

Article

Green Finance and Urban Ecological Resilience: Institutional, Technological, and Behavioral Mechanisms

Xiaoyong Zhou ^{1,2} , Yingying Dong ^{1,2}, Zaozhuang Liao ^{3,*} and Zhengbo Peng ^{1,*}

¹ School of Public Administration, Guilin University of Technology, Guilin 541004, China; zhouxy@guat.edu.cn (X.Z.); dongyy@glut.edu.cn (Y.D.)

² College of Management, Guilin University of Aerospace Technology, Guilin 541004, China

³ Department of Education of Guangxi Zhuang Autonomous Region, Nanning 530022, China

* Correspondence: lzz@jyt.gxzf.gov.cn (Z.L.); whu007@163.com (Z.P.)

Abstract

Building resilient cities that can survive, adapt, and thrive amid climate and ecological challenges has become a global priority, yet achieving this goal requires adequate financial support. This study investigates the impact of green finance on urban ecological resilience (UER) by exploiting the establishment of China's Green Finance Reform and Innovation Pilot Zones (GFPZs) as a policy shock. Using a DPSIR-based (driving force–pressure–state–impact–response) evaluation framework and a staggered difference-in-differences approach with panel data from 277 cities (2011–2022), the empirical results show that (1) the GFPZ policy significantly enhances UER; (2) green finance improves UER through three transmission channels—government environmental governance, green technological innovation, and public environmental participation; (3) the policy effects display clear spatial and structural heterogeneity, with stronger impacts in southern, less-developed, and non-traditional industrial cities, as well as positive local effects, negative spatial spillovers, and significant synergies with national big data pilot zones. This study clarifies how financial instruments contribute to building resilient cities and offers insights for embedding green finance into urban ecological strategies.

Keywords: ecological resilience governance; DPSIR framework; policy evaluation; spatial spillover effects; China

1. Introduction

The accelerating interplay between global climate change and rapid urbanization is amplifying systemic risks to ecological resilience at an unprecedented scale. Frequent extreme weather events, escalating resource constraints, and persistent ecological degradation pose severe challenges to cities with dense populations and concentrated wealth, resulting in infrastructure damage, mounting economic losses, and social instability [1]. Beyond immediate risks of disaster, development trajectories driven by uncontrolled pollution emissions are fundamentally unsustainable, as the accumulation of pollutants erodes environmental carrying capacity and weakens resilience, ultimately generating negative externalities for socio-ecological-technical systems [2]. Against this backdrop, urban ecological resilience (UER)—defined as the capacity of urban ecosystems to withstand, recover, and adapt to external shocks—has emerged as a central priority for sustainable development [3–5]. Global initiatives, such as the Rockefeller Foundation's "100 Resilient Cities" and China's national strategies combining low-carbon, green, and resilient development [6–8],



Academic Editors: Ying Tu, Hanlin Zhou, Wei Lang and Tingting Chen

Received: 5 January 2026

Revised: 29 January 2026

Accepted: 5 February 2026

Published: 6 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

highlight the critical importance of strengthening UER to relieve development pressures and enhance societal well-being.

Under conditions of resource constraints, enhancing UER depends critically on adequate and well-functioning financial support. As a key policy instrument, green finance not only aligns capital allocation with ecological protection objectives but also holds substantial potential for strengthening UER. By integrating environmental considerations into financial decision-making, green finance converts ecological attributes into operational financial instruments, including green credit, green bonds, and green funds, thereby directing capital toward green industries and firms [9]. These instruments can curb carbon emissions, lower financing costs for green industries, and facilitate the green transformation of industrial structures [10]. In addition to these direct effects, green finance operates through indirect channels, including technological innovation diffusion, interregional capital mobility, and institutional improvement. Through these pathways, it enhances energy and resource use efficiency and may generate spatial spillover effects that influence the ecological resilience of neighboring cities.

Amid the global pursuit of long-term economic growth and sustainable development, a broad consensus has emerged on the need to establish and strengthen green financial systems. In the United States, the Superfund Act of 1980 formally linked environmental risk with financial risk [11]. At the international level, the EU Sustainable Finance Action Plan and the Green Bond Principles aim to guide financial resources toward climate adaptation and ecological restoration through financial innovation [12,13]. China has also taken a leading role in advancing green finance reforms. In June 2017, the State Council designated cities in provinces including Guangdong, Zhejiang, Jiangxi, Guizhou, and Xinjiang as the first batch of *Green Finance Reform and Innovation Pilot Zones* (GFPZ). The initiative was subsequently expanded twice, in December 2019 and August 2022, to include Lanzhou New Area in Gansu, Chongqing, and other regions (see Figure 1). Through the demonstration and replication effect, these pilot zones have launched nearly 100 green finance policies, providing stronger financial support for China's "dual carbon" goals, and driving the green transformation of socio-economic systems.

Building on local comparative advantages, the pilot zones have developed diverse pathways for advancing green finance. For instance, Zhejiang emphasizes the integration of digital technologies with green manufacturing; Jiangxi explores mechanisms for realizing the value of ecological products; Guangdong leverages its locational advantages to promote green ports and cross-border finance; Guizhou focuses on synergizing ecological protection with poverty reduction; Xinjiang prioritizes green energy development in alignment with the Belt and Road Initiative; and the Lanzhou New Area experiments with ecological transformation in resource-dependent cities. The GFPZ policy is centrally designed and implemented, which helps limit the extent to which policy assignment is directly correlated with cities' pre-existing levels of ecological resilience. This institutional feature contributes to relatively favorable identification conditions for examining the impact of green finance on UER [14]. Moreover, the staggered rollout of the policy across regions and over time generates meaningful intercity and intertemporal variation, providing a solid empirical basis for difference-in-differences (DID) and event-study analyses. Despite the expanding global practice of green finance, existing studies on policy pilot programs have largely concentrated on single outcomes—such as economic resilience, green total factor productivity, or low-carbon performance. Rigorous causal evidence on the effects of green finance on UER, particularly in large countries characterized by pronounced regional disparities, remains limited.

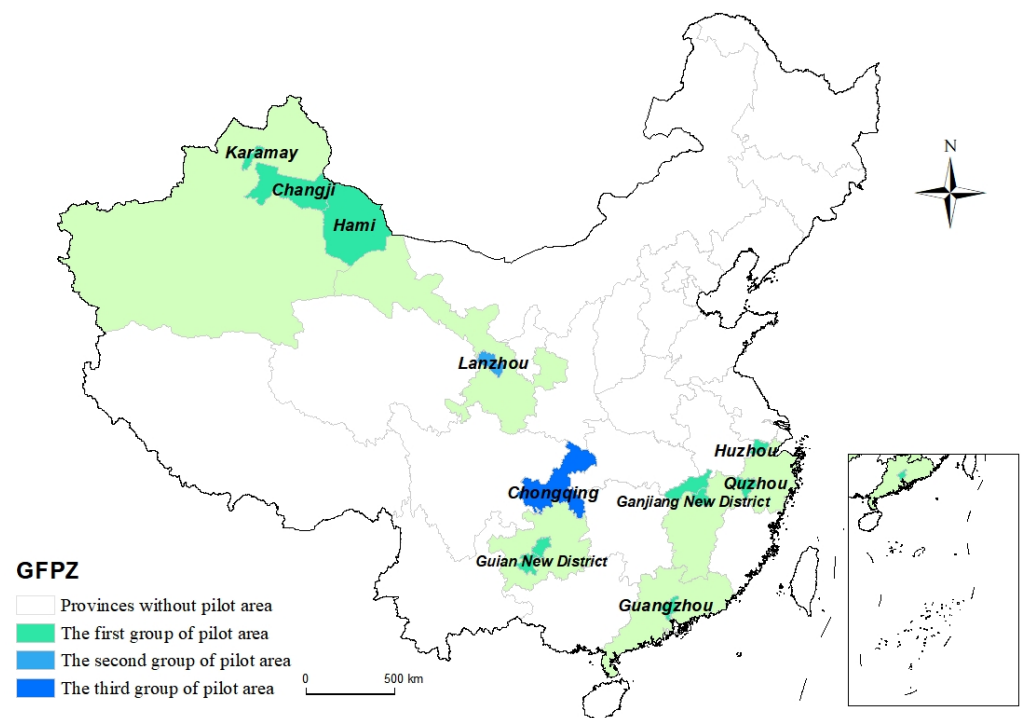


Figure 1. Phased distribution of China's GFPZ. Note: The lighter shade of green indicates the provincial-level region where the pilot city is located.

While a growing body of research has examined how factors such as economic development, fiscal decentralization, regulatory frameworks, governance incentives, and city-specific characteristics—including urban scale, population density, and industrial structure—shape UER [15–17], the literature remains fragmented. Methodologically, commonly used approaches include indicator-based assessments [18], simulation models [19], and case studies [20], with indicator systems being the most widely applied. However, these approaches are often constrained by arbitrary indicator selection, subjective weighting schemes, limited data availability, and a lack of dynamic tracking, which together hinder a comprehensive understanding of the evolutionary nature of resilience.

More importantly, a conceptual and theoretical gap persists in integrating mechanisms, spatial spillovers, and policy interactions into a unified analytical framework. Existing studies tend to focus either on isolated technological or institutional mechanisms or on spatial spillover effects examined in isolation. As a result, they fall short of simultaneously capturing the complex pathways through which green finance influences UER, the cross-regional externalities it may generate, and its potential synergistic or antagonistic interactions with other policy interventions. Consequently, current understanding of how green finance systematically shapes UER remains incomplete. These limitations underscore the need for a more integrated investigation into the multi-mechanism, spatially interconnected, and policy-interactive effects of green finance on UER.

This study exploits China's GFPZ as a policy-based quasi-experimental setting to identify the effects of green finance policy on UER and to uncover the underlying mechanisms. Specifically, the study seeks to answer three interrelated research questions: through which institutional, technological, and behavioral pathways does green finance enhance UER? Do these effects generate spatial spillovers across cities? And can interactions between green finance policies and digital economy initiatives produce synergistic effects? To answer these questions, we construct an UER assessment system grounded in the DPSIR framework and systematically examine the multidimensional channels through which green finance influences UER, including green technological innovation, public environmental

attention, and government environmental governance efficiency. In addition, accounting for heterogeneity in regional location and industrial structure, we assess differential policy effects and employ a Spatial Durbin Model (SDM) to investigate geographic spillovers and cross-policy interactions.

The contributions of this study are threefold. First, it develops an operational DPSIR-based framework for assessing UER and provides robust empirical evidence on the systemic effects of green finance, thereby addressing existing gaps in mechanism- and space-oriented analyses. Second, by integrating institutional, technological, and behavioral dimensions, the study deepens theoretical understanding of how green finance enhances UER and introduces a mechanism-based perspective to the literature. Third, by explicitly incorporating spatial spillovers and cross-policy interactions, this study extends the policy relevance of green finance research and offers evidence-based insights for the design of future green finance and urban sustainability policies. Overall, the study not only provides evidence on the role of green finance in strengthening UER but also advances existing theoretical and policy discussions through an integrated mechanism and spatial analytical framework.

2. Theoretical Analysis and Hypotheses Development

2.1. Direct Effect of Green Finance on UER

The critical role of green finance in advancing ecological sustainability has driven a steady deepening of academic research. Early studies primarily focused on conceptual discussions, while more recent work has expanded toward empirical analyses of the relationship between green finance and ecological resilience, with increasingly diverse methodologies providing strong support for practice. Green finance supports sustainable transformation by embedding environmental objectives into the financial system and, in doing so, enhances urban UER by strengthening cities' capacity to cope with and adapt to environmental pressures and climate-related risks.

Green finance enhances UER through three core mechanisms: capital redundancy, market incentives, and institutional transformation. Drawing on the socio-ecological-technical systems framework green finance inject targeted capital via instruments such as green credit and ecological restoration bonds, prioritizing investments in sponge facilities, distributed green spaces, and other forms of natural capital redundancy, thereby strengthening cities' ability to absorb ecological shocks and mitigate the impacts of extreme climate events. The application of low-carbon, energy-saving, and environmentally friendly technologies improves the efficiency of urban resource utilization, reduces pollution emissions, and facilitates the gradual recovery and reorganization of urban ecosystems. At the same time, carbon pricing mechanisms and climate bond markets provide clear price signals [21], compelling firms to optimize energy structures and reduce emission intensities, thus linking financial resource allocation with long-term ecological stability and resilience enhancement. By incentivizing and guiding multiple stakeholders to participate in collective action, green finance contributes to coordinated responses to environmental risks across sectors. Institutionally, systemic changes in capital allocation rules, embedding environmental standards into fiscal and regulatory systems, promote the institutionalization of green asset assessment, green credit, and environmental risk management [22]. These arrangements enable cities to respond to environmental uncertainty through more anticipatory and adaptive governance mechanisms, thereby contributing to the formation of a durable and sustainable ecological governance framework. For instance, inclusive green finance improves financial accessibility, supporting green infrastructure development, ecological restoration, and environmental protection in impoverished areas, thereby enhancing their capacity to cope with environmental stress and climate-related risks [23].

China's GFPZ, as a key institutional arrangement within the green finance system, further consolidates the function of green finance in promoting ecological resilience at the urban scale. The policy also drives the green finance governance framework from pilot exploration to institutional embedding by establishing a green finance standard system, improving environmental information disclosure, and enhancing green risk assessment mechanisms, thus providing institutional support for the sustained enhancement of UER.

H1. *The establishment of GFPZ significantly enhances UER.*

2.2. Indirect Effects of Green Finance on UER

This study examines the indirect effects of green finance on UER within the institutional–technological–behavioral governance framework. Accordingly, the mediating roles of green technological innovation, public environmental participation, and environmental governance efficiency can be identified. The specific theoretical analysis and hypothesis development are as follows.

2.2.1. Mediating Role of Environmental Governance Efficiency

Green finance policy also improves government efficiency in environmental governance. The institutional logic assigns responsibility for environmental regulation and policy implementation, thereby strengthening government environmental oversight in pilot cities. First, strengthened auditing and dynamic supervision increase transparency and enhance regulatory capacity, enabling local governments to channel green capital toward environmental projects via stricter regulations [24]. Second, green finance provides sufficient funding and technological support, improving the allocation of government resources and facilitating project implementation, thereby enhancing governments' capabilities in environmental monitoring, risk warning, and resource allocation under conditions of environmental uncertainty [25]. Third, green finance reforms foster institutional transformation by promoting organizational restructuring, interdepartmental coordination, and data sharing, thus reducing implementation barriers, improving efficiency, and alleviating resource misallocation [26].

Such improvements imply that limited public resources can generate higher desired outputs while reducing unintended consequences [27]. More importantly, enhanced governance efficiency not only reinforces short-term policy effects but also contributes to the accumulation of long-term institutional capacity. This capacity enables governments to respond more rapidly and precisely to ecological crises and emerging environmental risks, thereby reflecting a city's adaptive capacity to disturbances and its potential for recovery from environmental shocks [28]. Ultimately, improvements in government efficiency facilitate ecological infrastructure development, strengthen dynamic risk management, and promote collaborative governance. Through these channels, they enhance the stability, flexibility, and recovery potential of urban ecological governance systems [29], thereby contributing to a more robust and adaptive governance structure and reinforcing UER.

H2. *The establishment of GFPZ enhances UER by improving environmental governance efficiency.*

2.2.2. Mediating Role of Green Technological Innovation

Technology empowerment is one of the core mechanisms through which green finance enhances ecological resilience. Green technological innovation aims to reduce resource consumption, mitigate pollution, address climate change, and strengthen ecosystem sustainability by advancing new technologies, processes, and products from experimental development to widespread adoption [30]. Existing research demonstrates that green

finance plays a critical role in fostering green innovation [31]. Specifically, green finance policy reduces R&D costs through targeted financing and policy incentives, facilitating breakthroughs in pollution control, energy efficiency, and clean technologies such as distributed solar power and industrial carbon capture [32]. Moreover, green bonds and subsidies accelerate the large-scale adoption of mature technologies, increasing penetration rates and lowering pollution abatement costs [33,34].

This dual “innovation–diffusion” mechanism not only enhances environmental carrying capacity but also strengthens the stability and adjustability of urban ecological systems when confronted with environmental stress and climate-related risks. In addition, knowledge and data spillovers further improve environmental sensing and decision-making, providing more timely and reliable support for urban ecological risk management and long-term resilience planning [35].

H3. *The establishment of GFPZ enhances UER through the facilitation of green technological innovation.*

2.2.3. Mediating Role of Public Environmental Participation

Public participation is a vital component of China’s environmental governance system. Beyond firms and governments, green finance policy also affects society by shaping public attention to environmental issues through their signaling effect [36]. Within GFPZ, financial innovations—such as green credit and carbon finance instruments—enhance environmental disclosure and education. These measures facilitate a shift in public attention from short-term, policy-driven awareness toward more cognition-based and sustained engagement, embedding environmental concerns more deeply into everyday public awareness and social interaction.

According to the Attention-based View, increased public attention to environmental issues can translate into pro-environmental behaviors, including green consumption choices and environmental monitoring [37]. Such behaviors represent substantive forms of public participation in environmental governance. They exert bottom-up pressure on firms to incorporate environmental considerations into investment and production decisions, while simultaneously encouraging governments to strengthen ecological restoration institutions and regulatory responsiveness. Within China’s governance context, a collaborative model—where government acts as the primary regulator and public participation serves as a complementary force—remains both feasible and effective [38]. Sustained public attention supports the institutionalization and continuity of participatory practices, helping alleviate governance burdens and enhance the adaptive capacity of environmental governance over time.

Moreover, the policy spillover effects of GFPZ may amplify public environmental participation through media diffusion and interregional communication networks. By extending environmental awareness and participatory behaviors beyond administrative boundaries, these spillovers contribute to more coordinated societal responses to environmental challenges. Such cross-jurisdictional diffusion of public engagement can enhance collective risk awareness and reinforce UER through more stable and adaptive governance processes.

H4. *The establishment of GFPZ enhances UER by increasing public environmental participation.*

2.3. Spatial Spillover Effect of Green Finance on UER

The spatial spillover effects of green finance on UER stem from the cross-boundary nature of economic activity and environmental governance. According to Krugman’s

(1991) [39] new economic geography, GFPZ reshape regional factor allocation: low-carbon industrial agglomerations stimulate clean technology diffusion [40], but regulatory disparities may also drive pollution-intensive industries to relocate to neighboring areas, producing a “pollution haven” effect [41].

From the perspective of spatial externality theory, the public goods nature of environmental governance further reinforces spillovers. Due to atmospheric diffusion and watershed connectivity, policy effects inevitably transcend administrative boundaries. Spillovers occur through two channels: (1) market integration of green financial systems improves factor allocation efficiency; and (2) institutional imitation generates knowledge spillovers, forming a “market–institution” dual transmission mechanism.

At the dynamic level, three mechanisms underpin spatial spillovers: factor flows concentrate resources around growth poles created by green credit; industrial linkages, via green supply chain standards, drive regional industrial upgrading; and intergovernmental regulatory competition fosters “race-to-the-top” strategies that reshape policy ecosystems [42].

H5. While the establishment of GFPZ enhances UER within pilot cities, it also induces significant spatial spillover effects on surrounding cities.

In summary, we argue that green finance policy generates direct effects on resilience (via capital redundancy, market incentives, and institutional reforms), indirect effects through green technological innovation, public attention, and government governance, and spatial spillover effects through cross-regional market and institutional linkages. On this basis, we construct the conceptual framework illustrated in Figure 2.

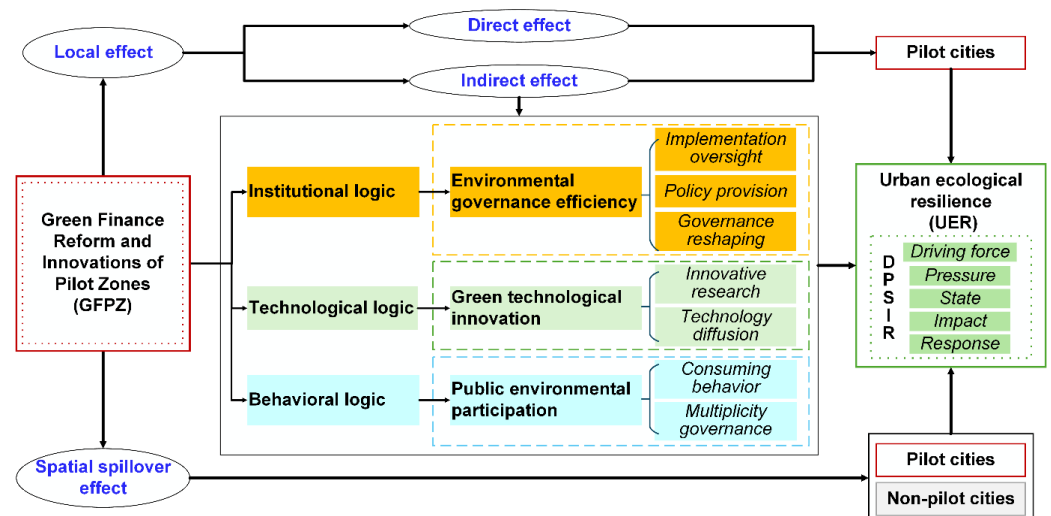


Figure 2. Theoretical mechanisms between GFPZ and UER.

3. Models, Variables, and Data

3.1. Empirical Models

This study treats the establishment of GFPZ as a quasi-natural experiment. A simple before-and-after comparison of cities that implemented GFPZ may lead to biased estimates. To obtain a more accurate causal inference, we employ a staggered DID approach, which compares changes in outcomes between treated and control groups before and after the policy intervention [43]. Since Chongqing was only recently designated as a GFPZ, it is excluded from the analysis because the policy effects are not yet observable. Accordingly,

we focus on the policy shocks introduced in 2017 and 2019, covering nine pilot sites across six provinces, and construct the following baseline DID specification:

$$UER_{it} = b_0 + b_1GFPZ_{it} + aX_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where UER_{it} represents the ecological resilience of city i in year t . $GFPZ_{it}$ is a policy dummy that equals 1 if city i is designated as a GFPZ in year t , and 0 otherwise. X_{it} is a vector of control variables capturing population density, government fiscal self-sufficiency, fiscal investment intensity, financial development, foreign direct investment, industrial structure upgrading, and primary industry value added. μ_i and λ_t denote city and year fixed effects, respectively, and ε_{it} is the error term.

Based on the mechanism analysis, we hypothesize that GFPZ enhance UER through mediating channels such as green technological innovation, public environmental attention, and government environmental governance efficiency. Since the academic debate on the endogeneity of mediation models remains unresolved, we follow the methodological framework of Zhao et al. (2010) [44], which examines the impact of the treatment variable on mediators as an intermediate step to test mechanisms. Accordingly, we specify the following mediation model:

$$Mediator_{it} = \omega_0 + \omega_1GFPZ + \omega_2X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

where $Mediator_{it}$ denotes the mediating variable, specifically including measures of green technological innovation, public environmental attention, and government environmental governance efficiency. All other variable definitions are consistent with Equation (1). Equation (2) is used to test whether the GFPZ policy significantly influences these mediators.

The implementation of green finance policy may generate spillover effects on surrounding regions. Ignoring such spatial interdependencies in empirical analysis could lead to biased or incomplete estimates of the true impact of green finance on UER. To address this concern, we employ spatial econometric models to further investigate whether the GFPZ policy exhibits spatial spillover effects.

Given the significant spatial diffusion characteristics of green finance policy, this study moves beyond the limitations of traditional regression analysis by adopting the SDM framework. This approach allows us to construct a composite model that incorporates both policy intervention effects and spatial interaction mechanisms. The SDM effectively combines the evaluation strength of the DID method with the ability of spatial econometrics to account for spatial correlation. The model is specified as follows:

$$UER_{it} = \theta_0 + \rho GFPZ_t + \theta_1 WUER_{it} + \theta_2 X_{it} + \varepsilon_i + \lambda_t + \mu_{it} \quad (3)$$

where the dependent variable, explanatory variable, and control variables are consistent with those in Equation (1). W denotes the spatial weight matrix, constructed based on city adjacency. The parameter ρ captures the degree of spatial spillover effects, while $WUER_{it}$ reflects the tempo-spatial interactions through which policy effects are transmitted across regions.

3.2. Variables

3.2.1. Dependent Variable: UER

Both the *United Nations 2030 Agenda for Sustainable Development* and the *New Urban Agenda* emphasize the importance of building resilient cities. From an urban systems and planning perspective, UER refers to a city's capacity to prevent, withstand, and recover

from external disturbances and shocks. Rather than representing a mechanical combination of “urban ecology” and “resilient cities,” the concept emphasizes the dynamic balance and interaction between the ecological environment and the built environment. Through appropriate planning and governance arrangements, UER enhances cities’ abilities to cope with shocks and to recover following disturbances, thereby contributing to public safety and long-term sustainability.

UER emerges from the interactions among natural, economic, and social systems and constitutes a foundational component of sustainable urban development. In this study, cities are conceptualized as adaptive systems capable of responding to environmental risks and adjusting to future challenges, with particular attention paid to the sustainability of social and environmental subsystems. Recent research has integrated the DPSIR framework with analytical approaches such as partial least squares structural equation modeling (PLS-SEM) and ecological network analysis to uncover synergistic effects among subsystems, identify key policy intervention points, and highlight the importance of economic–ecological coupling [45].

Compared with traditional PSR or DSR frameworks, the DPSIR model offers a more comprehensive integration of ecological, economic, and social dimensions, thereby reducing the risk of omitted-variable bias and facilitating comparisons across regions and over time. Importantly, the “Response” dimension explicitly incorporates governance-related variables—such as green investment and pollution control expenditures—allowing policy interventions to be embedded within the analytical framework. The application of the DPSIR framework in this study reflects a cautious and deliberate methodological choice grounded in a critical assessment of its strengths and limitations. Although DPSIR has been criticized for its tendency toward linear representations of complex systems [46] and has been less frequently applied at the urban scale—particularly in analyses involving economically oriented response instruments such as financial policies [47]—its logical structure closely aligns with the policy design of GFPZ [48]. In this context, the pilot policy constitutes a clearly defined “response,” intended to reshape investment-related “driving forces,” alleviate environmental “pressures,” and ultimately improve ecological “states.”

Building on this, this study constructs a multi-layer UER index covering four subsystems—ecology, economy, society, and infrastructure—and, in combination with the improved causal framework of the European Environment Agency (2006), designs a dynamic monitoring system that systematically integrates indicators of driving force, pressure, state, impact, and response. Finally, an 18-indicator system is developed, providing a robust basis for scientifically quantifying UER, evaluating the effects of green finance policy, and formulating differentiated governance strategies, drawing on existing studies [49,50], and commonly used indicators from international organizations such as the United Nations and the World Bank.

(1) Driving force indicators: Capture the positive drivers of economic development for resilience. For example, the urbanization rate reflects the scale and pace of urban development, where higher levels typically imply stronger economic foundations and resource allocation capacities. Total retail sales of consumer goods indicate market vitality, which also enhances resilience.

(2) Pressure indicators: Measure ecological and environmental pressures. Indicators such as per capita industrial wastewater discharge, per capita SO₂ emissions, per capita daily water consumption, and per capita built-up area reflect stress from resource consumption and pollution. These are expected to negatively affect UER.

(3) State indicators: Reflect the current ecological and environmental status. Indicators include per capita water resources, green coverage rate of built-up areas, and per capita public green space, which positively contribute to resilience.

(4) Impact indicators: Capture the effects of economic activity and innovation on resilience. R&D expenditure and the number of R&D personnel proxy for technological innovation capacity, which positively affects resilience. Considering China's commitment to carbon neutrality by 2060, indicators such as carbon intensity and industrial value added are also incorporated.

(5) Response indicators: Measure governance capacity in addressing ecological and environmental issues. Indicators include the share of environmental protection expenditure in fiscal spending, the harmless treatment rate of household waste, and the centralized treatment rate of sewage plants, all of which positively affect resilience.

To handle the differing positive and negative effects of these indicators, we adopt the normalization and entropy weighting method proposed by Abolhassani et al. (2025) [51]. This ensures objectivity and robustness in assigning indicator weights. Using this framework, we evaluate the ecological resilience of 277 prefecture-level cities in China, thereby constructing a comprehensive and elastic urban system assessment. Table 1 provides a detailed overview of the indicator system, including indicator levels and expected directions of influence.

To further validate whether the UER index accurately reflects the resilience of Chinese cities, we examine its temporal and spatial evolution across 277 prefecture-level cities from 2011 to 2022. As shown in Figure 3, the spatial distribution of UER demonstrates a clear expansion pattern. Between 2014 and 2022, regions with relatively high UER evolved from three core areas into three major resilience belts along the coast, the Yangtze River, and the Chengdu–Chongqing region. Specifically, in 2022, the top ten cities in terms of UER were Shanghai, Beijing, Shenzhen, Dongguan, Chongqing, Guangzhou, Chengdu, Hangzhou, Ningbo, and Suzhou, while the bottom ten included Dingxi, Baise, Yunfu, Heyuan, Hezhou, Hechi, Chongzuo, Laibin, Lincang, and Guigang. This ranking closely aligns with China's regional development realities: the top ten cities are largely first-tier and emerging first-tier cities, characterized by strong economic foundations, extensive sponge facilities and emergency nodes, and comprehensive resilience planning that integrates multiple scenarios such as extreme weather, public health crises, and industrial chain disruptions. These cities thus exhibit rapid response and adaptive capacity under shocks. By contrast, the bottom ten cities are located mainly in the southwestern and northwestern peripheries, in less-developed regions experiencing population outflow and industrial monoculture. With aging infrastructure, gaps in digital governance, and repeated occurrences of the “small disaster, big loss” phenomenon, these cities reveal amplified vulnerabilities under compound disasters. This spatial contrast highlights the dynamic heterogeneity of urban resilience and risk-bearing capacity along China's development gradient.

We further explore the dynamic evolution of UER using kernel density estimation for the period 2011–2022. The overall distribution exhibits a pronounced right-skew, as illustrated in Figure 4. Several distinct phases can be identified. From 2011 to 2015, the UER index increased steadily from a relatively low level, with the distribution shifting rightward and narrowing. This can be attributed to the growing emphasis on ecological protection during the early stage of urbanization, when governments began to implement green infrastructure projects such as park construction and wetland restoration, accompanied by improvements in environmental regulations targeting pollution control and carbon emissions. In particular, resilience building gradually gained strategic importance after “ecological civilization construction” was incorporated into China's national development strategy in 2012 and embedded within the “Five-sphere Integrated Plan”.

Between 2016 and 2019, however, the UER index experienced fluctuations and even temporary declines in certain years. This was driven by multiple factors: on the one hand, the increasing frequency of extreme climate events exposed the fragility of urban ecological

systems; on the other hand, rapid urban expansion resulted in land overdevelopment, reduced green spaces, and exacerbated heat island effects. Additionally, environmental improvement is a complex and gradual process involving multiple feedback mechanisms in ecosystems, and policy implementation typically requires time to produce significant ecological effects, resulting in a notable time lag.

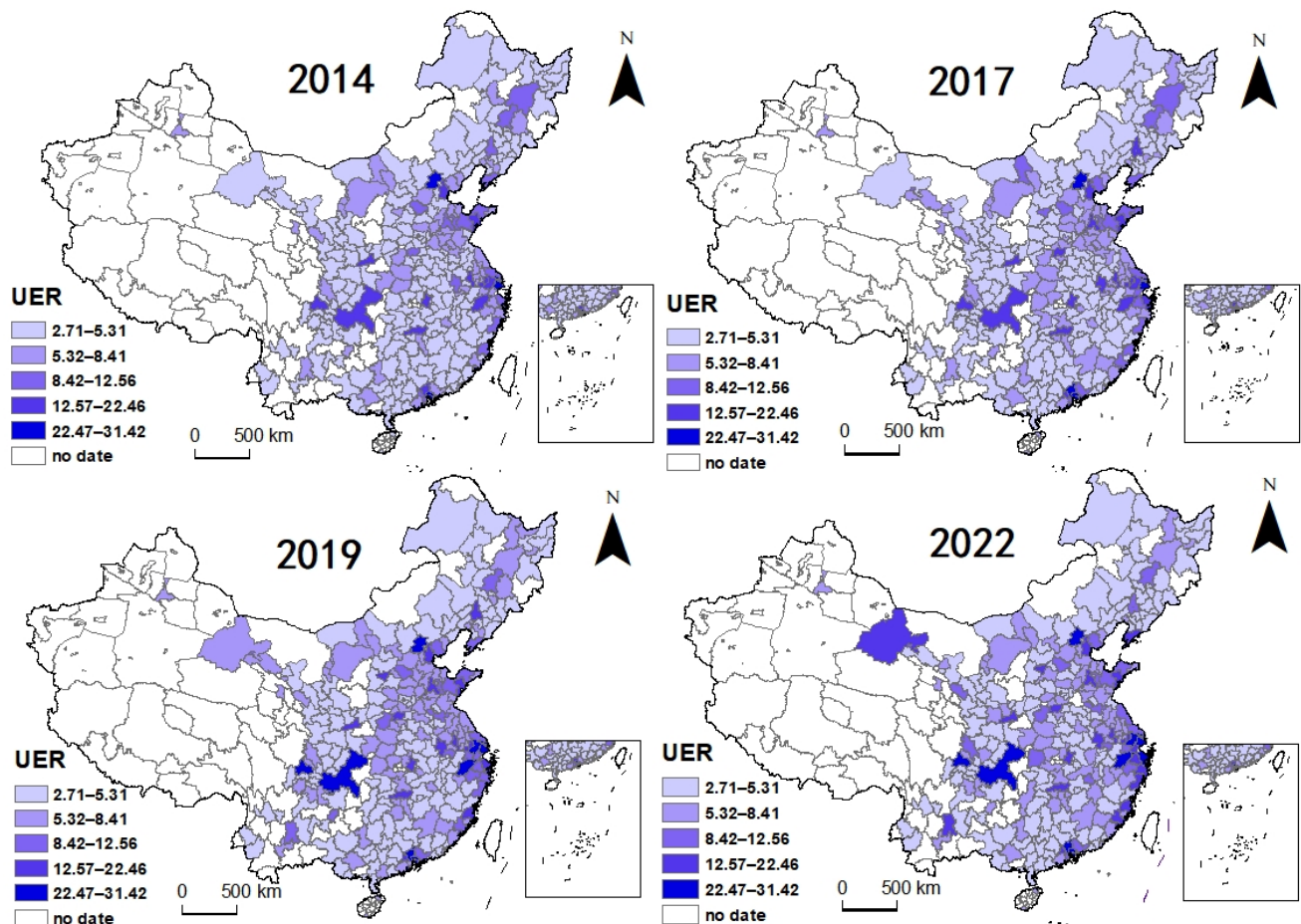


Figure 3. Spatial distribution of UER across China between 2011 and 2022.

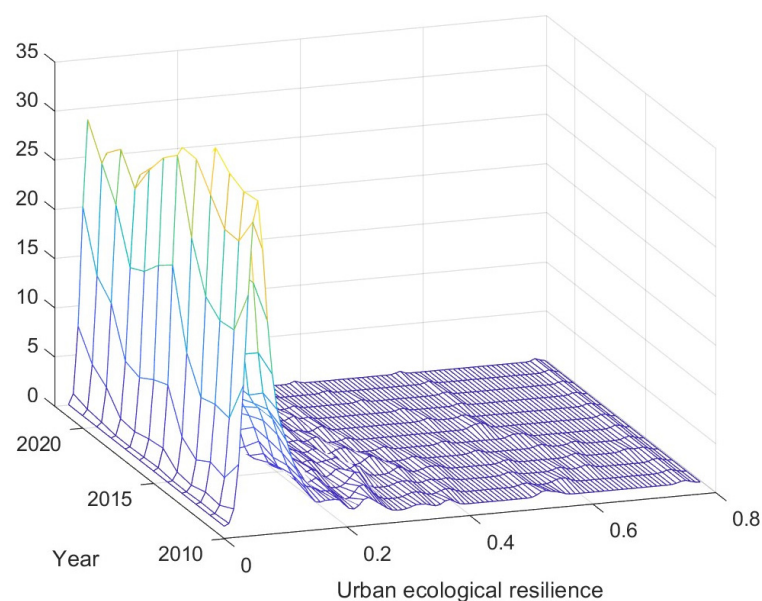


Figure 4. Kernel density distribution of UER between 2011 and 2022.

Table 1. Evaluation index system of UER using DPSIR framework.

Target Layer	System Layer	Index Layer	Unit	Attribute	Author(s)
UER	Driving force (D)	Urbanization rate	%	+	Shi et al. (2022) [52]; Chen H Z et al. (2022) [45]
		Total retail sales of consumer goods	108 CNY	+	Zhao et al. (2021) [15]; Xu et al. (2024) [8]
	Pressure (P)	Per capita industrial sulfur dioxide emissions	t·cap ^{−1}	−	Wang et al. (2018) [53]; He et al. (2024) [54]; Shi et al. (2022) [52]
		Per capita daily water consumption	L·cap ^{−1} ·d ^{−1}	−	Zhao et al. (2021) [15]; Sharifi (2023) [2]; Wang et al. (2018) [53]
		Per capita built-up area	km ² ·104 cap ^{−1}	−	Chu et al. (2023) [55]; Shi et al. (2022) [52]; Li et al. (2023) [56]
		Per capita water resources	m ³ ·cap ^{−1}	+	Chu et al. (2023) [55]; Li et al. (2023) [56]
	State (S)	Green coverage in built-up areas	%	+	Zhang et al. (2024) [7]; He et al. (2024) [54]
		Per capita park green spaces	ha·cap ^{−1}	+	Shi et al. (2022) [52]; Xu et al. (2024) [8]
		Carbon intensity	tCO ₂ /104 CNY	−	Wang et al. (2024) [18]; He et al. (2024) [54]
	Impact (I)	R&D expenditure	10 ⁸ CNY	+	Zhao et al. (2021) [15]; Chen H Z et al. (2022) [45]
		R&D personnel	year·cap ^{−1}	+	Xu et al. (2024) [8]; Shi et al. (2022) [52]
		Industrial value added	10 ⁸ CNY	−	Wei et al. (2019) [49]; Shi et al. (2022) [52]
		Share of environmental protection expenditure	%	+	Wang et al. (2024) [18]; He et al. (2024) [54]
	Response (R)	Disposal rate of municipal solid waste	%	+	Li et al. (2023) [56]; Xu et al. (2024) [8]
		Centralized sewage treatment rate	%	+	Zhang et al. (2024) [7]; He et al. (2024) [54]
		Built-up area green space	ha	+	Wang et al. (2024) [18]; Sharifi (2023) [2];
		Industrial solid waste utilization rate	%	+	Shi et al. (2022) [52]; Wang et al. (2018) [53]; Xu et al. (2024) [8]

From 2019 to 2022, the UER index returned to an upward trajectory, with the kernel density curve becoming “taller and narrower.” This change can be primarily attributed to the promotion of national strategic goals, which accelerated the implementation of various ecological restoration projects, such as the development of green infrastructure and the widespread use of renewable energy. Additionally, the development of big data technology significantly enhanced the city’s disaster warning and response capabilities. At the same time, local governments gradually improved the ecological performance evaluation mechanism, promoting the concretization and institutionalization of ecological protection measures, thereby further enhancing the quality and stability of urban ecosystems.

Overall, these spatiotemporal dynamics are consistent with China's practical experience and further confirm that the UER index constructed in this study provides a reliable measure of UER.

3.2.2. Independent Variable: GFPZ Policy

The core explanatory variable in this study is the interaction between a city-level dummy for the GFPZ policy and a time dummy. This interaction term identifies whether city i in year t implemented the GFPZ policy. The policy was introduced in 2017 and 2019. Cities designated as GFPZ pilots are coded as the treatment group with a value of 1; non-pilot cities form the control group with a value of 0. For pilot cities, the dummy equals 1 from the year of policy implementation onward, and 0 in all prior years. For non-pilot cities, the dummy remains 0 across all years.

3.2.3. Control Variables

To minimize bias from omitted variable problems, we include a set of control variables widely adopted in the literature [57–61]. Seven key factors are considered:

(1) Population density (*DEN*): Measured as the number of residents per square kilometer. Population density reflects urban size and concentration, which affect ecological resilience. Higher density may increase ecological pressures and reduce resilience; however, dense areas may also achieve more efficient resource use and stronger policy responsiveness.

(2) Government fiscal self-sufficiency (*Gov*): Defined as the ratio of local fiscal revenue to fiscal expenditure, capturing the extent of fiscal independence and resource allocation capacity. Higher self-sufficiency enhances governments' ability to support resilience building, for example by increasing environmental investment and improving infrastructure.

(3) Fiscal investment intensity (*REV*): Refers to the share or absolute amount of fiscal expenditure devoted to infrastructure, public services, and socioeconomic development. A higher level indicates greater governmental prioritization of ecological construction, such as green space expansion and sewage treatment capacity.

(4) Financial development (*Fin*): Captures the degree of financial deepening and risk management capacity, proxied by the ratio of total loans and deposits to GDP. Financial development enhances resilience by mobilizing investment and improving risk governance.

(5) Foreign direct investment (*FDI*): This paper uses the natural logarithm of the number of foreign-invested enterprises at the prefecture level as a proxy. FDI may enhance employment and economic resilience, but can also exert negative effects on ecological resilience if associated with pollutant-intensive production.

(6) Industrial structure upgrading (*Ind*): Represented by the ratio of tertiary to secondary industry value added. Industrial upgrading from high-pollution, high-energy industries to low-carbon, service-oriented sectors directly reduce ecological pressures and improves resilience.

(7) Primary industry value added (*AGDP*): Agriculture and related activities significantly shape urban ecological systems, particularly in peri-urban regions. We take the log of primary industry value added to account for its role in economic structure and urban transition.

3.2.4. Mediating Variables

To explore the mechanisms through which GFPZ policy affect UER, we construct three mediating variables:

(1) Government environmental governance efficiency (*GEG*): Following Li et al. (2019) [62] and Wang et al. (2024) [63], we adopt a non-radial, non-oriented super-efficiency

Slack-Based Measure (SBM) model under the assumption of constant returns to scale. This approach accounts for multiple inputs and outputs while avoiding bias from slack variables. Inputs include local fiscal expenditure on energy conservation and environmental protection, and the number of employees in environmental management. Outputs include both desirable and undesirable outcomes: desirable outputs consist of the comprehensive utilization rate of industrial solid waste, centralized sewage treatment rate, and newly added green area; undesirable outputs include industrial wastewater discharge and industrial soot emissions. This provides a comprehensive measure of government efficiency in environmental governance.

(2) Green technological innovation (GTI): Innovation capacity is measured by the number of patent applications, which provides a more accurate reflection of innovation activity than patent authorizations, as it is less affected by administrative delays [34]. Following Kong et al. (2022) [64], we use the number of green patent applications at the prefecture level as a proxy for green technological innovation. To address right-skewed distribution, the variable is transformed using the natural logarithm of (green patent applications + 1).

(3) Public environmental participation (PEP): Defined as the external manifestation of public environmental preferences, reflecting the degree of environmental concern and willingness to participate in governance. Higher attention generates demand for green products and policies, creating a “demand-side pull” [65]. As an informal regulatory force, public attention influences both firms and governments. We use the natural logarithm of the Baidu Search Index for the keyword “environmental pollution” plus one to measure PEP, capturing the frequency of public searches and attention to environmental issues.

3.3. Data Sources

This study employs panel data for prefecture-level and above cities in China. To ensure data consistency, cities with severe data deficiencies (e.g., Changji and Hami) were excluded from the sample. To mitigate the influence of outliers, all continuous variables were winsorized at the 1% level in both tails. For a small number of missing observations in specific years, linear interpolation was applied. The final balanced panel consists of 277 prefecture-level and above cities covering the period from 2011 to 2022. We exclude data after 2022 to ensure data consistency and reliability, as post-2022 data may be incomplete, unstable, and influenced by short-term policy and economic fluctuations. The data are drawn from multiple authoritative sources, including the China City Statistical Yearbook, China Energy Statistical Yearbook, China Environment Yearbook, CSMAR database, provincial and municipal statistical yearbooks. All econometric analyses in this study were conducted using Stata 17.0. Specifically, Figure 2 was created using Microsoft Professional Visio 2021, Figure 3 was generated with ArcGIS 10.8.1, and Figure 4 was produced using MATLAB R2021b. Descriptive statistics of the variables are reported in Table 2. The descriptive statistics of the other control variables are similar to those reported in previous studies.

Table 2. Descriptive statistics.

Variables	Obs.	Mean	S.D.	Min.	Max.
<i>UER</i>	3324	6.4015	4.6470	2.7067	31.4228
<i>GFPZ</i>	3324	0.0138	0.1168	0.0000	1.0000
<i>FDI</i>	3324	2.9429	1.5820	0.0000	6.1717
<i>AGDP</i>	3324	14.2757	0.8150	10.3447	16.8176
<i>Ind</i>	3324	1.0477	0.4523	0.4669	2.2011
<i>Fin</i>	3324	2.5805	1.1612	1.0270	6.7890

Table 2. Cont.

Variables	Obs.	Mean	S.D.	Min.	Max.
DEN	3324	435.9004	307.2052	12.0000	1472.0000
Gov	3324	0.4497	0.2069	0.1536	0.8541
REV	3324	5.1005	2.612	0.139	13.4898
GTI	3324	5.0632	1.6551	0.0000	10.3008
PEP	3324	2.7295	0.9651	0.0000	5.1090
GEG	3324	0.0664	0.1316	0.0003	1.0000

To further ensure the robustness of our results and avoid spurious regression problems, we conducted multicollinearity tests. The variance inflation factor (VIF) values, reported in Table A1 in Appendix A, show a maximum of 3.63, well below the commonly accepted threshold of 10. This indicates that multicollinearity is not a concern, thereby confirming the validity and reliability of the model estimations and providing a solid foundation for subsequent analyses.

4. Results

4.1. Main Results

Table 3 presents the estimated effects of the GFPZ policy on UER, along with a series of robustness checks. Across alternative model specifications, the estimated coefficients on GFPZ remain consistently positive and statistically significant at the 1% level. Overall, the evidence indicates that the GFPZ policy has a robust and positive effect on UER under multiple empirical settings. Although the inclusion of high-dimensional fixed effects influences the magnitude of the estimated coefficients and absorbs the overall intercept, it does not affect the interpretation of the policy effect. The core conclusion therefore remains stable, providing strong empirical support for H1.

Table 3. The effects of GFPZ policy on UER.

Variables	UER							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
GFPZ	0.6113 *** (0.1287)	0.6102 *** (0.1328)	0.5677 *** (0.1319)	0.5515 *** (0.1326)	0.6427 *** (0.1403)	0.6436 *** (0.1401)	0.6635 *** (0.1391)	0.7140 *** (0.1395)
DEN		−0.0011 (0.0008)	−0.0011 (0.0008)	−0.0011 (0.0008)	−0.0012 (0.0008)	−0.0012 (0.0008)	−0.0011 (0.0008)	−0.0011 (0.0008)
Ind			−0.3729 *** (0.0979)	−0.3541 *** (0.0991)	0.0102 (0.1119)	0.0102 (0.1119)	0.0398 (0.1131)	0.0294 (0.1139)
FDI				0.1284 *** (0.0452)	0.0296 (0.0448)	0.0287 (0.0442)	0.0301 (0.0445)	0.0625 (0.0442)
Fin					−0.4365 *** (0.0573)	−0.4356 *** (0.0591)	−0.4742 *** (0.0640)	−0.5286 *** (0.0703)
Gov						0.0336 (0.2625)	0.1261 (0.2664)	0.1751 (0.2666)
REV							−0.0415 *** (0.0114)	−0.0319 *** (0.0112)
AGDP								−0.6370 *** (0.1360)
_Cons	6.3930 *** (0.0155)	6.8848 *** (0.3548)	7.2792 *** (0.3842)	6.8639 *** (0.4429)	7.9293 *** (0.4389)	7.9144 *** (0.4684)	8.1260 *** (0.4766)	17.1812 *** (2.0406)
Obs.	3324	3324	3324	3324	3324	3324	3324	3324
Adj. R ²	0.964	0.964	0.964	0.964	0.966	0.966	0.966	0.966
City F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: *** $p < 0.01$.

4.2. Staggered DID Validity Tests

4.2.1. Parallel Trend Test

A critical prerequisite for the validity of the DID model is the parallel trend assumption, which requires that GFPZ cities and non-GFPZ cities follow comparable trajectories before the policy intervention [66]. The empirical specification is as follows:

$$UER_{it} = \beta_0 + \sum_{t=0}^5 \beta_1 GFPZ_{it} + \alpha X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

where $GFPZ_{it}$ is a set of dummy variables equal to one, if city i is a pilot in year t , and zero otherwise. All other terms are consistent with Equation (1).

Owing to limited data availability in the early pre-policy period, observations more than six years prior to policy implementation are aggregated into a single pre-treatment interval. Figure 5 reports the estimated dynamic effects of the GFPZ policy on UER. The results indicate that, prior to policy implementation, the estimated coefficients on the GFPZ variable are statistically indistinguishable from zero, providing no evidence of differential pre-trends between treated and control cities. After the policy is enacted, the coefficients become positive and statistically significant at the 1% level. These findings support the validity of the parallel trend assumption and confirm that the GFPZ policy exerts a significant positive effect on UER.

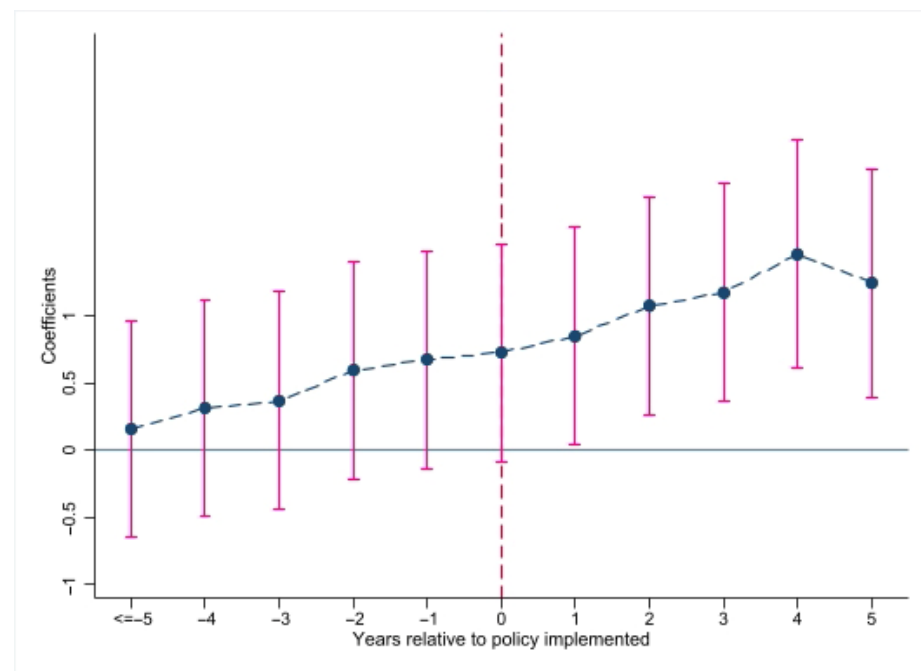


Figure 5. Parallel trend test.

Considering recent advances in DID methodology, standard pre-trend tests alone may not be sufficient to fully substantiate the parallel trend assumption. Accordingly, following Rambachan and Roth (2023) [67], we conduct a sensitivity analysis that permits bounded deviations from exact parallel trends. The results indicate that the estimated effects of the GFPZ policy remain robust under reasonable departures from the parallel trend assumption. Detailed results are reported in Figure A1 in the Appendix A.

4.2.2. Placebo Test

To assess whether the baseline estimates are spuriously driven by omitted variables or random fluctuations, we implement a mixed placebo test following the approach pro-

posed by Luan et al. (2025) [68]. Unlike conventional placebo tests that manipulate either units or timing alone, this method simultaneously randomizes both the treated units and the treatment timing, thereby offering a more stringent falsification exercise for the DID identification strategy.

Specifically, we randomly draw (without replacement) a subset of cities from the full sample and designate them as pseudo-treated units. We then randomly assign each pseudo-treated city a placebo treatment year, drawn from a uniform distribution spanning the earliest and latest actual policy adoption years. Using these artificially constructed treatments, we re-estimate the DID model to obtain placebo treatment effects. This procedure is repeated 500 times to generate the empirical distribution of placebo estimates under the null hypothesis of no treatment effect.

Figure 6 presents the resulting placebo distribution in the form of kernel density estimates and histograms. The baseline GFPZ treatment effect, marked by the vertical solid line, lies far in the tail of the placebo distribution. This pattern indicates that the estimated policy effect is unlikely to arise from random assignment or unobserved confounding factors, providing strong support for the causal interpretation of the baseline results and confirming that the GFPZ policy exerts a genuine impact on urban ecological resilience.

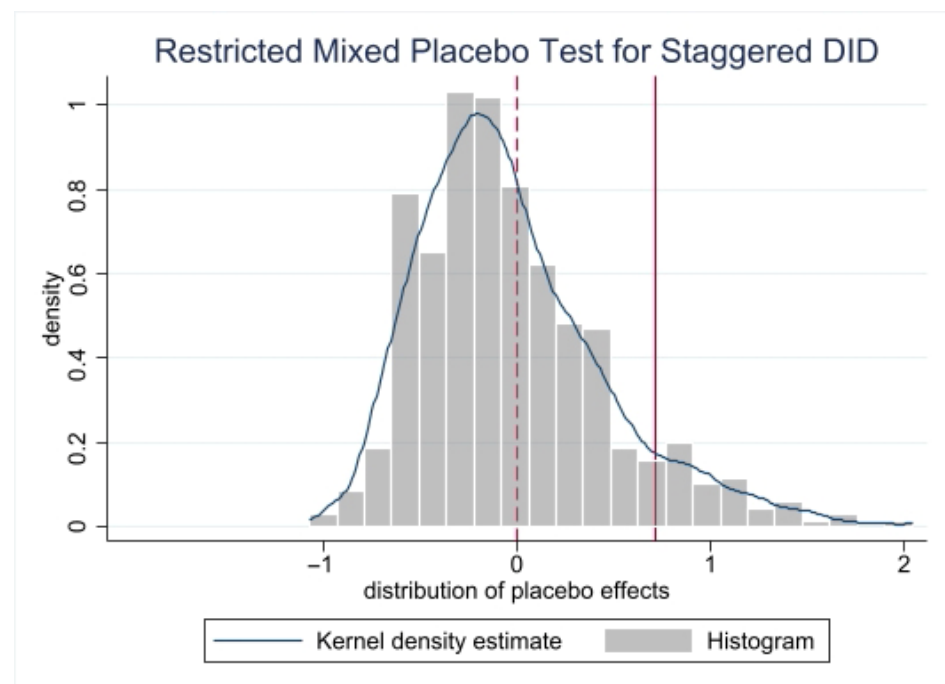


Figure 6. Placebo test results.

4.2.3. Heterogeneity Treatment Effect Test

Since staggered DID estimators essentially compute a weighted average of treatment effects, estimation bias can arise when the effects of policy shocks are heterogeneous across units. This issue may interfere with the identification of average treatment effects in two-way fixed effects (TWFE) models.

Following Goodman-Bacon (2021) [69], we apply the Bacon decomposition method to test for heterogeneous treatment effects. The results are presented in Table 4. The potentially problematic treatment comparison (later-treated vs. early control groups) produces an estimated coefficient of -0.012 with a weight of only 0.1%. This negligible contribution indicates that bias from treatment heterogeneity is minimal, thereby reinforcing the robustness of the baseline results.

Table 4. Bacon decomposition results.

Group	Estimated Coefficient	Weight
Earlier Treatment vs. Later Comparison	0.492	0.001
Later Treatment vs. Earlier Comparison	0.012	0.0007
Treatment vs. Never Treated	0.611	0.9981
Weighted estimated coefficient	0.611	

Although the Bacon decomposition suggests that bias arising from treatment effect heterogeneity is negligible in our baseline estimates, we further strengthen the causal identification by applying several recently developed staggered-DID–robust estimators. First, we employ the Sun and Abraham (2021) [70] estimator to examine dynamic treatment effects. By explicitly accounting for heterogeneous treatment timing and cohort-specific effects, this approach corrects the bias inherent in conventional two-way fixed effects DID models and provides more reliable estimates under staggered adoption. Second, following Borusyak et al. (2024) [71], we implement an imputation-based estimator that constructs counterfactual outcomes for treated units using only not-yet-treated observations. This method avoids reliance on potentially contaminated control groups and further mitigates concerns related to inappropriate comparisons across cohorts. Finally, we adopt a stacked DID design that explicitly restructures the data into cohort-specific treatment–control comparisons. By isolating each policy adoption cohort and redefining appropriate control groups, this approach directly addresses biases induced by heterogeneous treatment timing.

As reported in Table 5, estimates obtained from all three alternative specifications—including the stacked DID—remain positive and statistically significant at the 5% level. The consistency across these heterogeneous-treatment-robust estimators confirms that the positive effect of GFPZ on urban ecological resilience is not driven by methodological artifacts, thereby reinforcing the credibility and robustness of the baseline findings.

Table 5. Heterogeneity-robust estimators.

Variables	UER		
	(1)	(2)	(3)
	SA-DID	DID Imputation	Stacked DID
GFPZ	0.360 * (0.195)	0.738 ** (0.302)	1.073 ** (0.465)
Obs.	3324	3324	9780
Controls	Yes	Yes	Yes
City F.E.	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes

Note: * $p < 0.10$, ** $p < 0.05$.

4.3. Robustness Tests

4.3.1. PSM-DID and IV Estimation

Because the designation of China's GFPZ may not be entirely random and could be correlated with cities' pre-existing economic and financial characteristics, we further implement propensity score matching combined with DID (PSM-DID) and instrumental variable (IV) estimations to mitigate potential selection bias and endogeneity concerns.

First, we apply a PSM-DID strategy using all baseline control variables as matching covariates. Cities are matched through both radius matching and kernel matching procedures to ensure robustness to alternative matching algorithms. The DID model is then re-estimated using the matched samples. As reported in columns (1) and (2) of Table 6, the estimated coefficient of GFPZ remains positive and statistically significant, with magni-

tudes comparable to the baseline results. This finding suggests that the observed policy effect is not driven by observable differences between pilot and non-pilot cities.

Table 6. Regression results of PSM-DID and IV estimation.

Variables	PSM-DID			IV Estimation		
	(1) Nuclear Matching	(2) Radius Matching	(3) Phase I	(4) Phase II	(5) Phase I	(6) Phase II
GFPZ	0.6807 *** (0.140)	0.6933 *** (0.142)		23.727 *** (5.464)		22.034 *** (5.619)
IV			2.947 *** (0.615)		2.923 *** (0.645)	
K-P LM				22.531 [0.000]		20.107 [0.000]
C-D Wald F				31.028 {16.380}		42.123 {16.380}
K-P Wald F				22.994 {16.380}		20.568 {16.380}
Obs.	3168	3152	3324	3324	3324	3324
Controls	Yes	Yes	No	No	Yes	Yes
City F.E.	Yes	Yes	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes

Note: *** $p < 0.01$.

Second, to further address concerns related to omitted variables and potential reverse causality, we adopt an instrumental variable approach within a two-stage least squares (IV-2SLS) framework. Following Xiong et al. (2023) [72], the instrument is constructed as the interaction between the inverse geographic distance from each city to major national financial centers (Shanghai and Shenzhen) and the lagged national level of financial development. This design exploits exogenous spatial variation in accessing financial resources while remaining plausibly unrelated to contemporaneous shocks to urban ecological resilience.

The first-stage results confirm the validity of the instrument, with Kleibergen–Paap LM statistics rejecting under-identification and Wald F statistics well above conventional thresholds for weak instruments. As shown in columns (3)–(6) of Table 6, the IV estimates remain consistent with the baseline DID findings in both sign and significance. Together, the PSM-DID and IV results provide additional support for the causal interpretation that GFPZ implementation contributes to improvements in urban ecological resilience.

Overall, the results from both PSM-DID and IV estimations support the robustness of the baseline DID conclusions.

4.3.2. Other Robustness Tests

The additional robustness checks reported in Table 7 further confirm that the GFPZ policy has a stable and statistically significant positive impact on UER:

(1) Adjusting measurement methods. To verify that the baseline results are not driven by subjective weighting choices in the construction of the UER index, we re-estimate the index using principal component analysis (PCA) as an alternative to the entropy weighting method. The Pearson correlation coefficient between the PCA-based and entropy-based UER scores reaches 0.8641, indicating a high degree of consistency between the two measures. As shown in column (1) of Table 7, the estimated coefficient of GFPZ remains positive and statistically significant (0.225), suggesting that the main findings are robust to alternative measurement strategies. To further strengthen this conclusion, we additionally employ the CRITIC weighting method as an independent robustness check.

The corresponding results, together with a comparative discussion of entropy-, PCA-, and CRITIC-based indices, are reported in Appendix A Table A2. Taken together, these tests demonstrate that the estimated effect of the GFPZ policy is not sensitive to the choice of index weighting methodology, alleviating concerns that the baseline results may be driven by a small subset of highly volatile indicators.

(2) Adding province fixed effects. To account for persistent inter-provincial differences in natural endowments, industrial structures, and regulatory stringency, we introduce province fixed effects. Column (2) results remain stable, eliminating omitted variable bias and correcting intra-province standard errors.

(3) Lagged policy variable: Column (3) introduces a one-period lag of the GFPZ variable, which yields even stronger coefficients, suggesting cumulative policy effects.

(4) Excluding core cities: Column (4) drops central cities from the sample. The results remain unchanged, indicating robustness to sample composition.

(5) Other environmental policies: Given potential confounding from policies such as the *Air Pollution Prevention and Control Action Plan* (APPCAP) and the *Emissions Trading Scheme Pilot* (ETS) issued in 2013, we re-estimate regressions excluding their pilot cities. Columns (5) and (6) confirm that our results are unaffected by these policies.

(6) Excluding COVID-19 years: To address potential confounding effects arising from the COVID-19 pandemic, we exclude the years 2020–2022 from the sample and re-estimate the baseline models. As reported in column (7) of Table 7, the estimated coefficient of the GFPZ policy remains close in magnitude and statistically significant relative to the full-sample results. This finding indicates that the positive effect of GFPZ on urban ecological resilience is not driven by pandemic-related shocks and remains robust after accounting for this major structural disturbance.

Table 7. Other robustness test results.

Variables	UER						
	(1) Adjusting Measurement Methods	(2) Adding Fixed Effects	(3) Lagged Effects	(4) Excluding Core City	(5) APPCAP Policy	(6) ETS Policy	(7) Excluding COVID-19 Years
GFPZ	0.2258 ** (0.1006)	0.710 *** (0.140)		0.5307 *** (0.1263)	0.3062 *** (0.1020)	0.4936 *** (0.1107)	0.549 *** (0.160)
L.GFPZ			0.636 *** (0.133)				
_Cons	−0.4884 (1.0132)	17.63 *** (2.060)	16.97 *** (2.133)	14.9854 *** (1.9179)	5.7944 ** (2.2557)	18.8023 *** (2.3400)	
Obs.	3324	3324	3047	2904	2664	2880	2493
Adj. R ²	0.917	0.966	0.968	0.949	0.938	0.929	0.980
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province F.E.	No	Yes	No	No	No	No	No

Note: ** $p < 0.05$, *** $p < 0.01$.

Across all specifications, adjusted R² values exceed 0.91, and the models consistently incorporate city fixed effects, year fixed effects, and full controls. These results further substantiate the reliability of the baseline DID findings.

4.4. Mechanism Analysis

The preceding analyses demonstrate that the GFPZ policy has significantly enhanced UER, and this conclusion has been validated through multiple identification strategies and robustness checks. Building on the established associations between green technological innovation, public environmental attention, and government environmental governance, we further test the mediating channels using the same identification framework. If GFPZ are found to significantly influence these mediators, the hypothesized pathways can be considered effective. The mechanism analysis results are shown in Table 8.

Table 8. Mechanism analysis results.

Variables	(1)	(2)	(3)	(4)
	UER	GEG	GTI	PEP
GFPZ	0.7140 *** (0.1395)	0.0629 ** (0.0297)	0.1045 ** (0.0476)	0.1398 *** (0.0496)
_Cons	17.1812 *** (2.0406)	−0.1543 (0.1931)	3.5666 *** (0.7796)	3.5773 *** (0.6935)
Obs.	3324	3324	3324	3324
Adj. R ²	0.966	0.592	0.955	0.920
Controls	Yes	Yes	Yes	Yes
City F.E.	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes

Note: ** $p < 0.05$, *** $p < 0.01$.

First, the GFPZ policy improves government environmental governance efficiency by fostering resource optimization and regulatory innovation. This enables local governments to exhibit greater effectiveness and coordination in regulatory enforcement, fiscal investment, and policy implementation, thus providing stronger institutional support for resilience enhancement.

Second, green technological innovation contributes to UER by improving resource efficiency, reducing pollutant emissions, and promoting circular economy practices. These processes strengthen cities' adaptive capacity and environmental sustainability.

Third, the GFPZ policy promotes public environmental attention by enhancing environmental information disclosure. This strengthens public awareness of ecological issues and generates bottom-up pressure for environmental protection. These demand-side forces encourage local governments to enhance regulatory stringency while inducing firms to allocate more resources toward pollution mitigation, thereby indirectly improving the institutional environment for resilience building.

Overall, the results indicate that the positive effect of GFPZ on UER operates through mediating mechanisms of green technological innovation, public attention, and government governance. The policy effects exhibit a “technology-driven, institutionally supported, behavioral response” pattern, confirming the validity of **H2**, **H3**, and **H4**.

4.5. Heterogeneity Analysis

To further investigate whether the effects of the GFPZ policy on UER vary across different city characteristics, we conduct heterogeneity analyses along three dimensions: geographic region, level of high-quality development, and industrial base. The results are reported in Table 9.

Table 9. Heterogeneity analysis results.

Variables	Geographic Region		High-Quality Development Level			Industrial Base	
	(1) Northern	(2) Southern	(3) Leading	(4) Ordinary	(5) Lagging	(6) Non-Old	(7) Old
<i>GFPZ</i>	−0.0387 (0.1655)	0.5540 *** (0.1371)	0.5279 (0.3562)	0.4290 ** (0.1817)	0.7529 *** (0.2196)	0.8324 *** (0.1782)	−0.0244 (0.1111)
_Cons	9.7852 *** (3.3847)	26.1493 *** (2.6537)	36.2618 *** (5.8134)	10.4957 *** (2.6182)	11.8829 *** (3.7106)	23.1313 *** (2.9274)	4.0490 ** (2.0263)
Obs.	1500	1824	576	1968	780	2196	1128
Adj. R ²	0.966	0.969	0.978	0.950	0.873	0.968	0.876
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: ** $p < 0.05$, *** $p < 0.01$.

4.5.1. Geographic Region

China's regions differ markedly in economic development stages, industrial structures, and ecological endowments, which may lead to regional heterogeneity in policy effects. Using the Qinling–Huaihe line as the geographical boundary, we split the sample cities into southern and northern sub-samples and re-estimated the model to examine the north–south heterogeneity in the effect of green finance on UER. As shown in columns (1) and (2) of Table 9, the GFPZ policy has the strongest positive impact on UER in southern cities. By contrast, the effect is statistically insignificant in northern cities. This result aligns with the more advanced economic and financial foundations of the southern region, while certain southern pilot cities may have relative advantages in resource endowments, policy support intensity, or project implementation capacity.

4.5.2. High-Quality Development Level

A city's development quality critically influences its capacity to absorb and translate policy measures into tangible outcomes. To examine this, we adopt the evaluation framework of Wei et al. (2018) [73] and classify cities into three tiers: leading (“star”) cities, ordinary cities, and lagging cities. Columns (3)–(5) of Table 9 show that the GFPZ policy exerts no significant effect on leading cities, but generates significant positive effects in ordinary cities and even larger, highly significant effects in lagging cities. This indicates that incremental policy effects are more salient in cities with weaker or moderate development foundations. Leading cities, already possessing high baselines, face diminishing marginal returns and therefore exhibit limited “additionality.” In contrast, ordinary and lagging cities gain greater marginal improvements in resource allocation, project acquisition, and institutional capacity, leading to more pronounced enhancements in ecological resilience.

4.5.3. Industrial Base

A city's industrial structure—particularly its historically formed industrial base—plays a critical role in shaping both its development path and its capacity to adapt to policy-induced transformation. Accordingly, we classify sample cities into old industrial base cities and non-old industrial base cities. Columns (6) and (7) of Table 9 show that the GFPZ policy has a positive and statistically significant effect on urban ecological resilience in non-old industrial base cities, whereas the estimated effects for old industrial base cities are small and statistically insignificant. This contrast suggests that cities with more flexible and diversified industrial structures are better positioned to absorb green financial resources and translate them into resilience-enhancing outcomes, while path dependence

and structural rigidities in old industrial base cities may constrain the effectiveness of green finance interventions.

4.6. Spatial Spillover Effect Analysis

To assess whether the effects of green finance policy exhibit spatial interdependence, we begin by examining the spatial autocorrelation of UER across Chinese cities. Specifically, Moran's I statistic is employed to conduct a two-level spatial dependence analysis [74]. The global Moran's I capture the overall strength of spatial correlation, while the local indicators of spatial association are used to identify heterogeneous clustering patterns.

As reported in Table 10, the global Moran's I for UER consistently exceed 0.253 throughout the sample period and are significant at the 1% level, indicating a pronounced positive spatial dependence. These values are well above the conventional benchmarks used in spatial economic analysis. The Moran scatterplots in Figure 7 provide further visual support, showing that most observations cluster in the high-high and low-low quadrants. This distribution reveals a clear pattern of spatial agglomeration, suggesting that cities with similar levels of UER tend to be geographically concentrated. This suggests the existence of "club convergence" among city clusters in resilience building. Although the intensity of clustering declined slightly between 2011 and 2022, the spatial gap in resilience has not fundamentally narrowed, and pronounced regional disparities persist [75].

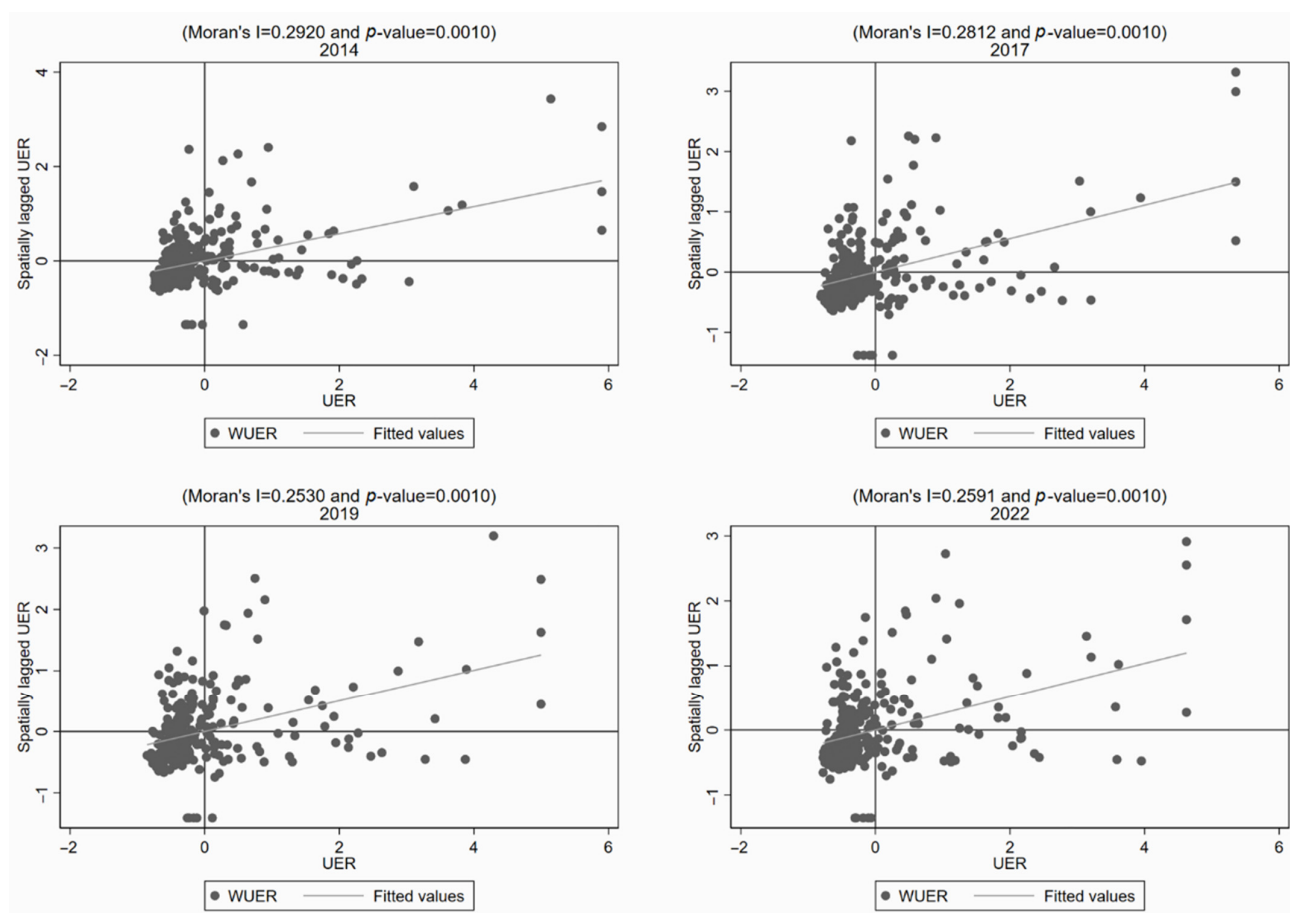


Figure 7. Scatterplots of UER in China between 2011 and 2022.

Within a spatial econometric framework, the effects of GFPZ policy on UER can be decomposed into local direct effects and regional spillover effects. As shown in Table 11, after accounting for spatial dependence, GFPZ implementation is positively associated with ecological resilience in pilot cities, and this pattern remains consistent under the

spatial Durbin model specification, suggesting that the estimated relationship is not driven by omitted spatial interactions. In contrast, the indirect effect on neighboring non-pilot cities is negative, leading to a negative total effect, which points to the presence of adverse spillovers [76].

Table 10. Moran's I of UER in China from 2011 to 2022.

Variables	Moran's I	EP	Std.	Z-Score	p-Value
2011	0.303	−0.004	0.040	7.724	0.000
2012	0.286	−0.004	0.040	7.287	0.000
2013	0.304	−0.004	0.040	7.745	0.000
2014	0.292	−0.004	0.040	7.426	0.000
2015	0.299	−0.004	0.040	7.583	0.000
2016	0.289	−0.004	0.040	7.316	0.000
2017	0.281	−0.004	0.040	7.105	0.000
2018	0.260	−0.004	0.040	6.543	0.000
2019	0.253	−0.004	0.040	6.366	0.000
2020	0.256	−0.004	0.040	6.453	0.000
2021	0.256	−0.004	0.040	6.420	0.000
2022	0.259	−0.004	0.040	6.504	0.000

Table 11. Estimation results of spatial DID model.

Variables	Direct	Indirect	Total
	(1)	(2)	(3)
<i>GFPZ</i>	0.775 *** (0.187)	−1.654 *** (0.443)	−0.879 * (0.480)
<i>FDI</i>	0.0362 (0.0626)	−0.0475 (0.121)	−0.0113 (0.135)
<i>AGDP</i>	−0.726 *** (0.122)	−0.574 *** (0.201)	−1.300 *** (0.246)
<i>Ind</i>	−0.0152 (0.0852)	0.0532 (0.172)	0.0380 (0.177)
<i>Fin</i>	−0.530 *** (0.0426)	0.0859 (0.0733)	−0.444 *** (0.0837)
<i>DEN</i>	−0.00114 *** (0.000358)	2.60×10^{-5} (0.000831)	−0.00111 (0.000885)
<i>Gov</i>	0.140 (0.290)	−0.686 (0.532)	−0.545 (0.611)
<i>REV</i>	−0.0121 (0.00998)	−0.0148 (0.0194)	−0.0269 (0.0207)
<i>rho</i>	−0.0725 *** (0.0268)		
Obs.	3324	3324	3324
R ²	0.100	0.100	0.100
N	277	277	277
LM Error	216.667 ***		
LM Error (Robust)	278.286 ***		
LM Lag	12.867 ***		
LM Lag (Robust)	74.486 ***		
LR-SAR	51.42 ***		
LR-SEM	51.57 ***		
Wald-SAR	52.14 ***		
Wald-SEM	54.96 ***		

Note: * $p < 0.1$, *** $p < 0.01$.

Possible explanations include the spatial concentration of green financial resources and technologies within pilot cities, which may intensify inter-regional competition, the relocation of pollution-intensive activities to surrounding areas with relatively weaker environmental regulation, and factor market siphoning effects that constrain neighboring cities' capacity for green development.

4.7. Policy Convergence Analysis

In China's governance context of "multiple overlapping policies", the effect of a single policy is often magnified, offset, or reshaped by subsequent or parallel policies [77]. According to policy convergence theory, when different policy instruments target the same governance objective, their interactive effects may be synergistic, antagonistic, or neutral, depending on the degree of functional complementarity, goal alignment, and resource interdependence [78]. However, existing studies tend to focus on single-policy evaluations, paying insufficient attention to the combined effects of policy portfolios, which risks either overestimating or underestimating actual governance performance [79].

Following the release of the *Action Plan for Promoting Big Data Development* in August 2015, China approved two waves of provinces—ten in total—to establish *National Big Data Comprehensive Pilot Zones* (NDPZ). Within the digital economy, data have increasingly emerged as a strategic production factor, generating agglomeration effects that can reshape both economic structures and environmental governance systems. NDPZ are therefore particularly well suited for examining policy synergies with green finance, as they possess distinctive strengths in digital infrastructure development and data-driven financial innovation. Compared with other pilot initiatives, NDPZ place greater emphasis on cross-sectoral coordination, enabling closer integration between green finance, environmental regulation, and technological innovation policies [80]. Additionally, NDPZ policy has strong scalability and replicability, and once successfully implemented, they can serve as a model for nationwide green finance development [81]. This raises the need to investigate the overlapping effects of the GFPZ policy and the NDPZ policy.

Theoretically, NDPZ, through data openness and institutional innovation, reduce information asymmetry and transaction costs in green projects. Green finance capital, in turn, channels additional investment into technology, forming a closed "data-finance" feedback loop. Moreover, resource-based cities in central and western China may leverage digital infrastructure to overcome financing gaps and exploit latecomer advantages, thereby breaking through the diminishing marginal returns of single policy [82].

We conduct empirical analysis to examine the individual and combined effects of GFPZ and NDPZ policies on UER. The estimation process mirrors the baseline regressions but emphasizes the coefficients of the dual-pilot policy. Table 12 reports the results: column (1) presents the regression estimates of GFPZ alone, column (2) of NDPZ alone, column (3) of the dual-pilot policy, and column (4) excludes "non-pilot" cities from the sample used in column (3). The findings show that, although the NDPZ policy alone does not exert a significant positive impact on UER, the dual-pilot policy has a strong and significant effect. A possible explanation is that, during the initial phase of NDPZ implementation, e-waste, raw-material extraction, and pollutant emissions from digital infrastructure construction negatively impacted the ecosystem. In contrast, during the policy synergy phase, these digital capabilities are channeled through green-finance and fiscal-transfer mechanisms into green-infrastructure investment and ecological-restoration projects, simultaneously reducing emissions and enhancing carbon sinks, thereby significantly improving UER. The coefficients for the dual-pilot policy are 1.1957 and 1.1655, substantially larger than the baseline estimate of 0.714, indicating that policy combinations can significantly enhance UER.

Table 12. Policy convergence analysis results.

Variables	UER			
	(1)	(2)	(3)	(4)
	GFPZ	NDPZ	Dual-Pilot 1	Dual-Pilot 2
GFPZ	0.7140 *** (0.1395)			
NDPZ		−0.1204 * (0.0692)		
Dual			1.1957 *** (0.2912)	1.1655 *** (0.3220)
_Cons	17.1812 *** (2.0406)	16.8506 *** (2.0540)	17.6767 *** (2.0715)	13.6084 *** (2.2205)
Obs.	3324	3324	3324	1020
Adj. R ²	0.966	0.966	0.966	0.989
Controls	Yes	Yes	Yes	Yes
City F.E.	Yes	Yes	Yes	Yes
Year F.E.	Yes	Yes	Yes	Yes

Note: * $p < 0.1$, *** $p < 0.01$.

5. Discussion

Green finance has increasingly been recognized as a pivotal instrument for advancing ecological civilization and urban sustainability. Rather than operating solely as a channel for environmental investment, green finance reshapes governance structures, policy incentives, and development trajectories. By leveraging China's GFPZ as a quasi-experimental setting, this study situates green finance within a dynamic institutional context and examines its role in shaping UER. Consistent with recent governance-oriented perspectives [83], our findings suggest that green finance should not be understood as a narrowly defined financial intervention; instead, it functions as a systemic governance mechanism that reconfigures institutional capacities, technological pathways, and social behaviors within urban socio-ecological systems. This perspective extends existing research by shifting the analytical focus from isolated environmental performance indicators to resilience as an integrated, adaptive, and forward-looking property of urban development.

A central theoretical contribution of this study lies in articulating an institutional–technological–behavioral mechanism framework through which green finance enhances UER. Beyond expanding capital availability, green finance operates as a governance signal that strengthens regulatory credibility, aligns market expectations, and improves policy execution capacity, echoing arguments in the institutional finance and sustainability literature [83]. By lowering barriers to green technological innovation, accelerating the diffusion of environmentally friendly practices, and enhancing environmental information disclosure and public participation, green finance fosters coordinated adjustments across institutional, technological, and behavioral dimensions. This multi-layered mechanism moves beyond single-channel explanations commonly emphasized in prior studies and highlights resilience as an emergent outcome of multi-actor governance interactions rather than a by-product of environmental investment alone. The heterogeneous effects observed across regions, development stages, and industrial structures further support the view that institutional flexibility and governance capacity condition the effectiveness of green finance, reinforcing the importance of place-based and differentiated policy design [84].

The spatial dimension of green finance reveals important trade-offs that complicate overly optimistic expectations of universal positive spillovers. The identification of significant negative spatial spillovers associated with GFPZ implementation suggests the presence of a policy-induced “siphon effect,” whereby the concentration of green financial

resources, technological inputs, and skilled labor in pilot cities may weaken neighboring cities' access to these critical factors. Similar dynamics have been documented in studies on regional development and innovation policies, which show that growth poles and policy-favored regions can impose adjustment pressures and unintended ecological or innovation losses on surrounding areas [85–87]. These findings challenge the assumption that green finance inherently generates benign spatial diffusion effects and demonstrate that UER is relational in nature, shaped by inter-city competition, factor mobility, and uneven institutional capacities rather than confined within administrative boundaries.

It is important to emphasize that, although the spatial econometric results robustly establish the existence and direction of these spillovers, the use of city-level aggregate data does not permit direct identification of specific transmission channels, such as capital reallocation, talent migration, or industrial relocation. Accordingly, the siphon effect should be interpreted as an outcome-consistent mechanism rather than a fully decomposed causal pathway. This interpretation aligns with existing empirical studies that infer spatial externalities from aggregate patterns while acknowledging micro-level complexity [85,86]. From a policy perspective, these findings underscore the necessity of embedding cross-regional coordination instruments—such as ecological compensation schemes, joint green investment platforms, and inter-city policy alignment—into green finance frameworks to mitigate uneven spatial outcomes and promote collective ecological resilience.

The analysis of policy interactions further strengthens the study's contribution by demonstrating that green finance achieves its strongest resilience effects when embedded within complementary institutional environments. The significant synergy between GFPZ and the NDPZ illustrates how digital infrastructure enhances the informational efficiency and governance capacity of green finance. By reducing information asymmetry, lowering transaction costs, and improving project screening and monitoring, big data technologies amplify the effectiveness of green financial capital and reinforce innovation-driven resilience pathways. This finding is consistent with the growing literature on policy portfolios and institutional complementarity, which emphasizes that sustainability-oriented policies are most effective when designed as mutually reinforcing systems rather than isolated interventions [87].

Several methodological considerations warrant attention and point to promising avenues for future research. Although the staggered DID design strengthens causal inference, reliance on city-level aggregate data limits direct observation of firm- and household-level behavioral responses. In addition, while the spatial Durbin model captures key inter-city dependence, results may be sensitive to the specification of spatial weight matrices and may not fully reflect nonlinear or network-based interactions emphasized in recent spatial governance research [87]. Future studies could address these limitations by incorporating micro-level data on financial flows, labor mobility, and technological networks, as well as alternative spatial or network modeling approaches. Such extensions would allow for a more fine-grained examination of how green finance policy can reshape UER dynamics over time and across regions, thereby further advancing both theory and policy design in the field of sustainable urban governance.

6. Conclusions and Policy Implications

6.1. Conclusions

Green finance has become a key driver of ecological civilization and urban sustainability, with growing relevance for advancing environmental governance and supporting low-carbon transitions. Exploiting China's GFPZ policy as a quasi-natural experiment, this study examines the impact of green finance on UER and explores the mechanisms through which these effects materialize. Using a staggered DID approach and panel data from

277 Chinese cities over the period 2011–2022, we find robust evidence that the GFPZ policy significantly enhances UER. Relative to non-pilot cities, pilot cities experience sustained and substantial improvements in ecological resilience.

Beyond establishing the average treatment effect, this study demonstrates that green finance strengthens UER not through simple capital expansion, but through a compound governance mechanism characterized by institutional reinforcement, technological empowerment, and behavioral guidance. These findings underscore that effective environmental governance requires more than isolated economic incentives. Instead, green finance functions as an institutional innovation that reshapes capital allocation incentives, enhances local governments' environmental governance capacity, lowers entry barriers for green technologies, and guides the environmental preferences of firms and the public through signaling and rule-setting mechanisms. In this sense, green finance contributes to resilience by fostering coordinated adjustments across market actors, public institutions, and society, rather than by improving environmental performance alone.

The heterogeneity analysis provides a more nuanced understanding of where and under what conditions green finance is most effective. The policy effects are significantly stronger in southern regions, non-old industrial base cities, and cities with moderate development levels. This pattern suggests that green finance tends to deliver the greatest marginal benefits in contexts characterized by stronger institutional foundations, lower structural inertia, and greater scope for environmental improvement. These results provide empirical support for differentiated, place-based green finance strategies and caution against uniform policy implementation across regions with divergent development stages and industrial endowments.

At the same time, the spatial analysis reveals an important governance challenge. While the GFPZ policy generates substantial local gains in ecological resilience, it also produces negative spatial spillover effects that may exacerbate regional disparities. This finding carries both theoretical and practical implications. From a theoretical perspective, it highlights that UER is not solely a city-level attribute but a relational outcome shaped by inter-city interactions and factor mobility. From a policy perspective, it suggests that resilience-oriented strategies focused narrowly on individual cities risk shifting environmental pressures to neighboring regions. Addressing this tension requires embedding green finance within cross-regional coordination frameworks, including ecological compensation mechanisms and collaborative development arrangements, to promote collective improvements in resilience rather than localized gains.

Several limitations of this study point to promising avenues for future research. First, although multiple transmission channels are identified, further work is needed to examine the interaction intensity and boundary conditions among institutional, technological, and behavioral mechanisms. Second, while the spatial Durbin model captures key inter-city dependencies, results may be sensitive to the specification of spatial weight matrices and may not fully reflect complex, nonlinear, or network-based spatial interactions. Future studies could employ alternative spatial or network models and micro-level data to better identify both negative and positive spatial transmission channels, such as knowledge and technology spillovers. Finally, although this study documents strong synergies between green finance and digital economy policies, determining which combinations of policy instruments best balance local development objectives with regional equity remains an open question. Addressing this issue will require comparative policy analyses and simulation-based approaches to inform the design of integrated and equitable resilience strategies.

6.2. Policy Implications

Building on the findings, this study offers the following policy implication.

First, expand the coverage of green finance pilots and strengthen national-level institutional support. National authorities, including the *People's Bank of China* and the *Ministry of Ecology and Environment*, should further scale up green finance instruments—such as green credit, bonds, and funds—by extending pilot programs from major cities to medium- and small-sized cities with growth potential. Complementary fiscal subsidies, tax incentives, and risk-sharing mechanisms can lower financing barriers and broaden participation by financial institutions and firms. Such an expansion would accelerate capital flows toward clean energy and environmental industries, facilitate industrial upgrading, improve resource-use efficiency, and ultimately reinforce UER.

Second, enhance local governments' capacity for policy transmission and implementation. To ensure that green finance effectively translates into resilience-enhancing outcomes, local governments should establish standardized green project databases and robust performance evaluation systems to guide financial decision-making. Strengthening green certification and information disclosure mechanisms is essential to improve transparency, support public oversight, and reduce the risk of greenwashing. In addition, policy instruments should be tailored to local industrial structures and development conditions, improving adaptability, and enabling green capital to flow more efficiently into high-quality projects that support long-term ecological resilience.

Third, adopt differentiated strategies to reflect regional and structural heterogeneity. Given the heterogeneous effects identified in the empirical analysis, green finance policy should avoid one-size-fits-all implementation. Southern cities can leverage relatively mature green finance markets to innovate and diffuse financial instruments, reinforcing demonstration and spillover effects. In contrast, northern regions require stronger support for industrial restructuring and green-sector development through fiscal guidance funds, differentiated credit incentives, and targeted industrial policies. At the industrial level, non-old industrial base cities can more readily absorb green financial resources, while old industrial base cities should prioritize technological upgrading and institutional reform to overcome high-carbon path dependence. Such differentiated strategies can enhance policy effectiveness and reduce regional disparities.

Fourth, mitigate negative spillovers and strengthen regional collaborative governance. Although the GFPZ policy enhances local ecological resilience, they may also shift environmental pressures to neighboring cities. To address this challenge, cross-regional ecological compensation mechanisms should be established to equitably share the costs associated with industrial relocation and environmental adjustment. At the same time, facilitating the cross-regional flow of green finance and green technologies can help prevent resource siphoning. Regional coordination bodies should be empowered to align environmental targets, coordinate investment, and project approval standards, and jointly evaluate resilience outcomes. These measures would ensure that resilience gains in pilot cities do not generate unintended burdens elsewhere, promoting more balanced and cooperative green transitions.

Finally, integrate green finance with digital strategies to maximize policy synergies. Policymakers should actively promote the convergence of green finance initiatives with digital strategies, such as big data pilot zones. Digital technologies can reduce transaction costs, enhance risk identification, and improve project monitoring, while green finance can channel capital toward data-enabled innovation and green infrastructure. By linking digital monitoring systems with cross-city coordination mechanisms, policymakers can further enhance the effectiveness of green finance interventions and mitigate negative spatial spillovers. Such integration would transform green finance from a single-policy instrument

into a component of a broader governance system, generating sustained improvements in urban ecological resilience.

Although these policy implications are derived from the Chinese experience, they carry broader relevance. International practices—such as the *EU Sustainable Finance Action Plan* and the *Green Bond Principles* promoted by the *International Capital Market Association*—demonstrate that coordinated policy frameworks, differentiated regional support, and integration with digital monitoring can effectively mobilize private capital for climate adaptation and ecological resilience. These experiences suggest that the mechanisms identified in this study—regional coordination, policy differentiation, and digital–financial integration—can enhance the effectiveness of green finance across diverse institutional contexts.

Author Contributions: Conceptualization, X.Z., Z.L. and Z.P.; Methodology, Y.D.; Software, Y.D.; Data Curation, Y.D.; Formal Analysis, X.Z., Z.L. and Z.P.; Validation, X.Z.; Visualization, Y.D.; Writing—Original Draft, Y.D.; Writing—Review and Editing, X.Z., Z.L. and Z.P.; Supervision, Z.L. and Z.P.; Funding Acquisition, X.Z. and Z.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant Nos. 72564014 and 72064005); and the Natural Science Foundation of Guangxi Province (Grant No. 2020GXNSFAA159041).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. VIF test results.

Variable	VIF	1/VIF
FDI	3.63	0.275767
Gov	3.13	0.319033
Fin	2.13	0.469690
Ind	2.00	0.499581
AGDP	1.67	0.600315
DEN	1.49	0.669506
REV	1.18	0.850785
Mean VIF	2.18	

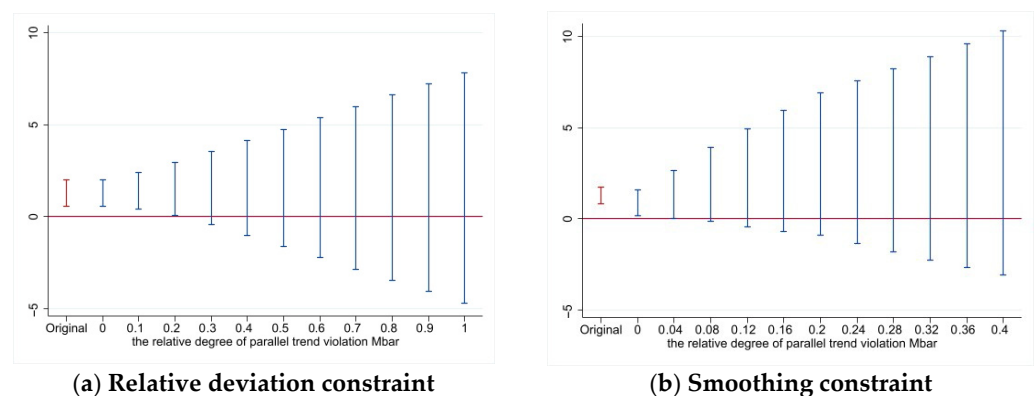


Figure A1. Analysis of sensitivity of confidence intervals for non-linear pre-trends.

Table A2. Data sources and indicator weights.

System Layer	Index Layer	Calculation Method	EWM Weights	CRITIC Weights	Data Source
Driving Force	Urbanization rate	Urban population $\div$ total population	0.0193	0.0872	Statistical Yearbooks from the National Bureau of Statistics and Local Bureaus
	Total retail sales of consumer goods	Revenue from retail sales and catering services	0.1588	0.0551	China City Statistical Yearbook
Pressure	Per capita industrial sulfur dioxide emissions	Total industrial SO ₂ emissions $\div$ total permanent population	0.0008	0.0514	China City Statistical Yearbook
	Per capita daily water consumption	Average daily domestic water consumption per urban resident	0.0038	0.0883	China Urban Construction Statistical Yearbook
	Per capita built-up area	Built-up area $\div$ total permanent population	0.0004	0.0167	China City Statistical Yearbook
State	Per capita water resources	Total local water resources $\div$ total permanent population	0.0029	0.0475	China City Statistical Yearbook
	Green coverage in built-up areas	Vegetation coverage area $\div$ total built-up area	0.0032	0.0167	China City Statistical Yearbook
	Per capita park green spaces	Public green space area $\div$ urban population	0.1363	0.0398	China Urban Construction Statistical Yearbook
Impact	Carbon intensity	CO ₂ emissions $\div$ GDP	0.0031	0.1041	EDGAR Database
	R&D expenditure	Total expenditure on research and experimental development	0.3343	0.0323	China City Statistical Yearbook
	R&D personnel	Number of employees engaged in research and experimental development	0.2604	0.0446	China City Statistical Yearbook
	Industrial value added	Gross industrial output – intermediate inputs + value-added tax payable	0.0027	0.0704	China City Statistical Yearbook
Response	Share of environmental protection expenditure	Environmental protection expenditure $\div$ total fiscal expenditure	0.0359	0.0654	Local Statistical Yearbooks
	Disposal rate of municipal solid waste	Harmlessly treated household waste $\div$ total household waste	0.0036	0.0989	China City Statistical Yearbook
	Centralized sewage treatment rate	Sewage treated by centralized plants $\div$ total sewage discharge	0.0047	0.0836	China City Statistical Yearbook
	Built-up area green space	Total green space area within built-up areas	0.0051	0.0167	China Urban Construction Statistical Yearbook
	Industrial solid waste utilization rate	Utilized industrial solid waste $\div$ total industrial solid waste	0.0247	0.0278	China City Statistical Yearbook

Table A3. CRITIC-based benchmark regression results.

Variables	UER	
	(1) CRITIC-Based	(2) PCA-Based
GFPZ	0.00686 *** (0.00153)	0.2258 ** (0.1006)
_Cons	0.464 *** (0.0835)	−0.4884 (1.0132)
Obs.	3324	3324
Adj. R ²	0.944	0.917
Controls	Yes	Yes
City F.E.	Yes	Yes
Year F.E.	Yes	Yes

Note: ** $p < 0.05$, *** $p < 0.01$.

References

1. IPCC. *Climate Change 2022: Impacts, Adaptation and Vulnerability*; Cambridge University Press: Cambridge, UK, 2022; pp. 912–916.
2. Sharifi, A. Resilience of urban social–ecological–technological systems (SETS): A review. *Sustain. Cities Soc.* **2023**, *99*, 104910. [[CrossRef](#)]
3. Meerow, S.; Newell, J.P.; Stults, M. Defining urban resilience: A review. *Landsc. Urban Plan.* **2016**, *147*, 38–49. [[CrossRef](#)]
4. Feng, X.; Zeng, F.; Loo, B.P.Y.; Zhong, Y. The evolution of urban ecological resilience: An evaluation framework based on vulnerability, sensitivity and self-organization. *Sustain. Cities Soc.* **2024**, *116*, 105933. [[CrossRef](#)]
5. Lee, C.-C.; Yan, J.; Li, T. Ecological resilience of city clusters in the middle reaches of Yangtze River. *J. Clean. Prod.* **2024**, *443*, 141082. [[CrossRef](#)]
6. Ningrum, D.; Malekpour, S.; Raven, R.; Moallemi, E.A. Lessons learnt from previous local sustainability efforts to inform local action for the Sustainable Development Goals. *Environ. Sci. Policy* **2022**, *129*, 45–55. [[CrossRef](#)]
7. Zhang, Z.; Zhu, J.; Yang, L.; Chen, L. Booster or inhibitor: Diagnosing effect of low-carbon pilot city policies on urban resilience from the perspectives of heterogeneity, mechanisms and spillover. *J. Clean. Prod.* **2024**, *474*, 143587. [[CrossRef](#)]
8. Xu, C.; Huo, X.; Hong, Y.; Yu, C.; de Jong, M.; Cheng, B. How do urban greening policies affect urban ecological resilience? Quasi-natural experimental evidence from three mega-urban agglomerations in China. *J. Clean. Prod.* **2024**, *452*, 142233. [[CrossRef](#)]
9. Wu, H. Trade openness, green finance and natural resources: A literature review. *Resour. Policy* **2022**, *78*, 102801. [[CrossRef](#)]
10. Xu, T.; Yang, G.; Chen, T. The role of green finance and digital inclusive finance in promoting economic sustainable development: A perspective from new quality productivity. *J. Environ. Manag.* **2024**, *370*, 122892. [[CrossRef](#)]
11. Garber, S.; Hammitt, J.K. Risk Premiums for Environmental Liability: Does Superfund Increase the Cost of Capital? *J. Environ. Econ. Manag.* **1998**, *36*, 267–294. [[CrossRef](#)]
12. International Capital Market Association (ICMA). *Green Bond Principles (GBP)*; ICMA: Zurich, Switzerland, 2025.
13. European Commission. *Action Plan: Financing Sustainable Growth*; European Commission: Brussels, Belgium, 2018.
14. Han, L.; Li, J. Does green finance reform promote corporate carbon emission reduction? Evidence from China's green finance reform and innovation pilot zones. *Econ. Anal. Policy* **2025**, *85*, 2091–2111. [[CrossRef](#)]
15. Zhao, R.; Fang, C.; Liu, H.; Liu, X. Evaluating urban ecosystem resilience using the DPSIR framework and the ENA model: A case study of 35 cities in China. *Sustain. Cities Soc.* **2021**, *72*, 102997. [[CrossRef](#)]
16. Li, Q.; Ge, J.; Zhang, X.; Wu, X.; Fan, H.; Yang, L. Assessment of the interaction between digital infrastructure and ecological resilience: Insights from Yangtze River Delta Urban Agglomeration in China. *J. Clean. Prod.* **2025**, *486*, 144364. [[CrossRef](#)]
17. Peng, J.; Liu, Y.; Wu, J.; Lv, H.; Hu, X. Linking ecosystem services and landscape patterns to assess urban ecosystem health: A case study in Shenzhen City, China. *Landsc. Urban Plan.* **2015**, *143*, 56–68. [[CrossRef](#)]
18. Wang, H.; Ge, Q. Ecological resilience of China's three major urban agglomerations from the perspective of environment–society coupling. *Ecol. Indic.* **2024**, *169*, 112944. [[CrossRef](#)]
19. Wang, Y.; Cai, Y.; Xie, Y.; Chen, L.; Zhang, P. A comprehensive approach for assessing the dynamics of urban ecological resilience in Chinese urban agglomerations. *Ecol. Indic.* **2023**, *146*, 109859. [[CrossRef](#)]
20. Xiong, S.W.; Yang, F. Ecological resilience in water-land transition zones: A case study of the Dongting Lake region, China. *Ecol. Indic.* **2024**, *166*, 112284. [[CrossRef](#)]
21. Yan, C.; Mao, Z.; Ho, K.-C. Effect of green financial reform and innovation pilot zones on corporate investment efficiency. *Energy Econ.* **2022**, *113*, 106185. [[CrossRef](#)]

22. Zhang, T. Can green finance policies affect corporate financing? Evidence from China's green finance innovation and reform pilot zones. *J. Clean. Prod.* **2023**, *419*, 138289. [\[CrossRef\]](#)
23. Sun, Y.; Li, T.; Mehmood, U. Balancing acts: Assessing the roles of renewable energy, economic complexity, fintech, green finance, green growth, and economic performance in G-20 countries amidst sustainability efforts. *Appl. Energy* **2025**, *378*, 124846. [\[CrossRef\]](#)
24. Shen, M.; Ma, N.; Qian, C. Has green finance policy promoted ecologically sustainable development under the constraints of government environmental attention? *J. Clean. Prod.* **2024**, *450*, 141854. [\[CrossRef\]](#)
25. Jiang, Q.; Cheng, S. Conflict or coordination? The cross-departmental interactions in local environmental governance of China. *Environ. Res.* **2024**, *260*, 119657. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Zhang, M.; Yang, Y.; Du, P.; Wang, J.; Wei, Y.; Qin, J.; Yu, L. The effect of public environmental participation on pollution governance in China: The mediating role of local governments' environmental attention. *Environ. Impact Assess. Rev.* **2024**, *104*, 107345. [\[CrossRef\]](#)
27. Shi, P.; Huang, Q. Alignment of words and actions? Government environmental attention and enterprise digital transformation. *Technol. Forecast. Soc. Change* **2025**, *210*, 123888. [\[CrossRef\]](#)
28. Zhao, X.; Lu, S.; Yuan, S. How does digitalization of government environmental governance affect environmental pollution? Spatial effects and threshold effects. *J. Clean. Prod.* **2023**, *415*, 137670. [\[CrossRef\]](#)
29. Zhang, G.; Wang, Y.; Zhang, Z.; Su, B. Can green finance policy promote green innovation in cities? Evidence for green finance reform and innovation in China. *J. Environ. Manag.* **2024**, *370*, 122816. [\[CrossRef\]](#)
30. Liu, S.; Wang, Y. Green innovation effects of green finance reform pilot zones: Evidence from a quasi-natural experiment. *Technol. Forecast. Soc. Change* **2023**, *186*, 122079. [\[CrossRef\]](#)
31. Bai, R.; Lin, B. Nexus between green finance development and green technological innovation: A potential way to achieve the renewable energy transition. *Renew. Energy* **2023**, *218*, 119295. [\[CrossRef\]](#)
32. Cui, X.; Fu, B.; Chen, Y.; Bai, S. Bridging digital and ecological resilience: Spatiotemporal dynamics and coordinated development paths in the Yellow River "inverted U-shaped" metropolitan belt. *J. Environ. Manag.* **2025**, *388*, 125990. [\[CrossRef\]](#)
33. Wang, Y.; Shi, M.; Zhao, Z.; Liu, J.; Zhang, S. How does green finance improve the total factor energy efficiency? Capturing the mediating role of green management innovation and embodied technological progress. *Energy Econ.* **2025**, *142*, 108157. [\[CrossRef\]](#)
34. Liu, Y.; Peng, Y.; Wang, W.; Liu, S.; Yin, Q. Does the pilot zone for green finance reform and innovation policy improve urban green total factor productivity? The role of digitization and technological innovation. *J. Clean. Prod.* **2024**, *471*, 143365. [\[CrossRef\]](#)
35. Wang, Y.F.; Shi, M.; Liu, J.N.; Huang, H.H.; Yu, K. Environmental pollution management effects of technological convergence between digital and real economy industries: A perspective of tripartite co-governance by company, government and public. *J. Clean. Prod.* **2025**, *501*, 145201. [\[CrossRef\]](#)
36. Zhao, X.; Li, S. Artificial intelligence and public environmental concern: Impacts on green innovation transformation in energy-intensive enterprises. *Energy Policy* **2025**, *198*, 114469. [\[CrossRef\]](#)
37. Gao, Q.Q.; Sui, X.Z.; Gu, C. Constructing government attention through policy synergy in China's haze governance. *J. Environ. Manag.* **2025**, *380*, 125118. [\[CrossRef\]](#)
38. Jiang, Y.; Xiao, Y.; Zhang, Z.; Zhao, S. How do central-local interactions affect local environmental governance? Insights from the transformation of central environmental protection inspection in China. *Environ. Res.* **2024**, *243*, 117668. [\[CrossRef\]](#)
39. Krugman, P. *Geography and Trade*; MIT Press: Cambridge, MA, USA, 1991.
40. Jaffe, A.B.; Newell, R.G.; Stavins, R.N. Technological change and the environment. In *Environmental Economics: Selected Readings*; Portney, P., Stavins, R.N., Eds.; University of Chicago Press: Chicago, IL, USA, 2003; pp. 206–232.
41. Kiso, T. Environmental policy and induced technological change: Evidence from automobile fuel economy regulations. *Environ. Resour. Econ.* **2019**, *74*, 785–810. [\[CrossRef\]](#)
42. Zhang, C.; Wang, C.; Jin, H.; Xu, M.; Balezentis, T.; Agnusdei, L. The impact of green finance on energy transition and carbon emission targets: Exploring the double threshold and spatial spillover effects among the regions. *Struct. Change Econ. Dyn.* **2025**, *73*, 1–10. [\[CrossRef\]](#)
43. Liu, Y.; Huang, H.; Mbanyele, W.; Li, X.; Balezentis, T. Harnessing supply chain digital innovation for enhanced corporate environmental practices and sustainable growth. *Energy Econ.* **2025**, *142*, 108161. [\[CrossRef\]](#)
44. Zhao, X.; Lynch, J.G.; Chen, Q. Reconsidering Baron and Kenny: Myths and truths about mediation analysis. *J. Consum. Res.* **2010**, *37*, 197–206. [\[CrossRef\]](#)
45. Chen, H.; Xu, J.; Zhang, K.; Guo, S.; Lv, X.; Mu, X.; Yang, L.; Song, Y.; Hu, X.; Ma, Y.; et al. New insights into the DPSIR model: Revealing the dynamic feedback mechanism and efficiency of ecological civilization construction in China. *J. Clean. Prod.* **2022**, *348*, 131377. [\[CrossRef\]](#)
46. Svarstad, H.; Petersen, L.K.; Rothman, D.; Siepel, H.; Wätzold, F. Discursive biases of the environmental research framework DPSIR. *Land Use Policy* **2008**, *25*, 116–125. [\[CrossRef\]](#)

47. Lewison, R.L.; Rudd, M.A.; Al-Hayek, W.; Baldwin, C.; Beger, M.; Lieske, S.N.; Jones, C.; Satumanatpan, S.; Junchompoo, C.; Hines, E. How the DPSIR framework can be used for structuring problems and facilitating empirical research in coastal systems. *Environ. Sci. Policy* **2016**, *56*, 110–119. [\[CrossRef\]](#)
48. Troian, A.; Gomes, M.C.; Tiecher, T.; Berbel, J.; Gutiérrez-Martín, C. The Drivers-Pressures-State-Impact-Response Model to Structure Cause–Effect Relationships between Agriculture and Aquatic Ecosystems. *Sustainability* **2021**, *13*, 9365. [\[CrossRef\]](#)
49. Wei, Y.; Zhu, X.; Li, Y.; Yao, T.; Tao, Y. Influential factors of national and regional CO₂ emission in China based on combined model of DPSIR and PLS-SEM. *J. Clean. Prod.* **2019**, *212*, 698–712. [\[CrossRef\]](#)
50. Gao, X.; Zhang, G.; Zhang, Z.; Wei, Y.; Liu, D.; Chen, Y. How does new energy demonstration city pilot policy affect carbon dioxide emissions? Evidence from a quasi-natural experiment in China. *Environ. Res.* **2024**, *244*, 117912. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Abolhassani, A.; Rahimikollu, J.; Gopalakrishnan, B. Towards a cleaner future: A novel approach to enhance energy efficiency in the US manufacturing industry with fuzzy logic-TOPSIS. *Energy* **2025**, *322*, 135594. [\[CrossRef\]](#)
52. Shi, C.; Guo, N.; Gao, X.; Wu, F. How Carbon Emission Reduction Is Going to Affect Urban Resilience. *J. Clean. Prod.* **2022**, *372*, 133737. [\[CrossRef\]](#)
53. Wang, Z.; Deng, X.; Wong, C.; Li, Z.; Chen, J. Learning Urban Resilience from a Social-Economic-Ecological System Perspective: A Case Study of Beijing from 1978 to 2015. *J. Clean. Prod.* **2018**, *183*, 343–357. [\[CrossRef\]](#)
54. He, W.; Zhang, J.; Wei, Z.; Gao, W.; Zhang, P.; Qu, N. Integrating Carbon Reduction and Ecological Resilience Strategies in the Silk Road Economic Corridor. *Heliyon* **2024**, *10*, e39582. [\[CrossRef\]](#)
55. Chu, E.; Sun, H.; Li, Y. Study on the Impact of Smart City Construction on Ecological Environment Resilience. *J. Manag.* **2023**, *36*, 21–37. (In Chinese)
56. Li, G.; Wang, L. Study of Regional Variations and Convergence in Ecological Resilience of Chinese Cities. *Ecol. Indic.* **2023**, *154*, 110667. [\[CrossRef\]](#)
57. Wang, H.; Wei, W. Coordinating technological progress and environmental regulation in CO₂ mitigation: The optimal levels for OECD countries & emerging economies. *Energy Econ.* **2020**, *87*, 104510. [\[CrossRef\]](#)
58. Zhang, Z.; Shang, Y.; Zhang, G.; Shao, S.; Fang, J.; Li, P.; Song, S. The pollution control effect of the atmospheric environmental policy in autumn and winter: Evidence from the daily data of Chinese cities. *J. Environ. Manag.* **2023**, *343*, 118164. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Liu, X.; Wang, C.; Wu, H.; Yang, C.; Albitar, K. The impact of the new energy demonstration city construction on energy consumption intensity: Exploring the sustainable potential of China's firms. *Energy* **2023**, *283*, 128716. [\[CrossRef\]](#)
60. Xu, L.; Wu, Y. Nexus between green finance, renewable energy and carbon emission: Empirical evidence from selected Asian economies. *Renew. Energy* **2023**, *215*, 118983. [\[CrossRef\]](#)
61. Tao, M.; Poletti, S.; Wen, L.; Sheng, M.S. Modelling the role of industrial structure adjustment on China's energy efficiency: Insights from technology innovation. *J. Clean. Prod.* **2024**, *441*, 140861. [\[CrossRef\]](#)
62. Li, H.; Zhu, X.; Chen, J.; Jiang, F. Environmental regulation, environmental governance efficiency and green transformation of China's iron and steel enterprises. *Ecol. Econ.* **2019**, *165*, 106397. [\[CrossRef\]](#)
63. Wang, H.; Guo, J. A new pathway out of the efficiency–equity dilemma: Digital technology enabling local government environmental governance. *Technol. Forecast. Soc. Change* **2024**, *200*, 123184. [\[CrossRef\]](#)
64. Kong, G.; Wang, S.; Wang, Y. Fostering firm productivity through green finance: Evidence from a quasi-natural experiment in China. *Econ. Model.* **2022**, *115*, 105979. [\[CrossRef\]](#)
65. Zhou, B.; Ding, H. How public attention drives corporate environmental protection: Effects and channels. *Technol. Forecast. Soc. Change* **2023**, *191*, 122486. [\[CrossRef\]](#)
66. Beck, T.; Levine, R.; Levkov, A. Big bad banks? The winners and losers from bank deregulation in the United States. *J. Financ.* **2010**, *65*, 1637–1667. [\[CrossRef\]](#)
67. Rambachan, A.; Roth, J. A more credible approach to parallel trends. *Rev. Econ. Stud.* **2023**, *90*, 2555–2591. [\[CrossRef\]](#)
68. Luan, L.; Liu, P.; Mei, Y. The impact of China's pilot carbon markets on firm performance. *Energy Econ.* **2025**, *142*, 108164. [\[CrossRef\]](#)
69. Goodman-Bacon, A. Difference-in-differences with variation in treatment timing. *J. Econom.* **2021**, *225*, 254–277. [\[CrossRef\]](#)
70. Sun, L.; Abraham, S. Estimating dynamic treatment effects in event studies with heterogeneous treatment effects. *J. Econom.* **2021**, *225*, 175–199. [\[CrossRef\]](#)
71. Borusyak, K.; Jaravel, X.; Spiess, J. Revisiting event-study designs: Robust and efficient estimation. *Rev. Econ. Stud.* **2024**, *91*, 3253–3285. [\[CrossRef\]](#)
72. Xiong, L.; Yan, S.; Yang, M. Financial development, environmental regulation, and industrial green technological innovation: A study based on the perspective of biased endogenous growth. *China Ind. Econ.* **2023**, *12*, 99–116. (In Chinese)
73. Wei, M.; Li, S. Measuring the quality of China's high-quality economic development in the new era. *J. Quant. Technol. Econ.* **2018**, *35*, 3–20. (In Chinese)

74. Cheng, Y.; Zhang, Y.; Wang, J.; Jiang, J. The impact of the urban digital economy on China's carbon intensity: Spatial spillover and mediating effect. *Resour. Conserv. Recycl.* **2023**, *189*, 106762. [[CrossRef](#)]
75. Liu, Y.; Zhao, C.; Dong, K.; Wang, K.; Sun, L. Policy spillover effect and action mechanism for environmental rights trading on green innovation: Evidence from China's carbon emissions trading policy. *Renew. Sustain. Energy Rev.* **2023**, *153*, 111779. [[CrossRef](#)]
76. Wang, D.; Chen, S. The impact of pilot climate-adapted city policies on urban climate resilience: Evidence from a quasi-natural experiment. *Cities* **2024**, *153*, 105316. [[CrossRef](#)]
77. Edmondson, D.L.; Kern, F.; Rogge, K.S. The co-evolution of policy mixes and socio-technical systems: Towards a conceptual framework of policy mix feedback in sustainability transitions. *Res. Policy* **2019**, *48*, 103555. [[CrossRef](#)]
78. Qing, Y.; He, Y.; Liu, P. Carrot or stick? Policy mix and its direct and spillover contributions to regional carbon emissions. *J. Environ. Manag.* **2025**, *389*, 126164. [[CrossRef](#)]
79. Jiang, N.N.; Jiang, W.; Wang, Y.F.; Zhang, J.N. Impact of financial reform on urban resilience: Evidence from China's financial reform pilot zones. *Socio-Econ. Plan. Sci.* **2024**, *94*, 101962. [[CrossRef](#)]
80. Wang, H.; Hao, Y.; Fu, Q. Data factor agglomeration and urban green finance: A quasi-natural experiment based on the National Big Data Comprehensive Pilot Zone. *Int. Rev. Financ. Anal.* **2024**, *96*, 103732. [[CrossRef](#)]
81. Pan, X.; Han, J.; Chen, K.; Wu, Y. Leveraging big data for environmental sustainability: Evidence from China's green transformation initiatives. *J. Environ. Manag.* **2025**, *392*, 126930. [[CrossRef](#)] [[PubMed](#)]
82. Del Rio Castro, G.; Camino González Fernández, M.; Uruburu Colsa, A. Unleashing the convergence amid digitalization and sustainability towards pursuing the Sustainable Development Goals (SDGs): A holistic review. *J. Clean. Prod.* **2021**, *280*, 122204. [[CrossRef](#)]
83. Yadav, A.; Gyamfi, B.A.; Asongu, S.A.; Behera, D.K. The role of green finance and governance effectiveness in the impact of renewable energy investment on CO₂ emissions in BRICS economies. *J. Environ. Manag.* **2024**, *358*, 120906. [[CrossRef](#)]
84. Luo, Z.; Junfeng, M.; Abbasi, B.N.; Zilong, L. Institutional structure and governance capability in universities: An empirical study from the perspectives of time, space, and quantity dimensions. *Humanit. Soc. Sci. Commun.* **2024**, *11*, 1035. [[CrossRef](#)]
85. You, J.; Zhang, B. The impact and spatial spillover effect of traditional culture on urban green innovation: Empirical evidence from China. *J. Environ. Manag.* **2024**, *369*, 122303. [[CrossRef](#)]
86. Liu, Y.; Tang, D.; Wang, F. Research on the spatial spillover effect of high-speed railway on the income of urban residents in China. *Humanit. Soc. Sci. Commun.* **2024**, *11*, 236. [[CrossRef](#)]
87. Dev, D.; Sharma, G.D.; Gupta, M.; Tiwari, A.K. Sustainable finance in action: A comprehensive framework for policy and practice integration. *Int. Rev. Econ. Financ.* **2025**, *103*, 104511. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.