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How the climate resilient cities construction accelerates urban green transformation: impact effects and mechanism tests

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Methods: This study constructs a quasi-natural experiment leveraging the pilot policy for climate resilient cities construction (CRCC), utilizing panel data from 296 prefecture-level cities in China spanning from 2006 to 2022. The Difference-in-Differences (DID) method is employed to identify the causal effect of CRCC on urban green transformation.

Results: Empirical results show that CRCC significantly accelerates urban green transformation, with a 9.8% increase in green technology innovation. Mechanism analysis reveals that CRCC drives green transformation through industrial structure optimization and upgrading, as well as governmental incentive and regulatory actions. Additionally, the promoting effects of CRCC on industrial structure upgrading and governmental behavioral adjustments are weaker in resource-based cities, while in cities with higher administrative hierarchy, CRCC more effectively drives green transformation by accelerating industrial structure optimization and strengthening governmental incentive behaviors. Heterogeneity analysis shows that the positive effect of CRCC on green transformation is more pronounced in cities located on the southeast side of the Hu Line, and cities within the Yangtze River Economic Belt. Extended test results indicate that CRCC has a considerable enhancing effect on the green transformation of neighboring cities, and that green transformation exhibits a positive spatial spillover effect.

Conclusion: For the first time, this study quantifies the causal effect of CRCC on urban green transformation using panel data, filling a research gap in the role of climate resilience policies in green development.

KEYWORDS

climate resilient cities construction, green transformation, industrial structure, governmental behavior, spatial spillover effect

1 Introduction

Climate change ranks among the most complex and far-reaching global crises the world is currently facing. Cities, being highly concentrated areas of population, industries, and energy consumption, are inherently major sources of greenhouse gas emissions (Yu Q. et al., 2024). In recent years, extreme climate events such as heavy rainfalls, floods, heatwaves, and the urban heat island effect have occurred with increasing frequency and severity (Li et al., 2023). These events have inflicted substantial impacts on urban infrastructure, residents' lives, and economic development. The rapid progress of urbanization has exacerbated resource consumption, environmental pollution, and the vulnerability of urban systems. Consequently, issues related to urban sustainable development triggered by climate change have become increasingly prominent. Urban green transformation represents a systematic overhaul of urban development models, aiming to achieve coordinated goals of resource conservation, environmental friendliness, and low-carbon development through economic structure optimization, production mode transformation, and social lifestyle adjustment (Sharifi et al., 2024).

In July 2024, "Opinions of the Central Committee of the Communist Party of China and the State Council on Accelerating the Comprehensive Green Transformation of Economic and Social Development" explicitly emphasized that encouraging the green and low-carbon transformation of economic and social development is the key to achieving high-quality development and the foundation for resolving resource and environmental issues. It is essential to integrate green transformation into all aspects and build a community of life where humanity and nature coexist harmoniously. China's "dual-carbon" goals of carbon peaking and carbon neutrality, proposed in 2020, further anchor these efforts. These goals not only align with the Paris Agreement's mandate to limit global warming to well below 2°C but also underscore CRCC's role as a tangible pathway for urban decarbonization. By promoting low-carbon industrial transformation and green technological innovation, CRCC exemplifies how developing economies can balance climate resilience with sustainable development under international climate frameworks.

However, in previous urban green transformation practices, the consideration of climate resilience capacity has been relatively insufficient. Global climate governance strategies have mostly focused on climate mitigation, emphasizing energy conservation and emission reduction measures. This has led to an imbalance between climate mitigation and resilience actions. The frequent occurrence of extreme climate events and the resulting severe disasters, as well as biodiversity losses, have highlighted the mismatch between current resilience measures and the increasingly severe climate risks. Therefore, urban green transformation should not only attach importance to mitigation strategies for greenhouse gas emissions reduction but also place greater emphasis on resilience actions such as establishing multi - hazard early warning systems and building resilient urban infrastructure to comprehensively address the challenges of climate change.

In accordance with the "Action Plan for Urban Resilience to Climate Change", in 2017, the National Development and Reform Commission and the Ministry of Housing and Urban-Rural Development selected 28 cities as pilot projects for CRCC, providing a demonstration for promoting climate resilience efforts and urban green transformation in China. CRCC refers to a development strategy that enhances cities' capabilities to withstand extreme climate events through systematic policy design and implementation, while promoting the sustainable transformation of urban economies, societies, and ecosystems. This paper intends to use the difference-in-differences (DID) method to analyze the impact of this pilot policy on urban green transformation, and deeply explore its mechanism of action, heterogeneity, and spatial effects. This article aims to explore the path of urban green transformation and provide policy recommendations for deepening urban climate resilience efforts.

This article comprises seven sections, organized as follows: The second part reviews the literature review. The third part presents the theoretical analysis and research hypothesis. The fourth part outlines the research design, encompassing variable selection, model setting, and data description. The fifth part displays the results and discussion. The sixth part offers further analysis. The seventh part concludes the study and puts forward policy recommendations.

2 Literature review

Literature relevant to this paper can be mainly classified into three categories. The first category consists of research on climate resilience. Shen et al. (2023) utilized the survey data of rural residents in Shanxi and Ningxia and found that farmers' climate-change-resilience behaviors effectively alleviated water poverty. There are also scholars who have conducted horizontal and vertical studies on China's climate-resilience policies. For example, Huang et al. (2021) analyzed and compared the characteristics and strategic evolution of the climate-resilience governance systems in China, Germany, and the United Kingdom, and proposed suggestions for improving China's climate-resilience policy system from three dimensions: technology, capital, and resilience knowledge. As the severe challenges of global climate change become increasingly prominent, the BRICS countries, as important representatives of emerging developing countries, have successively introduced targeted climate-change policies and carbon-emission-reduction measures driven by the carbon-neutrality goal. The research by Zheng et al. (2023) provides valuable insights for us to deeply understand the policy evolution of the BRICS countries in the field of climate-change response.

The second category focuses on the influencing factors of urban green transformation and development. Many scholars, based on different perspectives and research objects, have examined the impact of technological innovation on the green development of Chinese cities. Some scholars have also explored the role of the digital economy in urban green development, and proposed that the positive impact of the digital economy on urban green development has time-lag characteristics (Wei and Hou, 2022) and heterogeneity (Liu et al., 2024). Li et al. (2022) pointed out that the growth of green total factor productivity in resource-based cities is slow. From the government's perspective, local government green assessment significantly affects the green transformation of resource-based cities (Wang, 2024; Ren et al., 2024). There are differences in the green transformation performance among Chinese cities (Ren et al., 2023). The green development efficiency of cities in the western region first increases and then decreases, and the problem of spatial imbalance is relatively serious (Dou et al., 2023).

The third category concentrates on the policy effects of various policies on urban green transformation. Many scholars have examined the policy effects of national policies, such as the "Belt and Road" Initiative (Wang and Cheng, 2024), the pilot policy for low-carbon city construction (Zeng et al., 2023; Ma and Zhu, 2024), the pilot policy for national innovative city construction (Li et al., 2022; Zhang and Zheng, 2023), the construction of pilot demonstration cities for "Made in China 2025" (Wang W. L. et al., 2023), the construction of national-level urban agglomerations (Yuan et al., 2024), the new energy demonstration city policy (Liu et al., 2024), the transportation corridor of the China-Europe Railway Express (Mao et al., 2024), the vertical reform of environmental protection agencies (Zhang et al., 2024), the construction of national independent innovation demonstration zones (Yu et al., 2023), the smart city construction (Chen et al., 2024), and the establishment of Shanxi's "Comprehensive Reform Zone" (Liu et al., 2024).

By reviewing the existing literature, the following points are found: first, current literature on climate resilience has expanded to urban-level mechanisms, with recent studies like Mahmoud et al. (2025) analyzing the EU's Green City Accord and its emphasis on decentralized governance in Copenhagen. However, compared to China's CRCC, which integrates top-down policy piloting with industrial upgrading (Wu et al., 2024), global research on urban resilience still lacks systematic analysis of developing economies' needs. Second, the current research on the influencing factors of urban green transformation and development concentrates on technological innovation, economic development, resource consumption, environmental regulation, etc. There is relatively little exploration of the role of climate resilience in urban green transformation from the perspective of climate resilience. Third, although existing research has focused on the policy effects of multiple national policy pilot constructions on urban green transformation, few studies have paid attention to the impact of CRCC on urban green transformation. The research on the mechanism analysis, heterogeneity analysis, and spatial effects of the relationship between the two is not comprehensive enough.

Climate change poses unprecedented challenges to urban sustainability, with cities increasingly recognizing the need to integrate climate resilience into green transformation strategies. While existing research has made notable contributions, a critical examination reveals distinct gaps in our understanding of how CRCC influences urban green transformation. These gaps primarily manifest in three interrelated areas, which this study aims to address.

First, the majority of literature on climate resilience remains concentrated at the agricultural household level or focuses on comparative policy analysis across nations, with surprisingly limited exploration of urban-level resilience mechanisms. This oversight is particularly problematic because cities, as hubs of economic activity and carbon emissions, face unique challenges in balancing mitigation and adaptation strategies. For instance, while rural resilience research has highlighted farmers' adaptive behaviors (Li, 2023), urban contexts require distinct frameworks to address infrastructure vulnerability, industrial carbon footprints, and systemic governance gaps.

Second, existing studies on urban green transformation have predominantly focused on technological innovation, environmental regulation, or economic development factors (Lin et al., 2024; Wu et al., 2024), but the specific pathways through which CRCC policies drive green transformation lack systematic analysis. Notably, the interactive effects between industrial structure adjustment and governmental behavior have not been empirically tested. For example, while studies have shown that industrial upgrading enhances green total factor productivity (Hunjra et al., 2024), whether CRCC specifically accelerates this process through policy-induced industrial restructuring remains unquantified. Similarly, how governmental incentives and restrictive measures synergistically promote green transformation requires more rigorous empirical validation.

Third, the spatial dimension of CRCC effects has been largely overlooked. Most policy evaluations of urban green transformation focus on single-region impacts, ignoring potential spillover effects that could shape regional sustainability dynamics. For example, while the "pollution haven" hypothesis has been explored in the context of FDI (Chiriluș and Costea, 2023), whether CRCC in one city promotes green innovation in neighboring regions through knowledge diffusion, policy emulation, or resource reallocation remains a novel research frontier. This gap is particularly relevant for China's urban agglomerations, where spatial interdependencies may amplify or mitigate the effectiveness of CRCC.

In view of this, based on the panel data of 296 prefecture-level cities from 2006 to 2022, this paper constructs a DID model to study the impact of the pilot policy of CRCC on urban green transformation. The marginal contributions of this paper are mainly as follows: first, innovatively combining CRCC with urban green transformation, this paper systematically evaluates the direct impact of CRCC on urban green transformation by constructing a quasi-natural experiment. This not only enriches the evaluation dimensions of the effects of CRCC but also provides new empirical evidence and theoretical support for urban green transformation strategies. Second, from the perspectives of multiple mechanisms such as the optimization and upgrading of the industrial structure, and the government's incentive and restrictive behaviors, this paper deeply analyzes the internal logic of how CRCC promotes urban green transformation, offering more in-depth insights into the relationship between climate resilience and urban green transformation. Third, given the regional disparities in China's urban development, grouped regression within the DID framework can effectively capture the heterogeneity in policy effects. When combined with spatial econometric models, this approach further examines the spatial spillover effects of green transformation, forming a three-dimensional analytical framework that integrates "individual effects-group differences-spatial correlations." This methodological combination breaks through the limitation of traditional DID, which typically focuses only on policy effects in single regions, and innovatively reveals the regional synergistic effects of CRCC.

3 Theoretical analysis and research hypothesis

3.1 Climate resilient cities construction and urban green transformation

China's climate resilience policy system is characterized by its national strategic importance, policy systematization, and cross-departmental collaboration (Cui et al., 2024). However, existing policies face issues when dealing with climate governance, such as insufficient understanding of climate change at the grassroots level, weak basic capabilities, imperfect working systems and supporting guarantee measures, and unsound cross-departmental cooperation mechanisms (Sibiya et al., 2022). Therefore, implementing the pilot construction policy of climate resilient cities, featuring comprehensive planning, adaptable actions tailored to local conditions, institutional and mechanism innovation, and coordinated monitoring and early warning, becomes the key to solving these problems. Previous research indicates that local government departments lack a climate monitoring and evaluation system and a scientific evaluation process, which prevents them from providing precise guidance for climate change resilience practices and forming effective feedback (Biswas and Rahman, 2023; Chen et al., 2023). Moreover, the absence of an organizational and coordination mechanism for climate change resilience among the national, regional, and departmental levels leads to unclear main responsibilities for climate change resilience (Cid and Lerner, 2023). To improve China's climate resilience policies and further strengthen the closed-loop management of the policy framework, in 2017, the National Development and Reform Commission and the Ministry of Housing and Urban-Rural Development jointly issued the "Notice on Printing and Distributing the Pilot Work of Climate Resilient City Construction", designating 28 regions represented by Hohhot and Dalian as pilot areas for climate resilient city construction. The aim is to create a policy resilience base and deeply integrate the concept of climate change resilience into the entire process of urban construction and management.

The theoretical connection between CRCC and urban green transformation is rooted in the theories of sustainable development and transition, which are organically linked through a "pressure-response" mechanism. The essence of CRCC is to encourage cities to innovate in the institutions, technologies, and mechanisms of climate change resilience, so as to give play to the demonstration, breakthrough, and driving roles of the pilot projects (Zhang Y et al., 2024). On the one hand, from the perspective of ecosystem restoration and spatial layout optimization, the pilot policy supports the implementation of ecosystem protection and restoration projects. It also guides cities to accelerate the formation of a green-development spatial pattern, and build a complete urban ecological network. On the other hand, as seen from industrial structure adjustment, the pilot policy provides financial guarantee for scientific and technological innovation. It helps the advancement of intelligent urban management systems and the application of technological achievements in urban construction. Meanwhile, it phases out backward industries and the development of green industrial chains. Therefore, this paper proposes Hypothesis 1.

Hypothesis 1. Climate resilient city construction contributes to accelerating urban green transformation.

3.2 The influence mechanism of CRCC on urban green transformation

3.2.1 Industrial structure

The industrial structure mechanism is anchored in the resource reallocation theory. CRCC's green entry standards facilitate the exit of backward production capacity and the expansion of green industries. This aligns with the "structural dividend" hypothesis, where industrial upgrading improves resource efficiency and spurs green innovation. Firstly, the pilot policy of CRCC guides industrial optimization and elimination by setting green standards for industrial access. This policy framework, based on multiple dimensions such as environmental carrying capacity, resource utilization efficiency and carbon emissions, screens out and phases out backward production capacity, thus reallocating resources to industries with greater development potential and more pronounced green features (Gao et al., 2025). Secondly, the government adopts a variety of policy measures to increase the proportion of green industries in the urban industrial structure and foster new economic growth points (Sun and Feng, 2023). Finally, regarding existing traditional industries, the pilot policy encourages collaborative innovation between traditional and low-carbon industries, propelling the transformation of the industrial structure towards green and advanced forms. Existing research has widely confirmed that the upgrading process of the industrial structure is conducive to improving the urban green total factor productivity, and stimulating the vitality of green technology innovation (Wang Y. et al., 2023; Yan et al., 2023).

3.2.2 Government behavior

Government behavior builds on the "Porter Hypothesis," which posits that well-designed environmental policies can induce innovation to offset compliance costs (Lee, 2020). CRCC's incentive tools and restrictive measures reflect a dual governance approach. To address market failures, government incentive measures are of great significance. Government incentives in the pilot policy are mainly reflected in two aspects: first, the government, through means such as setting up special funds, providing financial subsidies, and offering tax incentives, encourages social capital to flow into green projects (Wang and Zhang, 2024). Second, government departments actively build urban climate change monitoring and prediction platforms, so as to enhance the climate resilience of urban infrastructure and the service capabilities of the ecosystem (Shang and Lv, 2023).

The government's policy intervention in urban green transformation also includes restrictive behaviors. The pilot policy emphasizes planning constraints and project risk assessment, requiring cities to incorporate climate change responses and green transformation measures into their designs. The government's restrictive behaviors are specifically reflected in two aspects: one is the restriction on resource utilization. The government strengthens the regulation of key urban resources such as water, land, and energy, and raises the threshold for industry access (Deng and Wu, 2024). The other is the strict limitation of pollutant and carbon emissions. The government sets clear standards for various pollutant emissions, covering exhaust gas, wastewater, solid waste, etc., determines the total carbon emission target, and decomposes it to various industries and enterprises (Liu et al., 2023; Liu and Yin, 2024). Based on the above analysis and drawing on the basic principles of sustainable development policies, this paper constructs the impact pathway diagram of CRCC on urban green transformation, as shown in Figure 1. Accordingly, we put forward Hypothesis 2a and Hypothesis 2b.

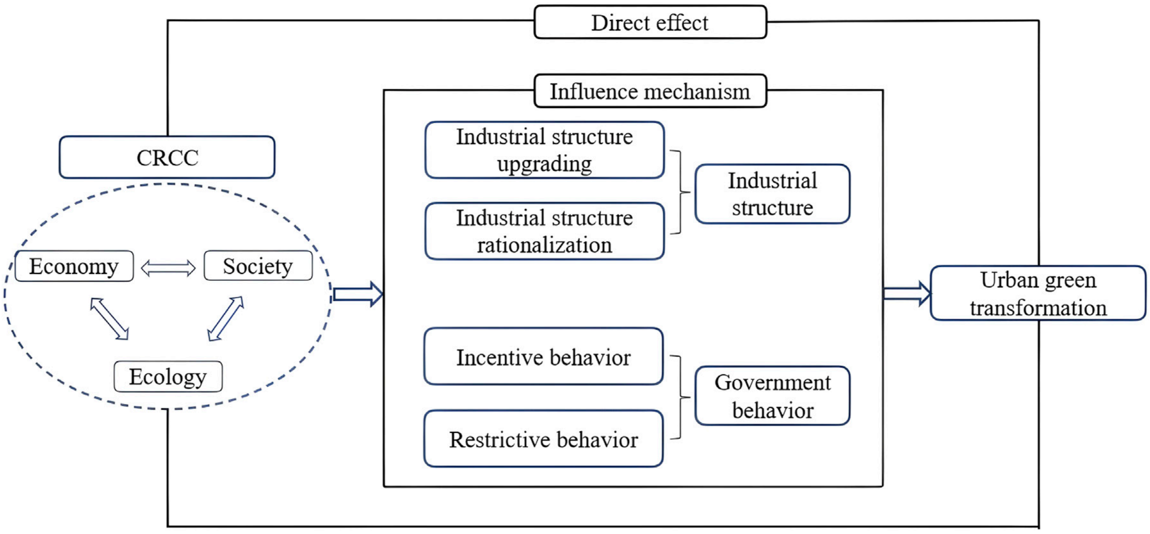

FIGURE 1
The impact path of CRCC on urban green transformation.

Hypothesis 2a. CRCC facilitates urban green transformation through the upgrading and rationalization of the industrial structure.

Hypothesis 2b. CRCC promotes urban green transformation through the government's incentive and restrictive behaviors.

3.3 Heterogeneity analysis of the impact of CRCC on urban green transformation

The policy impacts of CRCC on urban green transformation might differ depending on whether cities are located on either side of the Hu Huanyong Line. There are marked disparities in resource endowments and economic development levels across the two sides of this line. On the southeastern side, there are dense urban agglomerations, a relatively high level of urbanization, and urban development emphasizes the concurrent promotion of environmental protection and green transformation (Ma et al., 2023). In contrast, on the northwestern side, due to rigid constraints such as the natural environment, the urbanization process lags behind. The industrial structure is relatively homogeneous, with a high proportion of resource-based industries, which may pose more challenges during the green transformation process.

Whether a pilot city is located in the Yangtze River Economic Belt may influence the effect of implementing the pilot policy for CRCC. The Yangtze River Economic Belt is a region with a dense population, large-scale industries, developed economy, and a complete urban system. Cities in this region have more abundant resources and stronger implementation capabilities during the green transformation process (Yang and Ran, 2024). In contrast, regions outside the Yangtze River Economic Belt may face constraints in aspects such as financial support and technology introduction due to their relatively lower economic development levels, which may lead to differences in policy effects. In view of this, this paper proposes Hypothesis 3.

Hypothesis 3. The promoting effect of CRCC on urban green transformation is more evident in cities on the southeast side of the "Hu Huanyong Line", and in the Yangtze River Economic Belt.

4 Research design

4.1 Variable selection

Explained variable: degree of urban green transformation (gtd). Urban green transformation denotes a comprehensive shift in urban development models, aiming to achieve resource efficiency, environmental sustainability, and low-carbon growth through economic restructuring, production mode innovation, and lifestyle adjustments. Existing literature has emphasized that green technology innovation serves as a critical indicator for measuring this transformation, as it captures a city's capacity to adopt and implement novel eco-friendly technologies and concepts (Deng and Wu, 2024; Shahani et al., 2022). For instance, Du et al. (2021) and Li and Li (2024) both employed green innovation metrics to assess regional green transitions, while Deng and Wu (2024) specifically validated the use of green patent applications as a proxy for technological progress in resource-based cities. In this study, the number of green invention patent applications is adopted to reflect the level of green technology innovation, aligning with prior research to ensure the validity of measurement.

Explanatory variable: CRCC. When estimating the impact of CRCC on green transformation, a dummy variable for CRCC is set. If city i is selected as a pilot for CRCC in year t, then $policy_{it} = 1$; otherwise, $policy_{it} = 0$.

To accurately identify the causal relationship between CRCC and urban green transformation, this study introduces a comprehensive set of control variables, drawing on theoretical foundations and empirical evidence from existing literature. The selection of variables and their measurement methods are as follows:

Economic development level (gdp). Measured by the natural logarithm of *per capita* regional GDP. This variable is included as higher economic levels enable cities to allocate more resources to green technology and low-carbon development, with prior studies (e.g., Lin et al., 2024) confirming its role in driving green transformation through technological innovation and industrial structure upgrading.

Energy consumption (lig). Proxy measured by the natural logarithm of nighttime light intensity (constructed from DMSP-OLS images), reflecting regional energy consumption scale. Studies have suggested that energy consumption structure affects green technology innovation. For instance, Sun and Feng (2023) emphasized that energy conservation and emission reduction effects drive urban green development, making this variable crucial for capturing energy-related influences.

Population density (den). Calculated as the natural logarithm of the ratio of year-end total population to total area. High population density may enhance resource utilization efficiency and promote green practices. Zhang Z Q et al. (2024) found that population agglomeration positively correlates with urban green technology innovation, justifying its inclusion as a control variable.

Openness to the outside world (fdi). Represented by the proportion of foreign direct investment (FDI) in regional GDP. The "pollution haven" hypothesis suggests that FDI may introduce environmental risks. Yu and Liu (2024) confirmed that FDI under weak environmental regulations can hinder green transformation, making this variable essential for addressing external economic impacts.

Urbanization (urb). Measured by the ratio of permanent urban population to total population. Urbanization influences land use and energy demand. Pan et al. (2024) indicated that urbanization stages affect green development efficiency, necessitating its control to isolate policy effects.

Government size (gov). Defined as the proportion of fiscal expenditure in regional GDP. The "Porter Hypothesis" suggests that government intervention can promote green innovation. Dzwigol et al. (2023) found that larger government size enhances environmental regulation effectiveness, making this variable critical for capturing policy-driven influences.

Human capital (hum). Measured by the number of college students per 100 people. Human capital accelerates technological diffusion and green innovation. Meng et al. (2023) showed that high-level human capital promotes corporate green innovation, justifying its inclusion to control for intellectual capital effects.

Informatization (inf). Measured by the number of international internet users per 10,000 people, reflecting the level of digital infrastructure and information technology application in cities. This variable is included as digital technology drives urban green transformation through energy conservation, emission reduction, and industrial upgrading effects (Ma and Lin, 2025).

Industrialization (ind). Measured by the proportion of total industrial output value to GDP, reflecting the structural characteristics and development stage of the industrial economy. Industrial structure directly affects energy consumption and emissions. Hao et al. (2023) highlighted that industrial upgrading improves green total factor productivity, while excessive industrialization may hinder sustainability.

4.2 Model setting

To test whether the theoretical hypotheses of this paper hold true, based on the "Notice on the Pilot Work of CRCC" jointly issued by the National Development and Reform Commission and the Ministry of Housing and Urban-Rural Development in 2017, 28 climate-resilient city construction pilot cities such as Wuhan and Jinan are taken as the experimental group, and other cities are regarded as the control group. The DID method, by constructing a "time × group" interaction term, is able to effectively isolate the policy effect from the confounding influences of urban characteristics and time trends, thereby precisely identifying the causal effect of CRCC on urban green transformation. Considering that the individual characteristics of cities and time-trend characteristics may affect the model estimation, city fixed effects and time fixed effects are further introduced into the model. The specific model is set as follows:

$$gtd_{it} = \alpha_0 + \alpha_1 policy_{it} + \sum_{j=2}^{J} \alpha_j X_{it}^{j} + \omega_i + \omega_t + \varepsilon_{it} \tag{1}$$

Among them, gtd_{it} represents the degree of green transformation of city i in year t. $policy_{it}$ is a dummy variable indicating whether city i is a pilot city for CRCC in year t. If city i is a pilot city in year t, this variable takes a value of 1; otherwise, it is 0. The parameter α_1 is the focus of this paper. If $\alpha_1 > 0$, it indicates that CRCC is conducive to urban green transformation. X_{it} represents a series of control variables that may affect urban green transformation. ω_i and ω_t represent the city effect and year effect respectively, and ε_{it} is the random error term.

4.3 Data description

This paper selects panel data of 296 prefecture-level cities in China from 2006 to 2022 as the research sample. The list of pilot cities is compiled according to the "Notice on Carrying out the Pilot Work of CRCC". The night-time light intensity data is sourced from the National Geophysical Data Center of the United States. The green patent data were obtained from the China National Intellectual Property Administration (CNIPA) database and cross-validated with the China Science and Technology Statistical Yearbook. Green invention patent applications were identified using International Patent Classification (IPC) codes related to energy conservation and environmental protection. The data filtering and validation process involved excluding international patents to focus on domestic filings, deduplicating records by application number to avoid duplicates, matching patents to cities based on applicants' registered addresses, and validating against the China City Statistical Yearbook to ensure address accuracy. Data for other variables mainly come from the China City Statistical Yearbook, China Science and Technology Statistical Yearbook, China Urban and Rural Construction, Wind database, CSMAR database, etc. Some missing values are filled through interpolation. It should be emphasized that among the list of CRCC pilot cities, cities with severe data shortages (Korla, Shihezi, and Aksu) are excluded. Additionally, since Xixian New Area in Shanxi Province spans Xi'an and Xianyang, both cities are included in the construction

TABLE 1 Descriptive statistics.

Variables	Description	Observations	Average value	Standard deviation	Minimum value	Maximum value
gtd	Degree of green transformation	5,032	3.390	1.948	0	9.978
$policy$	Pilot policy for CRCC	5,032	0.030	0.170	0	1
gdp	Level of economic development	5,032	10.518	0.730	4.595	13.056
lig	Energy consumption	5,032	1.313	1.365	−6.110	4.095
den	Population density	5,032	5.626	1.140	0.073	8.100
fdi	Openness to the outside world	5,032	0.019	0.023	0	0.239
urb	Urbanization	5,032	0.454	0.481	0.015	6.357
gov	Government size	5,032	0.217	0.241	0.043	4.156
hum	Human capital	5,032	0.018	0.021	0	0.129
inf	Informatization	5,032	0.214	0.202	0.0001	3.663
ind	Industrialization	5,032	1.614	1.889	0.0003	27.555

pilot list. The descriptive statistical results of the variables are shown in Table 1.

5 Results and discussion

5.1 Benchmark regression results

Based on the panel data of prefecture-level cities in China from 2006 to 2022, a two-way fixed-effects DID model is employed to identify the impact of CRCC on green transformation. The regression results are presented in Table 2. In column (1), only control variables are included. On this basis, column (2)–(3) control for city fixed effects and year fixed effects respectively, and column (4) controls for both city and year fixed effects simultaneously. The results show that the regression coefficient of the core explanatory variable $policy$ focused on in this paper is significantly positive, indicating that CRCC can effectively enhance urban green transformation. Thus, Hypothesis 1 is verified. Notably, unlike the fuzzy logic approach used in water security assessments (Yuan et al., 2025), which handles uncertainty in ecological systems, our DID model rigorously identifies causal effects in policy evaluation, providing robust evidence for the effectiveness of climate resilience policies. This causal inference framework is particularly valuable for policymakers, as it distinguishes the net impact of CRCC from confounding factors, such as economic growth or regional trends.

Observing the control variables according to the results shown in column (4) of Table 2. The estimated coefficient of gdp is decidedly positive, suggesting that an increase in the level of economic development facilitates the acceleration of green transformation. The estimated coefficient of lig is distinctly positive. The possible reason is that the expansion of the scale of energy consumption contributes to promoting the optimization of the energy structure and the development of clean energy, thereby facilitating urban green transformation. The estimated coefficient of den is remarkably positive, indicating that cities with a high population density generally have higher resource-utilization efficiency, thus promoting green transformation. The estimated coefficient of gov exhibits a prominent positive, indicating that an expansion of government size is conducive to urban green transformation. This view, to some extent, validates the applicability of the "Porter Hypothesis" in the Chinese context (Sun et al., 2024). The estimated coefficient of inf is significantly positive, indicating that information technology boosts resource allocation efficiency and green tech adoption, driving green transformation. In contrast, the coefficient of ind is significantly negative, likely due to traditional industry's high energy consumption and pollution, which hinder urban green transformation.

5.2 Parallel trend test

In the application of the DID model, the parallel trend assumption is a core prerequisite to ensure the validity of causal inference. Before the policy implementation, the treatment group and the control group should maintain the same trend of change, which means that there are no other exogenous shocks affecting the explained variable before the event. Considering the possible dynamic persistence of CRCC, this paper refers to the approach of Dunbar et al. (2023) and constructs the following Equation 2 using the event-study method:

$$gtd_{it} = \alpha_0 + \sum_{t=2012, t\neq 2017}^{t=2022} \alpha_t policy_{it} + + \sum_{j=1}^{J} \beta_j X_{it}^{j} + \omega_i + \omega_t + \varepsilon_{it} \quad (2)$$

Among them, $policy_{it}$ is a dummy variable for CRCC, which is the observed value of the interaction term for 5 years before

TABLE 2 Regression results of the impact of CRCC on urban green transformation.

Variables	(1)	(2)	(3)	(4)
policy	0.561***	0.192***	0.298***	0.098**
	(8.02)	(3.23)	(4.22)	(2.07)
gdp	1.309***	1.426***	0.841***	0.439***
	(21.40)	(19.56)	(12.65)	(9.85)
lig	0.044	0.132**	0.155***	0.317***
	(0.74)	(2.42)	(2.59)	(8.00)
den	0.635***	1.662***	0.515***	1.168***
	(12.32)	(8.10)	(9.80)	(8.03)
fdi	0.749	−5.362***	5.830***	−1.128
	(0.74)	(−6.81)	(5.59)	(−1.54)
urb	−0.349***	0.546***	−0.275***	−0.155
	(−6.91)	(4.15)	(−5.42)	(−1.43)
gov	0.711***	0.948***	0.124	0.619***
	(5.63)	(6.85)	(1.16)	(6.12)
hum	14.244***	1.891*	19.038***	−0.002
	(14.97)	(1.71)	(19.12)	(−0.00)
inf	1.528***	1.110***	1.033***	0.442***
	(8.42)	(5.60)	(8.03)	(4.84)
ind	0.009	0.032**	0.009	−0.024*
	(0.64)	(2.57)	(0.63)	(−1.86)
Constant	−16.444***	−23.952***	−10.655***	−10.297***
	(−21.68)	(−26.94)	(−12.74)	(−11.86)
City FE	NO	YES	NO	YES
Year FE	NO	NO	YES	YES
N	5,032	5,032	5,032	5,032
R^2	0.7002	0.9069	0.7343	0.9333

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively (indicated by superscripts on the coefficient estimates). Values in parentheses are t-statistics. The estimated coefficient of 0.098 for “policy” (Column 4) indicates that the implementation of the CRCC pilot policy led to a statistically significant increase of approximately 9.8% in the level of urban green technology innovation, on average.

and 5 years after the construction of pilot cities. The dummy variables for non-pilot city construction are all 0. The settings of other variables are the same as those in Equation 1. Figure 2 reports the results of the dynamic effects. Before the CRCC ($t < 0$), the parameter αt fluctuates around zero and the 95% confidence interval includes zero, confirming no significant pre-treatment difference (parallel trends hold). After the policy implementation ($t \geq 0$), αt becomes significantly positive (confidence interval excludes zero), indicating the policy triggers a significant effect. However, starting from the implementation period of the policy, the parameter α_t begins to be significantly positive, which shows that CRCC significantly improves the degree of green transformation. Accordingly, we infer that the sample selected in this paper satisfies the parallel trend assumption.

5.3 Placebo test

To rule out the influence of unobserved factors and omitted variables on the benchmark regression results, the placebo test method is further employed to examine the robustness of the results. Referring to the approach of Yu M. G. et al. (2024), this paper constructs pseudo-policy implementation time and a pseudo-treatment-group dummy variable by randomly selecting CRCC pilot cities and their policy implementation time. Sampling is repeated 500 times among 296 cities, and each time the treatment group and policy time are randomly determined, thus ensuring the randomness of policy implementation. Figure 3 reports the P-values of the estimated coefficients of policy implementation and the kernel density distribution. The estimated values of the effects of the randomly simulated CRCC are concentrated around 0, indicating

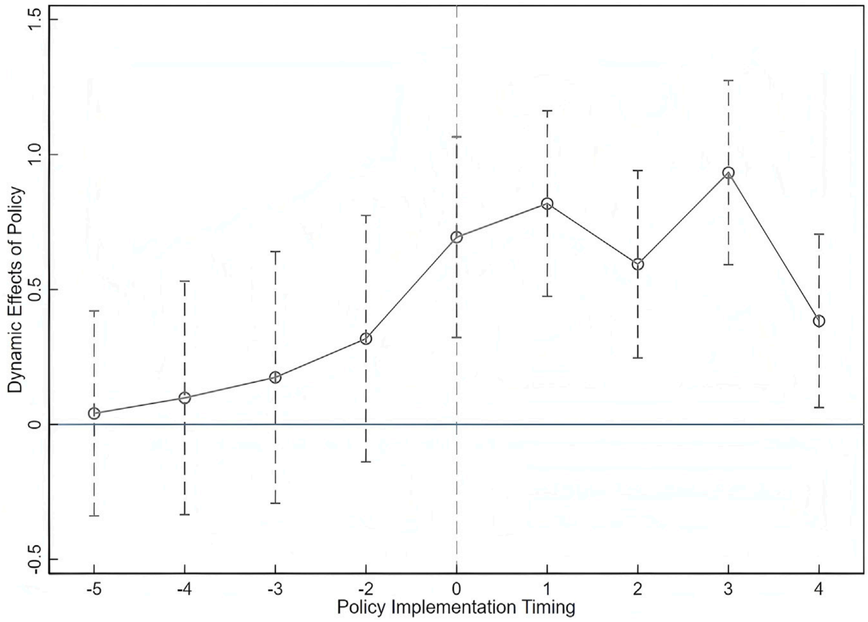

FIGURE 2
Parallel trend test. The figure plots the estimated coefficients and their 95% confidence intervals (represented by vertical lines) for the interaction terms between the treatment group dummy and year dummies relative to the policy implementation year (t = 0, marked by the vertical dashed line). The horizontal dashed line at zero indicates the null effect. The absence of statistically significant effects (confidence intervals overlapping zero) in the pre-treatment periods (t < 0) supports the validity of the parallel trends assumption, a prerequisite for causal inference using DID. The emergence of significant positive effects (confidence intervals excluding zero) post-implementation (t ≥= 0) indicates the dynamic effect of the CRCC policy.

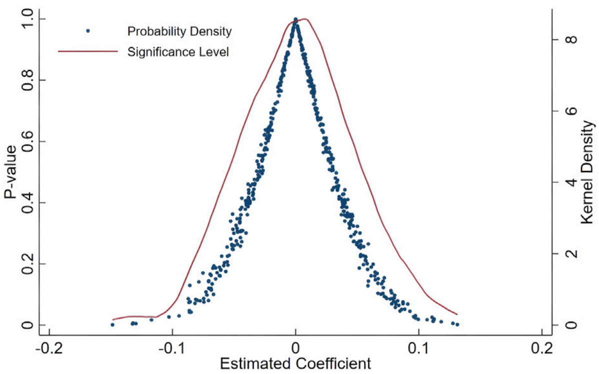

FIGURE 3
Placebo test results. The kernel density distribution (curve) shows the estimated coefficients from 500 random reassignments of the treatment group and policy timing.

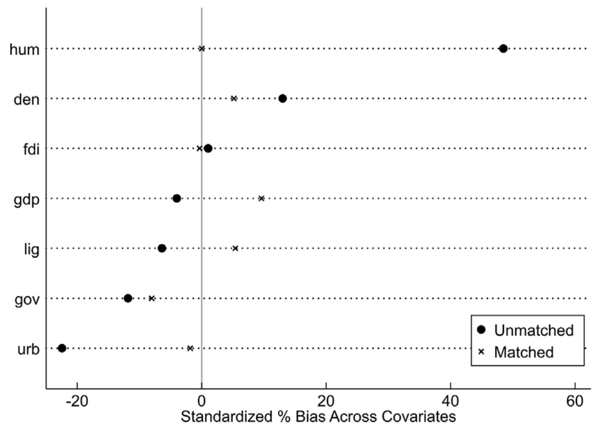

FIGURE 4
Standardized bias reduction before and after PSM.

that unobserved factors do not affect the empirical results of this paper, and the benchmark regression results are robust.

5.4 Addressing endogeneity issues

5.4.1 Propensity score matching-difference-in-differences (PSM - DID) method

Considering that the selection of pilot cities may be non-random, which may lead to selection bias in the estimation results, this paper uses the PSM-DID method to further test the robustness of the policy effects. First, the probability of each city being approved as a policy pilot is estimated based on urban characteristics. Then, cities in the control group that are closest in terms of the pilot probability to those in the treatment group are matched. Finally, the DID method is used to re-estimate the impact of CRCC on urban green transformation. The standardized bias graph in Figure 4 shows that after matching, the standardized biases of all covariates have decreased significantly and approached 0 (most are less than 10%), indicating that the distributions of the treatment group and the control group on the matching variables are highly consistent, meeting the co - support domain condition. The

TABLE 3 Endogeneity test.

Variables	PSM-DID	Instrumental variable method	
		First stage	Second stage
	(1)	(2)	(3)
policy	0.086*		0.142***
	(1.80)		(2.77)
IV_River		4.158***	
		(31.68)	
Control variables	YES	YES	YES
City FE	YES	YES	YES
Year FE	YES	YES	YES
Kleibergen-Paap rk LM		220.35***	
Kleibergen-Paap rk Wald F		1,003.81	
N	5,032	4,736	4,736
R^2	0.7002		0.9353

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively (indicated by superscripts on the coefficient estimates). Values in parentheses are t-statistics.

establishment of the co - supporting hypothesis means that the characteristic differences between the treatment group and the control group before the policy implementation can be eliminated through matching, effectively solving the problem of sample selection bias. Column (1) of Table 3 reports the estimation results of the PSM - DID method. It can be seen that the estimated coefficient of the pilot policy is significantly positive, meaning that the promoting effect of CRCC on green transformation is robust.

5.4.2 Instrumental variable method

To further address potential endogeneity issues, this paper uses the Two-Stage Least Squares (2SLS) method for robustness testing. The selection of instrumental variable needs to satisfy the principles of relevance and exclusivity. On the one hand, instrumental variable need to be highly correlated with the core explanatory variable (*policy*); on the other hand, instrumental variable should only affect the explained variable through the policy, rather than directly affecting green technological innovation. Referring to the construction method of instrumental variables in environmental policy research (Yang et al., 2024), this paper selects the interaction term of river density and time trend as the instrumental variable (IV_River). Among them, river density reflects the natural geographical characteristics of cities, and is correlated with the location selection of climate-resilient city pilot policies, because areas with rich water resources are more likely to be selected as pilots to cope with flood risks; and river density itself does not directly affect green technological innovation, meeting the exclusivity assumption.

This paper estimates the instrumental variable results of river density in columns (2) and (3) of Table 3. In the first-stage regression, the instrumental variable coefficient is statistically significant, indicating that the instrumental variable has a strong correlation with climate-resilient city construction. The Kleibergen-Paap rk Wald F value is greater than the critical value level of the Stock-Yogo test at 10%, excluding the problem of weak instrumental variables. The P-value of the Kleibergen-Paap LM statistic is less than 1%, strongly rejecting the hypothesis of insufficient instrumental variable identification. In the second-stage regression, the *policy* coefficient is significantly positive, indicating that after considering endogeneity issues, climate-resilient city construction still has a significant promoting effect on urban green transformation, and there is no significant difference from the benchmark regression results.

5.5 Robustness tests

5.5.1 Replacing the dependent variable

To assess the robustness of the model results from the perspective of variable measurement, this paper replaces the proxy variable for the degree of urban green transformation. In the benchmark regression, green technology innovation was measured by the number of green invention patent applications. Here, we use the total number of green patent applications to re-evaluate the impact of CRCC on urban green transformation. This substitution considers that green patent applications in a broader sense can more comprehensively reflect a city's overall efforts and achievements in green technology innovation and industrial transformation. The regression results after replacing the dependent variable are reported in Column (1) of Table 4. The coefficient of the core explanatory variable *policy* remains significantly positive at the 1% level, indicating that even when using a more comprehensive measure of green transformation, the promotion effect of CRCC on urban green transformation remains robust.

5.5.2 Adjusting the time window

Since the impact of the pilot policy may have a lag effect, the choice of different time windows before and after the policy

TABLE 4 Robustness results.

Variables	Replacing the explained variable	Adjusting the time window		Winsorization	CIC model	Counterfactual test	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
policy	0.150**	0.099**	0.086*	0.104**	0.098**	0.045	0.067
	(2.07)	(1.99)	(1.66)	(2.18)	(2.07)	(0.91)	(1.42)
Control variables	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
N	5,032	3,848	3,256	5,032	5,032	5,032	5,032
R^2	0.9560	0.9413	0.9452	0.9322	0.9333	0.9332	0.9332

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively (indicated by superscripts on the coefficient estimates). Values in parentheses are t-statistics.

implementation may also have a certain impact on the estimation results. To eliminate the bias in the regression results caused by sample selection, this paper adjusts the time window. Specifically, two new time windows, 2010–2022 and 2012–2022, are reset to replace the basic time window, in order to capture the variation in policy effects over different time periods. Column (2) and Column (3) of Table 4 respectively show the regression results under different time windows. It is found that the regression coefficients of CRCC are significantly positive, indicating that the research results are robust.

5.5.3 Winsorization

To eliminate the possible influence of extreme outliers in various variables on the evaluation of policy effects, this paper conducts bilateral winsorization on all variables at the 1% level. Column (4) of Table 4 reports the regression results of the pilot policy under the condition of winsorizing from 1% to 99%. It is found that the regression coefficient of $policy$ is significantly positive, indicating that CRCC can significantly enhance urban green transformation, which is consistent with the benchmark regression results. Thus, the robustness test is passed.

5.5.4 CIC model test

To address the problem that DID cannot handle unobservable heterogeneity (De Chaisemartin and d'Haultfoeuille, 2022), this paper refers to the DID method proposed by Athey and Imbens (2006) that allows for non - linearity and differences among individuals, also known as the changes-in-changes (CIC) model. The CIC method accurately identifies the net effect of a policy by analyzing the differences in changes between the treatment group (the group affected by a specific policy) and the control group (the group not affected) before and after the policy implementation. Column (5) of Table 4 reports the regression results of applying the CIC model. It is found that CRCC still has a significant promoting effect on green transformation, further corroborating the robustness of the benchmark regression results.

5.5.5 Counterfactual test

Before using the DID model for analysis, it is crucial to ensure that the experimental group and the control group are sufficiently comparable to avoid potential biases in the causal identification process. This paper conducts a counterfactual test by setting up a dummy variable for a false policy implementation time. Specifically, the policy implementation time of CRCC is advanced to 2013 and 2015 respectively, and then estimated using Equation 1. The regression results are shown in Column (6) and Column (7) of Table 4. It can be observed that after advancing the policy time, the regression coefficients of $policy$ do not pass the 10% significance level test, that is, CRCC does not have an effect on green transformation. This indicates that the benchmark regression results are robust.

5.6 Analysis of influence mechanisms

5.6.1 Mediating effects of industrial structure and government behavior

The benchmark regression and analysis above indicate that building climate-resilient cities has a positive effect on accelerating green transformation. However, with the gradual promotion and implementation of this concept in China, merely exploring the direct effects of CRCC is no longer sufficient. To more effectively promote the green transformation process and achieve a win-win situation in environmental protection and economic development, we must deeply analyze the action mechanisms of CRCC and the synergistic effects of its supporting policies. Therefore, this section will focus on exploring the action mechanisms by which CRCC promotes green transformation and conduct further analysis and elaboration.

Referring to the approach of Zhang Y et al. (2024), the following econometric models are set up:

$$med_{it} = \gamma_0 + \gamma_1 policy_{it} + \sum_{j=2}^{J} \gamma_j X_{it}^j + \omega_i + \omega_t + \varepsilon_{it} \quad (3)$$

TABLE 5 Mediation effect test: transmission mechanism between industrial structure and government behavior.

Variables	*sh*	*sr*	*mot*	*con*
	(1)	(2)	(3)	(4)
policy	0.055***	0.149***	0.0004*	0.093***
	(2.97)	(2.83)	(1.95)	(2.61)
Constant	0.0003	−6.552***	−0.035***	−4.030***
	(0.00)	(−9.26)	(−9.22)	(−4.39)
Control variables	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	5,032	5,032	5,032	5,032
R^2	0.8880	0.7394	0.6045	0.8682

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively (indicated by superscripts on the coefficient estimates). Values in parentheses are t-statistics.

In Equation 3, med_{it} represents the mediating variables, specifically including industrial structure and government behavior. The industrial structure is divided into industrial structure upgrading (*sh*) and industrial structure rationalization (*sr*). Referring to the research of Wang et al. (2024), the ratio of the added value of the tertiary industry to that of the secondary industry is used as the proxy variable for industrial structure upgrading. For the measurement of industrial structure rationalization, the Theil index method is adopted: $sr = \sum_{i=1}^{3} \left(\frac{Y_i}{Y}\right) \ln \left(\frac{Y_i}{Y} \Big/ \frac{L_i}{L}\right)$, where Y_i and L_i represent the added value and the number of employees in the industry i respectively, Y represents the total added value of all industries, and L represents the total number of employees. Generally, the Theil index is a negative indicator, that is, the larger the Theil index, the lower the level of industrial structure rationalization. For convenience, the reciprocal of the industrial structure rationalization indicator is taken for positive-direction processing.

Government behavior is divided into incentive behavior (*mot*) and restrictive behavior (*con*). Referring to the approach of Li Y X et al. (2023), government incentive behavior is measured by government support for science and technology. The calculation method is: government support for science and technology = government expenditure on science and technology/regional GDP. Government restrictive behavior is measured by the intensity of environmental regulation. The specific calculation method draws on the research of Tang and Chen (2024), as well as Wang and Ma (2024). The emissions of industrial "three-wastes" are used to calculate the urban environmental regulation intensity index, and the reciprocal of this index is taken to keep the direction of the indicator consistent.

Table 5 presents the results of the mechanism analysis regarding the impact of CRCC on green transformation. The findings in columns (1) and (2) indicate that CRCC significantly promotes both the upgrading and rationalization of the industrial structure. This suggests that the pilot policy accelerates urban green transformation by optimizing the industrial structure, which in turn enhances resource utilization efficiency. In column (3), the significantly positive regression coefficient of CRCC on government support for science and technology implies that the pilot policy spurs local governments to increase financial support for green technologies. This, in turn, propels the research, development, and application of green technologies, thereby facilitating urban green transformation. The results in column (4) demonstrate that CRCC remarkably strengthens the intensity of environmental regulation. This reveals that through the government's restrictive actions, the pilot policy creates a "back-forcing" mechanism for polluting enterprises. This mechanism compels enterprises to adopt more environmentally-friendly production methods, thus driving urban green transformation. Our findings complement recent research on regional sustainability by addressing a critical gap. While studies like Peng et al. (2024) assess water sustainability through static resource indicators (e.g., water quantity, quality), our research dynamic ally evaluates how policy interventions can actively reshape urban systems toward green goals. For example, the identification of industrial structure upgrading and governmental behavior as key mechanisms highlights the role of policy in fostering pro-innovation incentives and regulatory reforms, which are absent in traditional resource accounting frameworks. In summary, CRCC effectively promotes urban green transformation through multi-dimensional mechanisms.

5.6.2 Heterogeneity of mediating effects across subgroups

To further explore the heterogeneous mediating effects of the CRCC policy on urban green transformation across different city subgroups, this study examines the interactive effects of the policy with resource-based city status (*res*) and administrative hierarchy (*adm*). The variable *res* is defined as 1 for resource-based cities and 0 otherwise, while *adm* is set as 1 for municipalities directly under the central government or provincial capitals and 0 for other cities. This analysis aims to reveal whether the CRCC policy's mechanisms of action differ across cities with varying degrees of resource dependency and administrative capacity.

According to the empirical results in Table 6, the interaction term $policy{*}res$ exhibits significantly negative effects on industrial

TABLE 6 Heterogeneity of mediating effects across subgroups.

Variables	*sh*	*sr*	*mot*	*con*	*sh*	*sr*	*mot*	*con*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
policy	0.112***	0.214***	0.001**	0.184***	−0.033***	0.079	−0.000	0.130***
	(4.62)	(4.55)	(2.53)	(4.42)	(−2.65)	(1.11)	(−0.17)	(2.95)
*policy*res*	−0.179***	−0.204	−0.001*	−0.288***				
	(−6.34)	(−1.55)	(−1.86)	(−3.92)				
*policy*adm*					0.275***	0.217**	0.001***	−0.117*
					(6.10)	(2.56)	(2.65)	(−1.70)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
N	5,032	5,032	5,032	5,032	5,032	5,032	5,032	5,032
R^2	0.8887	0.7396	0.6048	0.8687	0.8897	0.7396	0.6054	0.8682

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively (indicated by superscripts on the coefficient estimates). Values in parentheses are t-statistics.

structure upgrading, government incentive behavior, and government restrictive behavior, whereas its effect on industrial structure rationalization is negative but insignificant. This indicates that the CRCC policy has weaker promoting effects on industrial structure upgrading and government behavioral adjustments (both incentive and restrictive measures) in resource-based cities. The underlying reason lies in the fact that resource-based cities often exhibit a rigid industrial structure with a high proportion of traditional resource-dependent industries, facing challenges such as high transformation costs and lagging technological innovation. These constraints hinder the CRCC policy from effectively driving industrial structure upgrading and government behavioral adjustments, while the process of industrial structure rationalization is obstructed by the inertia of resource dependency.

In terms of administrative hierarchy heterogeneity, the interaction term $policy*adm$ shows significantly positive effects on industrial structure upgrading, industrial structure rationalization, and government incentive behavior, but a significantly negative effect on government restrictive behavior. This suggests that municipalities and provincial capitals, with stronger administrative resource integration capabilities, higher policy implementation efficiency, and more mature market mechanisms, can more effectively promote industrial structure upgrading and rationalization through the CRCC policy while enhancing government incentives for green technological innovation. The lower reliance on government restrictive policies in high-administrative-level cities may stem from the stronger spontaneous green transformation capabilities of market entities or the greater adaptability of regional industrial bases to low-carbon development requirements, thus reducing the need for mandatory restrictive policies. These heterogeneous findings align with global policy debates: while EU cities rely on citizen participation under the Green City Accord (Mahmoud et al., 2025), China's CRCC demonstrates that top-down industrial policies can effectively drive green transformation in developing contexts. This offers generalizable insights for regions balancing resilience and economic growth, such as Southeast Asian cities facing similar climate risks.

5.7 Heterogeneity analysis

5.7.1 Division by the "Hu Huanyong Line"

The division of the "Hu Huanyong Line" is based on a comprehensive consideration of China's natural geographical conditions, especially the significant influence of climate and terrain factors. It quantitatively depicts the spatial characteristics of China's population for the first time, revealing the fact that there is a huge disparity in population density between the southeastern and northwestern halves of China. This line has important guiding significance for understanding China's national conditions and formulating regional development policies (Zhao and Zhang, 2022). In this paper, China is divided into the southeastern side and the northwestern side according to the "Hu Huanyong Line", and the impact of CRCC on green transformation is explored separately. The results are shown in columns (1)–(2) of Table 7. It can be found that in the southeastern region, CRCC significantly promotes green transformation in this area; while in the northwestern region, the regression coefficient of $policy$ does not pass the significance level test. The possible reason behind this is that there are significant differences in climate conditions, economic development levels, and resource endowments between the east and west sides of the "Hu Huanyong Line". The southeastern region has more favorable climate conditions and a higher level of economic development compared to the northwestern region. This enables the implementation of CRCC to play a more effective role in promoting green transformation in the southeastern region.

5.7.2 Division by location in the Yangtze River Economic Belt

The Yangtze River Economic Belt, as a crucial economic corridor spanning east-west and running through north-south in China, clearly

TABLE 7 Heterogeneity test results.

Variables	Southeastern	Northwestern	Yangtze river economic belt	Non-Yangtze river economic belt
	(1)	(2)	(3)	(4)
policy	0.085*	0.168	0.202***	−0.026
	(1.68)	(1.33)	(3.03)	(−0.40)
Constant	−11.448***	−2.632	6.254***	−12.830***
	(−12.37)	(−1.00)	(2.81)	(−13.62)
Control variables	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	4,522	510	1870	3,162
R^2	0.9334	0.8997	0.9444	0.9292

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively (indicated by superscripts on the coefficient estimates). Values in parentheses are t-statistics.

holds a core position in the country's economic development system. The Third Plenary Session of the 20th Central Committee of the Communist Party of China explicitly proposed to "optimize the development mechanism of the Yangtze River Economic Belt", which profoundly reflects the country's high hopes for the Yangtze River Economic Belt in leading green transformation and sustainable development. In light of this, grouping cities for research based on whether they are located in the Yangtze River Economic Belt is not merely a simple geographical division but a deep-seated consideration based on national development strategies and economic layouts. Columns (3)–(4) of Table 7 report the impact of CRCC on green transformation in the Yangtze River Economic Belt region and non-Yangtze River Economic Belt region respectively. The results show that the pilot of CRCC in the Yangtze River Economic Belt region can significantly promote green transformation, while for the non-Yangtze River Economic Belt region, the effect of CRCC in promoting green transformation is not yet obvious. A possible reason is that, as an important area for China's economic development, the Yangtze River Economic Belt has received high-level attention from the national level and a series of policy supports. This has not only promoted the rapid growth of the regional economy but also provided a strong institutional guarantee for CRCC and green transformation (Yang and Pan, 2024).

5.8 Examining whether the policy can achieve an "environment-friendly" outcome

The previous sections have clearly demonstrated the significant positive effect of CRCC on promoting urban green transformation, effectively facilitating cities' progress towards a more sustainable and low-carbon direction. On this basis, this paper further explores the in-depth impact of CRCC in the field of environmental protection, especially its potential for reducing pollutant emissions and building an "environment-friendly" city. Referring to the research of Chen et al. (2022), this paper selects industrial wastewater, industrial sulfur dioxide, and industrial smoke and dust as key pollutant indicators, and constructs a comprehensive environmental pollution index using the entropy-weight method. The larger this index is, the more pollutants are emitted. Column (1) of Table 8 reports the results of the impact of CRCC on pollutant emissions. It can be found that the regression coefficient is significantly negative, indicating that CRCC helps to reduce pollutant emissions. In addition, this paper further uses the pollutant emission level per unit of GDP as an evaluation indicator, that is, calculating the ratio of the total emissions of industrial wastewater, industrial sulfur dioxide, and industrial smoke and dust to GDP, to measure the environmental efficiency of urban economic development. The results in column (2) of Table 8 show that CRCC significantly inhibits the pollutant emission level per unit of GDP, indicating that while maintaining economic growth, the environmental efficiency of the city has been significantly improved, achieving a win-win situation for economic development and environmental protection.

6 Further analysis

The construction of climate-resilient cities has a promoting effect on urban green transformation. This may encourage neighboring regions to learn and imitate, adopt similar CACC strategies, and thus promote the deepening of economic green transformation in these cities, forming a positive spatial spillover effect. To empirically test whether CRCC generates spillover effects on neighboring cities' green transformation, we employ spatial econometric models. These methods specifically measure how one city's characteristics influence its neighbors - answering whether CRCC's benefits extend beyond pilot cities.

However, the CACC may also lead to a siphon effect. That is, due to the first-mover advantage of CACC, core cities may attract high-quality resources from surrounding areas to converge, thereby inhibiting the economic green transformation process of surrounding cities and generating a negative spatial spillover effect. Figure 5 visualizes spatial patterns of green transformation using Local Moran's I. The concentration of cities in "High-High" clusters (top-right quadrant) indicates that cities with advanced green transformation tend to be geographically grouped. This clustering pattern provides preliminary evidence that green transformation spreads across neighboring areas,

TABLE 8 Policy achieves environment-friendliness test.

Variables	Pollutant emissions	Pollutant emissions per unit GDP
	(1)	(2)
policy	−0.174***	−0.241***
	(−4.15)	(−5.23)
Constant	−11.234***	2.644***
	(−16.28)	(3.13)
Control variables	YES	YES
City FE	YES	YES
Year FE	YES	YES
N	5,032	5,032
R^2	0.9108	0.9043

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively (indicated by superscripts on the coefficient estimates). Values in parentheses are t-statistics.

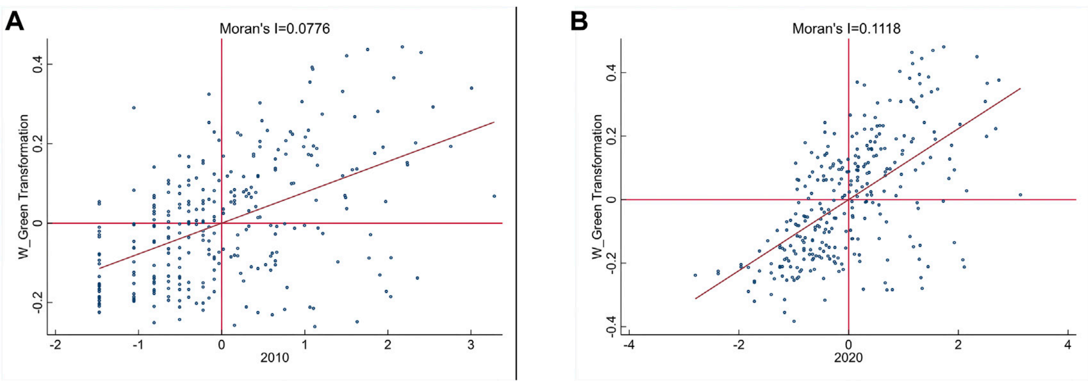

FIGURE 5
Moran's Scatterplots for Urban Green Transformation. The plots assess the spatial autocorrelation of the green transformation index across cities in **(A)** 2010 and **(B)** 2020. Each point represents a city. The quadrants represent different types of local spatial association: High-High (HH, top-right), Low-High (LH, top-left), Low-Low (LL, bottom-left), High-Low (HL, bottom-right).

justifying our spatial spillover analysis. It can be observed that most cities in 2010 and 2020 fall into the first quadrant (High-High clusters) and the third quadrant (Low-Low clusters). This clustering pattern reveals two key insights: (1) High-High clusters indicate that CRCC policies in pilot cities have promoted knowledge diffusion and policy emulation among neighboring cities, forming a positive spatial spillover effect; (2) Low-Low clusters suggest regional disparities in green transformation, possibly due to weak policy implementation or resource constraints in underdeveloped areas. These findings imply that policymakers should strengthen cross-regional cooperation mechanisms to leverage the demonstration effect of High-High clusters and address the lagging development in Low-Low regions, thereby promoting coordinated regional green transformation.

Furthermore, three spatial econometric models, namely the Spatial Autoregressive Model (SAR), the Spatial Error Model (SEM), and the Spatial Durbin Model (SDM), are established to analyze the spatial effects of CACC on urban green transformation. The results of the three spatial models in columns (1)–(3) of Table 9 consistently demonstrate that the coefficient of the CRCC policy ($policy$) remains significantly positive. This reconfirms our core finding that, even after formally considering spatial relationships, CRCC can still accelerate the urban green transformation process within the cities implementing the policy. More importantly, the spatial coefficients provide strong evidence of significant spillover effects: In the SAR model, the highly significant positive *rho* coefficient (0.755) indicates a strong positive interdependence in the levels of green transformation among neighboring cities. In other words, the higher the average level of green transformation in a city's neighboring areas, the higher the level of green transformation in that city itself. In the SEM model, the significantly positive *lambda* (0.952) confirms that some unobserved factors affecting green transformation also exhibit spatial correlations among neighboring cities. The SDM model offers the most comprehensive perspective. The significantly positive coefficient of $W \times policy$ (0.879) directly proves that the CRCC policy implemented in neighboring cities has a positive impact on the green transformation of the target city, which is the

TABLE 9 Spatial effect regression.

Variables	SAR	SEM	SDM	Direct effect	Indirect effect	Total effect
	(1)	(2)	(3)	(4)	(5)	(6)
policy	0.113**	0.106**	0.117**	0.127**	2.754**	2.881**
	(2.10)	(1.97)	(2.17)	(2.29)	(2.18)	(2.27)
W × *policy*			0.879*			
			(1.91)			
rho	0.755***		0.665***			
	(42.69)		(14.58)			
lambda		0.952***				
		(114.84)				
sigma2_e	0.262***	0.257***	0.255***			
	(50.15)	(50.07)	(50.11)			
Control variables	YES	YES	YES			
N	5,032	5,032	5,032			
R^2	0.5434	0.4620	0.5737			

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively (indicated by superscripts on the coefficient estimates). Values in parentheses are z-statistics. Columns (1) SAR, spatial autoregressive model; (2) SEM, spatial error model; (3) SDM, spatial durbin model; (4)–(6) SDM, direct, Indirect (Spillover), and Total Effects.

policy spillover effect. Additionally, the significant *rho* (0.665) once again reflects the interdependence among the results.

To accurately analyze the overall impact of CRCC, columns (4)–(6) report the direct effect, indirect effect (spillover effect), and total effect estimated using the preferred SDM model. The direct effect (0.127) quantifies the impact of implementing CRCC in a specific city on its own level of green transformation, and this value is positive and significant. The indirect effect (2.754) measures the average impact of implementing CRCC in all other cities on the level of green transformation of any single city. Its significantly large positive value indicates that the implementation of CRCC in neighboring cities generates a substantial positive spillover effect. The total effect (2.881), which is the sum of the direct and indirect effects, represents the comprehensive impact of implementing CRCC across various locations on the green transformation of a single city, and it also presents a significant positive value. These reliable research results indicate that the benefits brought by CRCC are not limited to the pilot cities themselves. The significant positive spillover effects suggest that CRCC can create a virtuous cycle through knowledge sharing, policy emulation, or the strengthening of regional infrastructure and networks. Evidently, the "demonstration effect" of CRCC appears to outweigh any potential "siphon effect" that might lead to the loss of resources from neighboring cities.

7 Conclusions and policy recommendations

This paper takes the CACC as the research starting point. Based on the panel data of 296 prefecture-level and above cities in China from 2006 to 2022, the DID method is used to empirically test the impact of climate resilience on urban green transformation. Moreover, through mechanism tests, heterogeneity analysis, and spatial econometric models, a comprehensive and systematic quantitative investigation is carried out from multiple-dimensional perspectives. The main research conclusions are as follows: first, the CACC can significantly accelerate urban green transformation, and this conclusion still holds after a series of robustness tests. Second, the mechanism tests indicate that the CACC can not only achieve the upgrading and rationalization of the industrial structure but also influence the incentive and restrictive behaviors of the government, thus accelerating urban green transformation. In addition, heterogeneity analysis of mediating effects indicates that CRCC faces constraints from rigid industrial structures in resource-based cities, yielding weaker promotion of green transformation, whereas in cities with higher administrative hierarchy, the policy more effectively facilitates green transformation by accelerating industrial structure upgrading and enhancing governmental incentives for green innovation, providing empirical basis for differentiated policy formulation. Third, in terms of heterogeneity analysis, the green-transformation effect of CACC is more obvious in cities on the southeastern side of the "Hu Huanyong Line", and node cities in the Yangtze River Economic Belt. Fourth, the CACC can significantly reduce pollutant emissions and the pollutant emission level per unit of GDP, thus effectively promoting the construction of an "environment-friendly" society. Fifth, the expansion tests show that the CACC can considerably promote the green-transformation process of neighboring cities, and there is a positive spillover effect in the green-transformation itself.

Based on the above research conclusions, the following policy recommendations are put forward in this paper. First, governments should establish coordination mechanisms among enterprises, residents, NGOs, and academia, while tailoring strategies to regional heterogeneity. For cities southeast of the Hu Line and in the Yangtze River Economic Belt, which have advanced economic bases and strong implementation capacities, market-driven tools like carbon trading and green bonds should be piloted to leverage their economic advantages. These instruments can efficiently guide resources toward low-carbon sectors and accelerate industrial green transformation. In contrast, northwestern cities and non-provincial capitals face constraints in natural environment and industrial structure, requiring targeted fiscal transfers and technology support. Special funds should be allocated to support ecological restoration and clean energy projects, while tax incentives can encourage enterprises to adopt green technologies and facilitate the transition of resource-based industries.

Second, provincial capital cities, as economic and administrative centers, should utilize their resource endowments to coordinate cross-sectoral resources and set green industry standards. They can allocate more funds to green infrastructure and scientific research, and establish industry-academia-research cooperation platforms to promote the commercialization of green technologies. Non-provincial capital cities, with relatively limited resources, may need simplified procedures for green projects and targeted training for local officials to enhance policy implementation capabilities.

Third, building directly on the finding of significant positive spatial spillovers, to amplify these beneficial ripple effects of CRCC, inter-city platforms should be created to share best practices and green patents. Cities in the Yangtze River Economic Belt can provide financial support for green infrastructure in neighboring regions to mitigate potential siphon effects, while compensation mechanisms can balance interests during industrial transitions. For example, transitional funding can assist high-emission enterprises in adopting sustainable practices, fostering coordinated development across regions.

Finally, a multi-dimensional evaluation framework should integrate indicators such as corporate emission reductions, resident participation, and NGO project outcomes, with regular progress reports to ensure transparency. Annual stakeholder forums can gather feedback to adjust policies, such as fine-tuning subsidy ratios for enterprises in different regions or enhancing resident engagement incentives, to address on-the-ground challenges effectively. These recommendations directly respond to the heterogeneity findings, ensuring that policy tools are context-specific and aligned with regional development stages.

The conclusions revealed in this paper, such as the green transformation of climate-adaptive city construction driven by industrial structure optimization and the government's incentive and restraint behaviors, as well as the existence of positive spatial spill - over effects, are of great reference significance for regions at different development stages and with different geographical backgrounds. CRCC's model of top-down policy piloting and bottom-up industrial adjustment offers developing economies a scalable path under the Paris Agreement, adaptable to local resources and governance. First of all, developing countries can learn from China's experience. They can guide resources to flow to low - carbon sectors through green industrial policies and strengthen the government's leading role in environmental regulation and technological innovation. Secondly, regions with similar geographical or economic characteristics can establish policy coordination mechanisms to amplify the spatial spill-over effects of green transformation. Finally, at the trans-national level, the flexible adaptation of policy tools can provide micro-level practical approaches for global climate governance, thus helping to achieve the coordinated goal of climate adaptation and green development.

Data availability statement

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

Author contributions

CG: Conceptualization, Methodology, Project administration, Resources, Writing – original draft. CZ: Supervision, Writing – review and editing. YW: Data curation, Software, Writing – review and editing. CW: Conceptualization, Methodology, Software, Writing – original draft.

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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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