routine land inspections still apply to cities with high fiscal pressure, the effectiveness of the policy is constrained by limited fiscal resources, resulting in smaller marginal effects.

Further research

Spatial spillover effect test

The Spatial Durbin Model (SDM) is effective in examining the spatial spillover effects of NLSS on ULCT. In this study, we construct three spatial weight matrices: distance-based spatial weight matrix (W_1), economic spatial weight matrix (W_2), and economic-distance spatial weight matrix (W_3) to explore the spatial spillover effects of NLSS on ULCT under different spatial weight configurations. W_1 and W_2 are matrices with diagonal elements of 0, where the off-diagonal elements are the inverse of the distances between cities for W_1 and the inverse of the absolute differences in per capita GDP for W_2. W_3 is a linear combination of W_1 and W_2 ($W_3 = 0.5W_1 + 0.5W_2$). Additionally, we apply partial differentiation methods to decompose the total marginal effects into direct effects,

	(1)	(2)	(3)	(4)
	High financial development	**Low financial development**	**High fiscal pressure**	**Low fiscal pressure**
NLSS	0.0012	0.0542***	0.0005	0.0168***
	(0.174)	(4.938)	(0.046)	(2.589)
Controls	Yes	Yes	Yes	Yes
_cons	0.7877***	1.3561***	1.0324***	0.7473***
	(11.139)	(11.284)	(9.515)	(9.823)
N	2227	1109	1206	2174
r2	0.8043	0.8156	0.7655	0.8067
r2_a	0.7798	0.7806	0.7301	0.7836
F	6.2648	16.9388	7.5795	7.1398

Table 8. Results of heterogeneity tests based on financial development and fiscal pressure. Note: same as Table 7.

Year	W1			W2			W3		
	I	Z	*P*	I	Z	*P*	I	Z	*P*
2005	0.050	7.569	0	0.174	4.939	0	0.081	5.936	0
2006	0.040	6.869	0	0.144	4.839	0	0.071	5.736	0
2007	0.034	5.869	0	0.113	3.891	0	0.063	5.11	0
2008	0.026	4.720	0	0.095	3.291	0	0.053	4.347	0
2009	0.027	4.828	0	0.095	3.299	0	0.053	4.338	0
2010	0.028	5.016	0	0.069	2.405	0.008	0.047	3.929	0
2011	0.028	4.987	0	0.051	1.831	0.034	0.048	3.949	0
2012	0.025	4.470	0	0.058	2.043	0.021	0.047	3.886	0
2013	0.018	3.382	0	0.055	1.959	0.025	0.038	3.19	0.001
2014	0.018	3.392	0	0.068	2.397	0.008	0.037	3.154	0.001
2015	0.034	5.896	0	0.055	1.964	0.025	0.051	4.225	0
2016	0.064	10.680	0	0.015	0.613	0.270	0.056	4.638	0

Table 9. Results of spatial correlation test for ULCT.

	Direct effect	Indirect effect	Total effect
W_1			
NLSS	0.0222***	1.0667***	1.0889***
	(4.008)	(2.866)	(2.914)
Controls	Yes	Yes	Yes
N	3396	3396	3396
W_2			
NLSS	0.0130**	0.0412***	0.0541***
	(2.440)	(2.949)	(3.655)
Controls	Yes	Yes	Yes
N	3396	3396	3396
W_3			
NLSS	0.0175***	0.2094***	0.2269***
	(3.275)	(3.702)	(3.965)
Controls	Yes	Yes	Yes
N	3962	3962	3962

Table 10. Results of spatial spillover effect test. Note: z-values are provided in parentheses. **, and *** indicate significance at the 5%, and 1% levels, respectively. Both spatial fixed effects and time fixed effects have been controlled .

indirect (spillover) effects, and total effects, estimating them using the Maximum Likelihood Estimation (MLE) method.

Table 9 presents the spatial correlation test results for ULCT, showing that under all three spatial weight matrices, Moran's I values are significantly positive. This indicates a positive spatial correlation for ULCT, meaning that cities with higher carbon emission efficiency tend to cluster together, and cities with lower carbon emission efficiency also exhibit similar spatial clustering effects. Table 10 provides the results of the spatial spillover effect test of NLSS on ULCT. Under all three spatial weight matrices, NLSS not only significantly promotes ULCT within the local region but also benefits the ULCT of surrounding areas through spillover effects. This suggests that after the implementation of NLSS, cities under inspection not only improve their own carbon emission performance but also influence neighboring cities' policies and development, fostering a low-carbon transition across the region. These findings highlight the important role of NLSS in promoting coordinated regional development.

Policy synergy effect test

To examine the policy synergy effects of the Smart City Pilot Policy (SCCPP), Low-Carbon City Pilot Policy (LCCPP), and Innovative City Pilot Policy (ICPP) in conjunction with NLSS on ULCT, this study conducts an interaction term analysis. Specifically, we construct interaction terms between NLSS and SCCPP, LCCPP, and ICPP to explore whether these policies generate synergistic effects when implemented together, thereby providing a deeper understanding of the comprehensive impact of multiple policy interventions on ULCT. Table 11 presents the results of the policy synergy effect test.

	(1)	(2)	(3)
NLSS	0.0152***	0.0217***	0.0060
	(2.793)	(3.853)	(1.096)
SCCPP	-0.0233		
	(-1.427)		
NLSS* SCCPP	0.0406**		
	(2.464)		
LCCPP		0.0398***	
		(4.169)	
NLSS* LCCPP		-0.0105	
		(-0.992)	
ICPP			0.0310***
			(2.600)
NLSS* ICPP			0.0627***
			(5.067)
Controls	Yes	Yes	Yes
_cons	1.0358***	1.0269***	0.9644***
	(14.682)	(14.607)	(14.287)
N	3396	3396	3396
r2	0.7852	0.7864	0.7925
r2_a	0.7641	0.7654	0.7721
F	15.0470	18.4890	33.2322

Table 11. Results of policy synergy effect test. Note: t-values in parentheses, **, and *** indicate significance at the 5%, and 1% levels, respectively. We controlled the city-fixed effect and year-fixed effect.

First, the interaction term between NLSS and SCCPP is significantly positive, indicating that NLSS and SCCPP work synergistically to promote ULCT. The Smart City policy, through data-driven management systems, provides real-time and accurate information to support the implementation of NLSS. For example, smart city systems can collect and analyze data in real time, allowing local governments to more quickly identify illegal land use or high-pollution industries and take timely actions. This enhanced information management and data support significantly increase the efficiency of NLSS enforcement, amplifying its impact on ULCT.

Second, the interaction term between NLSS and LCCPP is not significant, suggesting that NLSS and LCCPP do not form a synergistic effect in promoting ULCT. This may be due to the different focuses of the two policies. NLSS primarily targets the rational allocation of land resources and the improvement of land-use efficiency, while the Low-Carbon City policy focuses more on specific measures such as energy structure adjustments, transportation emission reductions, and green building initiatives. Although both aim to promote low-carbon urban transformation, their objectives do not fully align in practice. As a result, the expected synergy does not materialize. Additionally, the Low-Carbon City policy involves various sectors, such as energy, transportation, and construction, requiring broader coordination and cooperation among departments, whereas NLSS primarily focuses on land planning and use. This complexity in policy coordination may lead to inconsistencies in implementation, further limiting the potential for synergy.

Lastly, the interaction term between NLSS and ICPP is significantly positive, indicating that NLSS and ICPP work synergistically to promote ULCT. The Innovative City policy typically accompanies the development of high-tech industries, green manufacturing, and technology services, which have lower carbon emission intensity compared to traditional high-energy-consuming industries. NLSS, by rationally allocating land resources and preventing the expansion of inefficient and high-pollution industries, creates space for the development of innovative industries. The synergy between these two policies effectively promotes the transformation and upgrading of the urban industrial structure, further supporting the achievement of ULCT.

Discussion
Result interpretation
NLSS is a key policy tool implemented by the Chinese government to regulate land use, improve land-use efficiency, and protect the ecological environment. By strictly supervising land use, NLSS effectively prevents illegal land occupation and unreasonable development, ensuring the scientific planning and efficient utilization of land resources. This system not only plays a crucial role in land resource management but also has a profound impact on ULCT through various transmission mechanisms. This study finds that NLSS significantly promotes ULCT, primarily through three pathways: enhancing LUS, optimizing SUSS, and fostering TP. These findings provide scientific evidence for the government to further optimize and refine the land inspection system in the future, while also supporting the effective implementation of other related policies. By quantifying NLSS's specific contributions to promoting low-carbon transitions, the study helps clarify the strengths and limitations of the policy, offering empirical support for future policy improvements and innovations.

Compared to existing literature[41], this study shares a similar research background, focusing on the low-carbon sustainable development of pilot cities subject to routine land inspections. However, this study differs in terms of research subjects, content, and impact mechanisms, further expanding the understanding of NLSS's role, particularly its specific mechanisms and differentiated effects in promoting ULCT. The findings provide important insights for optimizing urban low-carbon transition policies and offer theoretical support and practical guidance for China in achieving its sustainable development goals.

NLSS plays a significant role in promoting ULCT, but it also exhibits notable heterogeneous effects. The study of these differentiated effects is of great importance. The findings suggest that NLSS is particularly effective in specific types of cities, helping the government identify key areas and priority targets for policy implementation. Cities in the central and western regions, northern cities, small to medium-sized cities, and resource-dependent cities often face significant challenges in resource efficiency, industrial structure optimization, and environmental governance. NLSS demonstrates stronger policy effects in these cities, highlighting its targeted approach and effectiveness. This suggests that the government can prioritize the implementation of NLSS in these regions to achieve higher policy efficiency, optimize resource allocation, and improve carbon emission performance. Additionally, NLSS shows significant effects in cities with low environmental attention, low marketization levels, low financial development levels, and high fiscal pressure. This indicates that NLSS not only compensates for the deficiencies in environmental awareness, market mechanisms, financial resources, and fiscal capacity in these cities but also drives their low-carbon transitions through policy enforcement. Studying these heterogeneous effects helps the government refine the targeting of policies, enhance resource-use efficiency, and promote coordinated regional development. By identifying and promoting successful experiences from these areas, the government can achieve low-carbon transition goals on a broader scale, providing crucial theoretical support and practical guidance for China's sustainable development and ecological civilization efforts.

NLSS not only significantly promotes local low-carbon transitions through strict land-use regulation and scientific planning, but also generates positive spillover effects on the low-carbon transitions of neighboring regions. Regional cooperation and policy diffusion enable surrounding cities to learn from the successful experiences of NLSS, collectively advancing low-carbon development goals, thereby enhancing the overall level of sustainable development across regions. Additionally, NLSS synergizes well with SCCPP and ICPP in promoting ULCT, but does not exhibit significant synergy with LCCPP. The synergistic effects between NLSS and the Smart City and Innovative City Pilot Policies arise primarily from their high complementarity in technological innovation, industrial upgrading, and intensive land use. The Smart City and Innovative City policies drive the efficient use of resources through technological advancements and industrial structure optimization, aligning with NLSS's objectives of land-use regulation and optimization, creating a strong synergistic effect. In contrast, LCCPP focuses more on energy structure adjustments and specific emission-reduction technologies. Although it also aims at reducing carbon emissions, its focus is somewhat independent of or overlaps with NLSS's land management objectives, resulting in the absence of significant synergy. This phenomenon reflects how differences in goals, pathways, and implementation mechanisms between policies impact ULCT. This study also reveals the specific mechanisms through which NLSS promotes ULCT, namely by enhancing LUS, optimizing SUSS, and advancing TP. These mechanisms not only clarify the pathways through which NLSS contributes to low-carbon transitions but also provide important insights for policymakers. By improving land-use efficiency, driving industrial structure upgrading, and encouraging technological innovation, NLSS can more effectively support cities in achieving sustainable development goals and transitioning to a low-carbon economy. The findings provide valuable theoretical and practical references for future policy design and implementation, especially in terms of how optimizing land use, adjusting industrial structures, and fostering technological innovation can promote low-carbon development. These insights offer a feasible pathway for global cities' sustainable development strategies.

NLSS has significantly promoted low-carbon transitions in Chinese cities, and its conclusions and practical experiences offer important lessons for other countries globally. First, the successful implementation of NLSS provides valuable policy insights for governments around the world. By adopting similar land regulation policies, national governments can effectively improve land-use efficiency and optimize resource allocation, thus advancing urban low-carbon development. NLSS's experience demonstrates that the effects of land regulation policies vary across different types of cities, reflecting their broad applicability at different stages of development and in diverse economic contexts. Other countries can tailor land management policies to their specific urban development stages, economic structures, and unique needs to address their distinct challenges and promote low-carbon transitions. Moreover, the significant spatial spillover effects observed in NLSS's promotion of ULCT highlight the importance of regional coordinated development and policy synergy. Regional cooperation and collaboration not only foster the sharing of resources and technologies but also accelerate the overall process of low-carbon transition through policy alignment. Other countries can engage in regional partnerships and policy integration to draw on successful practices and best-case examples, thereby achieving low-carbon development goals across broader regions. This model of coordinated development and knowledge sharing can aid the global community in addressing climate change and achieving sustainable development goals.

Limitations and future research

This study provides important insights into the impact of NLSS on ULCT, but several limitations and areas for improvement remain. (1) The study uses panel data from 283 Chinese cities between 2005 and 2016. While this dataset is highly representative, the policy environment and urban development dynamics may have evolved over time. Therefore, future research could consider using more recent data to capture the latest policy impacts and the dynamic trends of urban low-carbon transitions. (2) This study employed robustness checks such as parallel trend tests, placebo tests, and various instrumental variables to assess the effect of NLSS on ULCT. Although these tests provide reliable evidence, future research could incorporate more rigorous statistical methods, such as pre-treatment trend testing. Implementing these more formal statistical tests would not only strengthen the validation of the parallel trend assumption but also further enhance the robustness of the research methods. (3) This study focuses on China's NLSS, lacking consideration of an international perspective. Future studies could conduct cross-country comparisons to analyze the effects of land management policies on urban low-carbon transitions in different countries. Comparative analysis of policy practices across countries could provide a broader reference for the formulation of low-carbon policies on a global scale.

Conclusion

This study examines the impact of NLSS on ULCT using panel data from 283 Chinese cities between 2005 and 2016, and draws the following conclusions:

(1) NLSS has a significant positive impact on urban carbon emission performance, with supervised cities showing a 1.95% improvement in carbon emission performance. A series of robustness checks support this conclusion.
(2) NLSS promotes ULCT primarily through three channels: enhancing LUS, optimizing SUSS, and TP.
(3) Compared to eastern cities, southern cities, large cities, and non-resource-dependent cities, NLSS has a more significant effect on the low-carbon transitions of central and western cities, northern cities, small to medium-sized cities, and resource-dependent cities. Additionally, NLSS more effectively promotes ULCT in cities with low environmental attention, low marketization levels, low financial development levels, and low fiscal pressure than in cities with higher levels in these aspects.
(4) NLSS demonstrates significant spatial spillover effects in promoting ULCT. NLSS forms synergistic effects with the SCCPP and the ICPP, further advancing ULCT. However, no significant synergy was observed between NLSS and the LCCPP.

Data availability

Data will be made available on request. Please contact the corresponding author (Guangwu Luo).

Received: 31 July 2024; Accepted: 4 November 2024
Published online: 08 November 2024

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Author contributions

Conceptualization, C.L. and G.L.; methodology, X.-W.Y.; validation, C.L. and G.L.; formal analysis, X.-W.Y.; investigation, C.L.; resources, C.L.; writing—original draft preparation, G.L.; visualization, X.-W.Y.; supervision, C.L.; project administration, C.L.; All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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