

Article

Green Finance, Infrastructure Upgrading, and Urban Supply Chain Resilience: Evidence from China's Green Finance Reform and Innovation Pilot Zones

Yilin Wang ¹, Xujing Dai ² and Xueyan Li ^{2,*}¹ Business School, Shandong Normal University, Jinan 250014, China; 202322220315@stu.sdnu.edu.cn² School of Economics, Shandong Normal University, Jinan 250014, China; 202327230419@stu.sdnu.edu.cn

* Correspondence: lixueyan@sdnu.edu.cn

Abstract

The simultaneous pressures of low-carbon transition and repeated supply chain disruptions have made urban supply chain resilience an important concern for economic security and sustainable development. This study examines whether China's Green Finance Reform and Innovation Pilot Zones (GFRIZ) policy, launched in 2017, improved the resilience of urban supply chains. Using panel data for 285 prefecture-level cities from 2012 to 2024, we combine a partially linear Double Machine Learning framework with spatial econometric analysis. To address concerns about construct validity, urban supply chain resilience is reconstructed as a composite index covering four dimensions: resistance, innovation, coordination, and recovery. These dimensions are measured by industrial diversification, invention patent authorization, industrial product sales rate, and supply chain fluidity, respectively. The results show that the GFRIZ policy significantly enhances urban supply chain resilience. This conclusion remains robust after alternative machine learning estimators, different cross-fitting folds, interactive fixed effects, winsorization, exclusion of the COVID-19 year, and placebo tests. Mechanism analysis suggests that infrastructure upgrading remains an important transmission channel, especially through digital, green, and transport infrastructure. The effect is stronger in eastern and central cities, large cities, transport hubs, and old industrial bases. Spatial analysis further shows that although urban supply chain resilience displays negative spatial autocorrelation, the GFRIZ policy generates positive spillover effects on neighboring cities through capital flows, industrial linkages, and knowledge diffusion. The findings provide evidence that green finance reform can strengthen urban economic resilience beyond its environmental objectives.

Keywords: supply chain resilience; green finance; infrastructure upgrading; spatial spillovers; Double Machine Learning



Academic Editors: Yong Wang and Muqing Du

Received: 28 May 2026

Revised: 10 July 2026

Accepted: 21 July 2026

Published: 4 August 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.

1. Introduction

Urban supply chain resilience has become an increasingly important issue in both academic research and public policy discussions. This concern is closely related to two wider changes: the acceleration of the low-carbon transition and the growing frequency of supply chain disruptions. Climate volatility, geopolitical frictions, and the COVID-19 pandemic have exposed structural weaknesses in the production and distribution networks that support city economies. Urban areas are not simply locations where firms gather. They are spatial nodes where industrial activity, logistics circulation, factor allocation, innovation

resources, and public services interact. Once an urban supply chain is disrupted, the shock may affect local production, regional circulation, and even broader economic stability. Identifying policy instruments that can strengthen the ability of urban supply chains to resist shocks, maintain coordination, and recover from disruption therefore has clear practical significance [1].

Green finance provides a policy setting through which this issue can be examined. Through instruments such as green credit, green bonds, green insurance, and green funds, green finance redirects financial resources toward environmentally sustainable investment and seeks to reconcile economic growth with ecological constraints [2]. In 2017, China introduced the Green Finance Reform and Innovation Pilot Zones (GFRIZ) policy in selected areas of Zhejiang, Jiangxi, Guangdong, Guizhou, and Xinjiang. The policy was designed to encourage experimentation in green financial institutions, instruments, markets, and regulatory arrangements. It also created a relatively clear policy shock for evaluating whether place-based green finance reform can generate effects beyond environmental improvement.

The growing empirical literature has examined the consequences of green finance for green innovation [3], energy productivity [4], carbon emissions [5], and high-quality economic development [6]. These studies have substantially improved our understanding of the environmental and economic effects of green finance. Yet, one question remains insufficiently answered: can green finance strengthen urban supply chain resilience? This question is distinct from the existing focus on innovation or emissions. A city may perform well in green innovation but still face weak logistics continuity, insufficient industrial diversity, or poor supply–demand coordination. For this reason, supply chain resilience should not be reduced to green technological output alone. It is better understood as a multidimensional urban capability involving resistance to shocks, adaptive innovation, supply–demand coordination, and recovery through circulation.

The link between green finance and supply chain resilience is plausible for two reasons. First, the channels through which green finance operates, including infrastructure investment, technological upgrading, and resource reallocation, overlap with several core determinants of supply chain resilience identified in the literature [7,8]. Second, green finance may reshape the conditions under which urban supply chains function. By easing financing constraints and guiding capital toward cleaner industries and infrastructure renewal, the GFRIZ may improve the structural diversity of urban industries, support firms' innovation capacity, strengthen supply–demand matching, and enhance the fluidity of goods movement. These mechanisms suggest that the value of green finance reform may extend beyond its direct environmental mandate.

This study treats the GFRIZ as a source of quasi-experimental policy variation and estimates its effect on urban supply chain resilience. We use panel data for 285 Chinese prefecture-level cities from 2012 to 2024 and apply a Double Machine Learning framework to reduce bias from high-dimensional and nonlinear confounding [9]. To address the construct-validity concern surrounding the dependent variable, we reconstruct urban supply chain resilience as a composite index rooted in the operations and supply chain literature [10,11]. The revised index contains four dimensions. Industrial diversification captures resistance, invention patent authorization reflects innovation and adaptation, the industrial product sales rate measures supply–demand coordination, and freight volume relative to GDP reflects supply chain fluidity and recovery capacity. This design separates operational resilience from green patent output and avoids mechanically equating green finance with green innovation.

The empirical results indicate that the GFRIZ significantly improves urban supply chain resilience. The finding remains stable under alternative machine learning algorithms, different cross-fitting folds, interactive fixed effects, winsorization, exclusion of the

COVID-19 year, and randomization-based placebo tests. The estimated effect also varies across city types. It is more pronounced in eastern and central cities, large cities, transport hubs, and old industrial bases, suggesting that financial development, infrastructure conditions, and industrial foundations shape the effectiveness of green finance reform. Spatial analysis further shows that urban supply chain resilience displays negative spatial autocorrelation, while the GFRIZ generates positive spillover effects on neighboring cities through capital mobility, industrial linkages, and knowledge diffusion.

This study contributes to the literature in three respects. First, it extends research on green finance by shifting attention from conventional environmental and innovation outcomes to urban supply chain resilience, a policy-relevant dimension of economic security. Second, it improves the measurement of urban supply chain resilience by using a multidimensional index based on resistance, innovation, coordination, and recovery, rather than allowing green patent output to dominate the dependent variable. Third, it brings a spatial perspective into the analysis of green finance reform by examining whether local pilot policies generate cross-boundary effects among connected cities.

The paper proceeds as follows. Section 2 reviews the relevant literature. Section 3 develops the theoretical framework and hypotheses. Section 4 presents the empirical strategy, variable definitions, and data sources. Section 5 reports the baseline results, robustness tests, and heterogeneity analysis. Section 6 examines the transmission mechanisms and spatial spillovers. Section 7 discusses the findings and concludes with policy implications.

2. Literature Review

2.1. Green Finance and Economic Outcomes

Green finance originates from the need to correct environmental externalities and financing frictions in conventional capital markets. When environmental costs are not fully reflected in prices, private capital tends to flow toward sectors with higher short-term returns but heavier ecological burdens. Green finance seeks to change this allocation pattern through green credit, green bonds, green funds, environmental information disclosure, and other institutional arrangements. By lowering the financing cost of environmentally sustainable activities and raising the cost of pollution-intensive expansion, it provides a financial mechanism for coordinating economic growth and environmental protection [2].

Existing studies have mainly examined green finance from the perspectives of environmental performance, innovation, and economic transformation. Empirical evidence suggests that green finance can improve green total factor productivity [2], stimulate corporate green innovation [3,12], promote energy efficiency [4], improve air quality [13], and reduce carbon emissions [5,14]. These findings show that green finance can affect firms and cities not only through direct environmental regulation but also through financial incentives and resource reallocation.

More recent research has extended this discussion to broader economic outcomes. The GFRIZ policy has been associated with employment creation [15], higher corporate investment efficiency [16], stronger green investment activity [17], and improved quality of energy development [18]. Other studies point to the interaction between green finance and digital transformation in promoting green innovation [19], while some work links green finance to the formation of new quality productive forces [20]. Taken together, the literature has established that green finance can influence both environmental and economic outcomes.

However, the resilience implications of green finance remain less understood. Most existing studies focus on green innovation, emissions reduction, energy efficiency, or growth quality. These outcomes are important, but they do not directly capture whether an urban economy can maintain production and circulation when facing disruptions. Supply chain

resilience is conceptually different from environmental performance. It concerns whether production networks, logistics channels, and supply–demand relations can withstand shocks and recover afterward. This gap leaves room to examine whether green finance reform can strengthen the operational and structural resilience of urban supply chains.

2.2. Supply Chain Resilience: Concepts and Determinants

Supply chain resilience refers to the capacity of a supply system to resist disruption, maintain essential functions, recover after shocks, and adapt to changing risk conditions [10,21]. The COVID-19 pandemic, climate-related disasters, geopolitical tensions, and energy market volatility have made this issue especially salient. These events show that supply chain failures often spread through production networks, transport channels, and input–output linkages rather than remaining within a single firm or sector [22,23].

The existing literature has identified several sources of supply chain resilience. Digital technologies, including artificial intelligence, big data analytics, and industrial internet platforms, can improve information visibility, support real-time risk monitoring, and accelerate response decisions [8,24,25]. Digital transformation also lowers transaction costs, improves coordination among firms, and helps firms diversify suppliers and markets [26]. At the same time, firm-level digitalization may generate spillover effects that stabilize broader industrial networks [27].

Organizational and structural factors are also central to resilience. Operational flexibility and redundancy help supply chains absorb disruption when key nodes fail [28]. Coordination mechanisms and social capital improve the ability of firms to share information and mobilize resources under uncertainty [29]. Risk management practices reduce the probability that local shocks turn into systemic supply failures [30]. In addition, transport infrastructure affects recovery speed by shaping the cost, reliability, and substitutability of physical goods movement [31]. Industrial robot adoption has also been shown to strengthen manufacturing supply chains against disruptions by improving production continuity and operational adaptability [32].

Although these studies provide important insights, two limitations remain. First, much of the literature focuses on firms, dyadic supply relationships, or individual supply networks. City-level supply chain resilience has received less attention, even though cities are the spatial units where industrial structure, logistics circulation, innovation resources, and public policy interact. Second, existing studies pay more attention to technological and organizational determinants, while the role of financial policy remains underexplored. For urban supply chains, financial policy may matter because it affects infrastructure investment, industrial upgrading, and firms' ability to finance adjustment under uncertainty.

In this study, urban supply chain resilience is understood as a multidimensional capacity rather than a single output indicator. At the city level, resilience depends on whether the industrial structure can resist sector-specific shocks, whether local firms have sufficient innovation capacity to adapt, whether production and demand remain coordinated, and whether logistics circulation can recover after disruption. This perspective is consistent with the supply chain resilience literature but adapts it to the urban context.

2.3. Infrastructure as the Missing Link

Infrastructure provides the material and technological foundation for urban supply chains. Digital infrastructure, such as data centers, industrial internet platforms, and intelligent logistics systems, enables faster information exchange, risk identification, and coordination among firms [33,34]. These functions are especially important when supply chains face uncertainty because timely information can reduce mismatch between produc-

tion, inventory, and demand. Improvements in digital infrastructure therefore strengthen the innovation and coordination dimensions of urban supply chain resilience.

Green infrastructure also matters for supply chain resilience, but its role should be understood carefully. Renewable energy facilities, green buildings, ecological protection projects, and environmental treatment systems can reduce energy-related risks, environmental compliance costs, and exposure to resource constraints [35,36]. These effects do not mean that every form of urban infrastructure is automatically a green project. Rather, green infrastructure contributes to resilience when it lowers environmental and resource risks that may interrupt production and circulation. This distinction is important for separating sustainable infrastructure from general public works.

Transport infrastructure shapes the physical connectivity of urban supply chains. Road networks, rail systems, ports, logistics hubs, and urban transport facilities determine how quickly goods, intermediate inputs, and production factors can move across space. Better transport conditions reduce trade costs, improve the substitutability of routes, and increase the capacity of cities to recover when a particular logistics channel is disrupted [31,37]. For this reason, transport infrastructure is closely related to the recovery dimension of supply chain resilience.

Green finance policy may connect these infrastructure channels with urban supply chain resilience. Through green credit, green bonds, and related financial instruments, the GFRIZ can guide capital toward infrastructure renewal, digital upgrading, and cleaner forms of industrial development. These investments may improve the information, environmental, and logistics conditions under which urban supply chains operate. In this sense, infrastructure upgrading is a plausible transmission channel linking green finance reform to resilience outcomes.

In summary, the literature suggests three unresolved issues. First, the green finance literature has not sufficiently examined supply chain resilience as an outcome. Second, the supply chain resilience literature has not fully incorporated financial policy and city-level institutional variation. Third, the infrastructure pathway linking green finance to urban supply chain resilience remains underdeveloped. This study addresses these gaps by examining whether the GFRIZ policy strengthens urban supply chain resilience and whether digital, green, and transport infrastructure help transmit this effect.

3. Theoretical Framework and Hypotheses

3.1. Green Finance and Urban Supply Chain Resilience: Direct Effect

Green finance may affect urban supply chain resilience through resource allocation, financing support, and risk mitigation. From the perspective of resource allocation, financial capital does not enter all sectors evenly. It tends to follow differences in expected returns, risk exposure, policy incentives, and information conditions. Green finance changes this allocation process by using green credit, green bonds, environmental disclosure, project certification, and related institutional arrangements to reduce financing frictions for cleaner and more sustainable activities [2].

This process can influence urban supply chain resilience in several ways. First, green finance may encourage the upgrading and diversification of local industries. A city with a more diversified industrial structure is less dependent on a narrow set of sectors and therefore has more substitution possibilities when a specific industry or input channel is disrupted. This strengthens the resistance dimension of supply chain resilience. Second, green finance can ease the financing constraints of firms engaged in technological upgrading and cleaner production. Better financing conditions allow firms to invest in equipment renewal, process improvement, digital management, and supplier adjustment, all of which improve their capacity to adapt under uncertainty. Third, green finance may improve

the infrastructure and institutional environment in which supply chains operate. Better infrastructure, information systems, and environmental governance can reduce operational risks and support smoother supply–demand coordination.

These mechanisms are consistent with the resilience literature, which emphasizes that a system’s ability to withstand and recover from shocks depends on the quality, diversity, and adaptability of its resource base [10]. Firms with access to green credit and green bond markets may also be better able to sustain resilience-related investment during periods of financial pressure, reducing the probability that local disruptions develop into wider supply chain failures [3,15]. Based on this logic, we propose the following hypothesis:

Hypothesis 1 (H1). *The implementation of the GFRIZ policy significantly improves urban supply chain resilience.*

3.2. Digital Infrastructure Channel

Digital infrastructure is an important channel through which green finance may improve supply chain resilience. The GFRIZ encourages financial institutions and local governments to support green and technology-oriented projects. In practice, this may include investment in data centers, industrial internet platforms, intelligent logistics systems, and other digital facilities that improve the information environment of urban supply chains [38].

Digital infrastructure strengthens resilience mainly by improving information visibility and coordination. Supply chain disruptions often become more severe when firms cannot identify risks in time, locate alternative suppliers, or adjust production and logistics decisions quickly. Digital platforms reduce such frictions by allowing firms to share information, monitor demand changes, track logistics flows, and coordinate production schedules. Prior evidence suggests that digitally enabled supply-chain integration can improve inter-firm coordination and firm performance [39]. Big data and artificial intelligence can further support real-time risk identification and operational adjustment [24], while industrial internet platforms make it easier for firms to reorganize production links when disruptions occur [8].

At the urban level, digital infrastructure contributes to both the innovation and coordination dimensions of supply chain resilience. It supports firms’ adaptive capacity and improves the matching between production, inventory, logistics, and market demand. The expansion of the digital economy may also create resilience spillovers along industrial chain networks [40]. Therefore, we propose the following hypothesis:

Hypothesis 2 (H2). *Green finance improves urban supply chain resilience by promoting the development of digital infrastructure.*

3.3. Green Infrastructure Channel

Green infrastructure refers to infrastructure assets that directly reduce environmental pressure, resource consumption, or ecological risk. It includes renewable energy facilities, green buildings, ecological protection projects, environmental treatment systems, and related low-carbon urban facilities. Unlike general public works, green infrastructure has a clearer sustainability orientation and is more closely aligned with the objectives of green finance [4].

The resilience effect of green infrastructure operates through environmental and resource-risk reduction. Supply chain operations rely on stable energy supply, resource availability, and compliance with environmental regulations. When firms face high energy intensity, resource dependence, or environmental compliance pressure, their operations

become more vulnerable to energy price shocks, regulatory tightening, and ecological constraints. Green infrastructure can reduce these vulnerabilities by improving energy efficiency, lowering pollution treatment costs, and supporting cleaner production and distribution systems [41]. It can also improve the environmental conditions under which firms operate and reduce the probability that environmental risks interrupt production and circulation [36].

In this study, green infrastructure is therefore treated as a specific sustainable infrastructure channel rather than a broad label applied to all urban infrastructure. Its contribution to supply chain resilience lies in reducing resource and environmental risks that may weaken the stability and recovery capacity of urban supply chains. This logic is consistent with the view that environmental sustainability and economic resilience can reinforce each other when infrastructure investment lowers long-term operational risks [35]. Accordingly, we propose the following hypothesis:

Hypothesis 3 (H3). *Green finance improves urban supply chain resilience by promoting the development of green infrastructure.*

3.4. Transport Infrastructure Channel

Transport infrastructure differs from green infrastructure in both function and mechanism. While green infrastructure reduces environmental and resource-related risks, transport infrastructure affects the physical circulation of goods, intermediate inputs, and production factors. Roads, railways, ports, logistics hubs, and urban transport facilities determine how quickly and reliably supply chain activities can be maintained across space.

The GFRIZ may influence transport infrastructure through financing support for low-carbon logistics, energy-saving transport facilities, multimodal transportation, and logistics network modernization. However, the mechanism emphasized here is not that all transport infrastructure is automatically a green project. Rather, transport infrastructure matters because it directly affects the recovery and circulation capacity of urban supply chains. Better transport conditions reduce logistics costs, shorten delivery time, increase route substitutability, and make it easier for firms to adjust transport paths when disruptions affect specific nodes or corridors. Recent Chinese evidence further shows that greater highway accessibility can promote non-agricultural activity, improve supporting infrastructure, and strengthen regional coordination [37].

From the perspective of supply chain resilience, transport infrastructure mainly strengthens the recovery dimension. When disruption occurs, cities with better logistics connectivity are more capable of restoring flows of goods and inputs. They also have greater capacity to switch routes, connect alternative suppliers, and maintain market access. Existing research has shown that transport conditions are closely related to recovery speed and supply chain continuity [31]. Thus, we propose the following hypothesis:

Hypothesis 4 (H4). *Green finance improves urban supply chain resilience by promoting transport infrastructure upgrading.*

3.5. Spatial Spillover Effects

The effect of green finance reform may extend beyond the administrative boundaries of pilot cities. Urban supply chains are connected through inter-city trade, logistics networks, factor mobility, industrial linkages, and policy learning. When a pilot city improves its financial institutions, infrastructure conditions, or industrial coordination capacity, neighboring cities may also be affected through these channels.

Several mechanisms may generate spatial spillovers. First, capital flows may move across city boundaries when green finance reforms create new investment opportunities and financial service models. Second, firms located in neighboring cities may benefit from improved logistics, supplier relationships, and production coordination with pilot cities. Third, local governments may learn from the institutional practices of pilot zones and adopt similar green finance measures. These channels imply that GFRIZ may influence not only local resilience but also the resilience of nearby cities [42].

Urban supply chain resilience itself may also exhibit spatial dependence. Cities in the same region are linked by industrial chains, transport systems, and factor markets. Improvements or weaknesses in one city may therefore affect the production and circulation conditions of surrounding cities. Prior studies on industrial chain resilience have also shown that resilience outcomes can display significant spatial correlation [43]. Based on this logic, we propose the following hypothesis:

Hypothesis 5 (H5). *The GFRIZ policy generates positive spatial spillover effects on the supply chain resilience of neighboring cities.*

4. Research Design

4.1. Empirical Strategy

4.1.1. Standard Regression Model

We follow the empirical framework of Tao et al. [44] and employ a partially linear Double Machine Learning (DML) model proposed by Chernozhukov et al. [9]:

$$Y_{it} = \theta_0 D_{it} + g_0(X_{it}) + U_{it} \quad (1)$$

$$E(U_{it} | D_{it}, X_{it}) = 0 \quad (2)$$

where Y_{it} denotes urban supply chain resilience and D_{it} is the treatment indicator capturing whether city i belongs to the Green Finance Reform and Innovation Zone (GFRIZ) after 2017. The parameter θ_0 represents the causal effect of the GFRIZ policy on urban supply chain resilience. X_{it} is a high-dimensional vector of control variables. The unknown function $g_0(X_{it})$ captures potentially complex and nonlinear effects of the controls on the outcome variable, while U_{it} is the stochastic disturbance term satisfying the orthogonality condition.

Following the partially linear DML framework, the treatment assignment equation is specified as

$$D_{it} = m_0(X_{it}) + V_{it} \quad (3)$$

$$E(V_{it} | X_{it}) = 0 \quad (4)$$

where $m_0(X_{it})$ denotes the conditional expectation of the treatment variable given the high-dimensional controls and V_{it} represents the residual component orthogonal to X_{it} .

Given the relatively high dimensionality of the control variables, this study adopts random forest as the primary machine learning algorithm in the baseline specification. Random forest is particularly suitable for approximating complex nonlinear relationships and capturing high-order interactions among covariates without imposing restrictive parametric assumptions.

Direct estimation of the nuisance functions may introduce regularization bias because machine learning estimators generally converge at rates slower than $n^{-1/4}$. To address this issue, we implement the orthogonalization and cross-fitting procedure developed by Chernozhukov et al. [9]. Specifically, the nuisance functions $g_0(\cdot)$ and $m_0(\cdot)$ are first estimated using machine learning methods, after which the treatment effect pa-

parameter is recovered through orthogonalized residual regression. The estimator can be expressed as

$$\hat{\theta} = \left(\frac{1}{NT} \sum_{i=1}^N \sum_{t=1}^T (D_{it} - \hat{m}_0(X_{it}))^2 \right)^{-1} \left(\frac{1}{NT} \sum_{i=1}^N \sum_{t=1}^T (D_{it} - \hat{m}_0(X_{it}))(Y_{it} - \hat{g}_0(X_{it})) \right) \quad (5)$$

The orthogonal score construction substantially mitigates regularization bias, while cross-fitting improves robustness against overfitting. As a result, the DML estimator remains consistent and asymptotically normal even under high-dimensional settings.

Cross-fitting is applied throughout the estimation. In the baseline configuration, the sample is randomly divided into $K = 5$ equal-sized folds. For each fold, the nuisance functions are estimated using the remaining $K - 1$ folds, and the parameter of interest is computed from the held-out fold. The reported estimate equals the average across folds. To test robustness, results under $K = 3$ and $K = 7$ are also presented.

4.1.2. Mediation Model

The infrastructure transmission channels are tested using the three-equation stepwise mediation framework introduced by Baron and Kenny [45]. The analysis focuses on three mediators: digital infrastructure, green infrastructure, and transport infrastructure. For each mediator, the first equation regresses urban supply chain resilience on the GFRIZ indicator, the second equation regresses the mediator on the GFRIZ indicator, and the third equation regresses urban supply chain resilience on both the GFRIZ indicator and the mediator. Evidence consistent with mediation is obtained when the GFRIZ policy significantly affects the mediator and the mediator significantly predicts resilience in the full model. If the GFRIZ coefficient remains significant but becomes smaller after the mediator is included, the result indicates partial mediation.

$$SCR_{it} = \alpha_0 + \alpha_1 DID_{it} + \sum \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (6)$$

$$M_{it} = \beta_0 + \beta_1 DID_{it} + \sum \gamma Control_{sit} + \mu_i + \lambda_t + \varepsilon_{it} \quad (7)$$

$$SCR_{it} = \delta_0 + \delta_1 DID_{it} + \delta_2 M_{it} + \sum \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (8)$$

To further verify the statistical significance of the mediating effect, this study applies the Sobel test as a supplementary test following Sobel [46]. The indirect effect is calculated as the product of the coefficient of GFRIZ in the mediator equation and the coefficient of the mediator in the resilience equation. A significant Sobel statistic indicates that the indirect effect through the mediator is statistically different from zero. All mediation regressions include city fixed effects and year fixed effects, and standard errors are clustered at the city level.

4.1.3. Spatial Spillover Model

Urban supply chains are closely connected across cities through logistics networks, industrial linkages, factor mobility, and interregional trade. Therefore, the effect of the GFRIZ policy may not be confined to pilot cities themselves. Green finance reform in one city may affect neighboring cities by reshaping capital flows, improving cross-city industrial coordination, and strengthening regional logistics connections. To examine whether such cross-boundary effects exist, this study adopts a Spatial Durbin Model (SDM) to test the spatial spillover effect of the GFRIZ policy.

The SDM is chosen because it provides a more flexible framework for spatial policy evaluation. A spatial autoregressive model mainly captures the dependence of the dependent variable across regions, while a spatial error model mainly accounts for spatial correlation in unobserved shocks. The SDM can incorporate both the spatial lag of urban

supply chain resilience and the spatial lag of explanatory variables. It is therefore suitable for this study, as the GFRIZ policy may affect not only the resilience of the pilot city itself but also that of neighboring cities through policy diffusion, industrial linkages, and factor circulation. In this sense, the SDM allows us to distinguish the local effect of the policy from its regional spillover effect.

The model is specified as follows:

$$SCR_{it} = \rho \sum_{j=1}^N W_{ij} SCR_{jt} + \beta DID_{it} + \theta \sum_{j=1}^N W_{ij} DID_{jt} + \mu_i + \lambda_t + \varepsilon_{it} \quad (9)$$

In this setup, SCR_{it} denotes urban supply chain resilience, DID_{it} is the treatment indicator, W_{ij} is the geographic distance spatial weight matrix, ρ captures the spatial autoregressive parameter, μ_i and λ_t are city and year fixed effects, and ε_{it} is the disturbance. The term $W \times DID$ picks up the effect of green finance policy in neighboring cities.

4.2. Variable Measurement

4.2.1. Explanatory Variable

The key explanatory variable is a binary indicator of GFRIZ treatment. The treatment arm consists of cities designated as pilots in 2017; all other cities form the control arm. The indicator equals 1 for treatment-group cities in years 2017 and beyond, and 0 otherwise, conforming to the canonical difference-in-differences treatment definition.

This classification produces the following binary treatment variable:

$$DID_{it} = Treat_i \times Post_{it} \quad (10)$$

where $Treat_i$ identifies treatment-group cities. When city i is listed on the official GFRIZ roster published jointly by the People's Bank of China and is $Treat_i$ partner ministries in 2017, $x = 1$; otherwise, $Treat_i = 0$. $Post_{it}$ is a time dummy equal to 1 for years from 2017 onward and 0 for earlier years.

4.2.2. Dependent Variable

The dependent variable is urban supply chain resilience. In the original version of the index, green technology innovation was included as a subdimension of supply chain resilience. To improve construct validity and avoid mechanically linking the dependent variable to green finance policy, this study reconstructs the index and excludes green patent applications from the measurement of resilience. Urban supply chain resilience is defined as the capacity of a city-level production and distribution system to resist external shocks, adapt through innovation, maintain supply–demand coordination, and recover through smooth factor and goods circulation.

Drawing on the supply chain resilience literature, the revised index contains four dimensions: resistance, innovation, coordination, and recovery.

First, resistance is measured by industrial diversification. A diversified industrial structure provides more substitution possibilities when a specific sector, supplier, or production link is disrupted. We calculate the Herfindahl–Hirschman Index based on the shares of primary, secondary, and tertiary industry value added in GDP and use $1 - HHI$ to measure industrial diversification. A higher value indicates lower industrial concentration and stronger resistance to sector-specific shocks.

Second, innovation is measured by the number of invention patents authorized. Innovation capacity reflects the ability of firms and cities to adjust technologies, production processes, and organizational routines under changing external conditions. Compared with green patent applications, invention patent authorization captures broader technological

capability and avoids mechanically equating green finance with green innovation. The indicator is measured as $\ln(1 + \text{number of invention patents authorized})$.

Third, coordination is measured by the industrial product sales rate. This indicator reflects the matching between industrial production and market demand. A higher sales rate indicates that industrial output can be more effectively converted into sales revenue, suggesting stronger supply–demand coordination within the urban production system.

Fourth, recovery is measured by supply chain fluidity. Freight volume relative to GDP is used to reflect the circulation intensity of goods and production factors. The purpose of this indicator is not to measure logistics scale alone but to capture whether goods movement can support economic output. A higher value indicates smoother circulation and stronger recovery capacity after disruption.

All four indicators are positive indicators. They are standardized using the range method and then aggregated through the entropy-weighted TOPSIS method. The entropy method determines weights according to the information content of each indicator, while TOPSIS calculates the relative closeness of each city-year observation to the ideal solution. The final index is normalized to the [0, 1] interval, with higher values indicating stronger urban supply chain resilience. Table 1 summarizes the indicator composition and measurement framework.

Table 1. Urban supply chain resilience index: indicator composition and weight structure.

Primary Indicator	Capability Dimension	Secondary Indicator	Measurement	Direction
Supply chain resilience	Resistance	Industrial diversification	$1 - \text{HHI}$, where HHI is calculated from the shares of primary, secondary, and tertiary industry value added in GDP	+
	Innovation	Invention patent authorization	$\ln(1 + \text{number of invention patents authorized})$	+
	Coordination	Industrial product sales rate	Industrial product sales revenue/gross industrial output value	+
	Recovery	Supply chain fluidity	Freight volume/GDP	+

Note: All indicators are positive indicators. The final index is calculated using entropy-weighted TOPSIS after standardization. Green patent applications are excluded from the revised dependent variable to avoid mechanically equating green finance policy with green technological output. The + sign denotes a positive-direction indicator.

4.2.3. Control Variables

To reduce omitted-variable bias, the model includes a set of city-level controls that may influence supply chain resilience. The baseline controls include population density, economic development level, trade openness, financial development, and human capital. Educational investment is not included together with human capital in the baseline specification to avoid conceptual overlap, but it is considered in robustness checks.

Population density (pop). The concentration of urban residents shapes market size, labor availability, and the operating environment for supply chain activities; agglomeration economies that strengthen resilience may also arise.

Economic development level (pgdp). A city's development stage determines its capacity for infrastructure investment and the baseline quality of the environment in which supply chain firms operate.

Trade openness (ope). Greater openness deepens a city's embedding in global supply networks, widening access to diverse intermediate inputs and logistics services that can underpin resilience.

Financial development (fin). A mature financial sector supplies enterprises with funding channels and risk management instruments that enable supply chains to absorb disruptions and recover afterward.

Human capital (human). The stock of human capital reflects a city's capacity for technological innovation and its ability to run complex operational systems, both of which are integral to supply chain resilience.

4.2.4. Mediating Variables

To examine the channels through which the GFRIZ policy affects urban supply chain resilience, this study considers three types of infrastructure upgrading: digital infrastructure, green infrastructure, and transport infrastructure. These three mediators correspond, respectively, to the information, environmental, and circulation foundations of urban supply chains.

Digital infrastructure reflects a city's capacity to support information exchange, digital coordination, and intelligent logistics. Following Zhao et al. [47], it is constructed from four indicators: internet employment, internet-related output, mobile connectivity, and digital inclusive finance. Specifically, internet employment is measured by the ratio of computer service and software employees to total employment; internet-related output is measured by per capita telecommunication business revenue; mobile connectivity is measured by the number of mobile phone users per 100 persons; and digital inclusive finance is measured by the Peking University Digital Inclusive Finance Index.

Green infrastructure captures infrastructure investment directly related to environmental improvement and resource sustainability. Referring to Lin and Yang [36], and Liao et al. [48], it is measured using urban landscaping investment, environmental sanitation investment, waste treatment investment, and sewage treatment investment. These indicators reflect the environmental infrastructure base that may reduce ecological risks, resource constraints, and compliance pressure faced by urban production and circulation systems.

Transport infrastructure reflects the physical circulation capacity of urban supply chains. It is measured by rail and public transit investment and road and bridge investment, following the infrastructure measurement framework of Lin and Yang [36], and Liao et al. [48]. Unlike green infrastructure, transport infrastructure is not treated as a green project by definition. Its role in this study lies in improving logistics connectivity, route substitutability, and recovery capacity after supply chain disruption.

All mediating indicators are positive indicators. For each infrastructure category, the raw indicators are first standardized and then aggregated using the entropy-weighted TOPSIS method. The resulting composite indices are normalized to the [0, 1] interval, with higher values indicating stronger infrastructure development. The complete measurement framework is reported in Table 2.

Table 2. Infrastructure mediating variables: measurement framework.

Primary	Secondary	Tertiary
Digital infrastructure	Internet employment	Computer service and software employees/total employment
	Internet-related output	Per capita telecom business revenue
	Mobile internet users	Mobile phone users per 100 persons
	Digital inclusive finance	Peking University Digital Inclusive Finance Index

Table 2. Cont.

Primary	Secondary	Tertiary
Green infrastructure	Landscaping investment	Urban landscaping investment (10 ⁴ yuan)
	Environmental sanitation inv.	Environmental sanitation investment (10 ⁴ yuan)
	Waste treatment investment	Waste treatment investment (10 ⁴ yuan)
	Sewage treatment investment	Sewage treatment investment (10 ⁴ yuan)
Transport infrastructure	Rail/public transit investment	Rail and public transit investment (10 ⁴ yuan)
	Road and bridge investment	Road and bridge investment (10 ⁴ yuan)

4.3. Data Sources and Descriptive Statistics

The analysis uses a balanced panel of 285 prefecture-level and above Chinese cities spanning 2012 through 2024. Data are drawn primarily from the China Urban Statistical Yearbook and the China Urban Construction Statistical Yearbook, supplemented by provincial statistical bulletins. The official GFRIZ pilot city list was obtained from the 2017 joint announcement by the People's Bank of China and six co-issuing ministries. Missing values are filled through linear interpolation. All nominal variables are deflated to constant 2012 prices using provincial-level price indices.

5. Empirical Results and Analysis

A causal interpretation of the DML estimates depends on the plausibility of the parallel trends assumption: had the GFRIZ not been implemented, treated and control cities would have followed similar trajectories in supply chain resilience. We evaluate this condition using an event-study design that retrieves dynamic treatment effects for each year relative to the policy's introduction.

Under this design, year-specific dynamic policy effects are estimated, with the period immediately before adoption (2016) designated as the reference category. Periods five or more years prior to treatment are binned at the endpoint to improve estimation stability.

$$SCR_{it} = \alpha + \sum_{k=-5}^5 \beta_k \cdot D_{it}^k + \lambda_i + \delta_t + \varepsilon_{it} \quad (11)$$

where D_{it}^k is a set of dummies capturing relative policy timing. For city i in year t , when the observation falls k periods from policy onset, the corresponding indicator equals 1 and all others equal 0. λ_i and δ_t represent city and year fixed effects; ε_{it} is the error term. The coefficients of interest are the β_k estimates.

The estimated coefficients are small in magnitude and statistically insignificant for both treatment and control groups in every pre-policy period. The 95% confidence intervals always contain zero and oscillate around the null. This evidence confirms the absence of any meaningful pre-existing trend divergence.

Analysis of the post-policy dynamics uncovers a distinct lag structure. Beginning with the implementation period, coefficients turn positive, become statistically significant, and gain magnitude in subsequent years. This pattern aligns with the expectation that green finance instruments, infrastructure projects, and firm-level behavioral responses require time to materialize and register in resilience metrics.

These findings effectively eliminate the concern that differential pre-existing trends drive the baseline estimates. The parallel trends condition is satisfied, lending credibility to the causal reading of the DML results presented below. Figure 1 presents the estimated dynamic treatment effects.

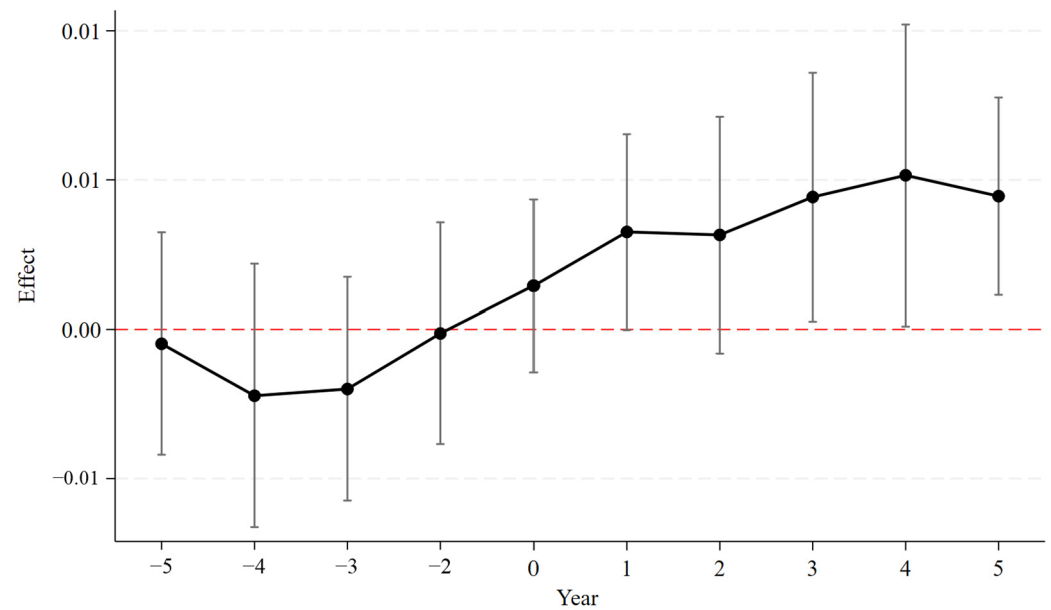


Figure 1. Dynamic treatment effects from the event-study specification. Black circles and the connecting line show point estimates; gray capped lines show 95% confidence intervals; the red dashed line marks zero.

5.1. Baseline Regression

Table 3 reports the baseline DML estimates of the GFRIZ impact on urban supply chain resilience. Column (1) contains results from a specification with linear controls only, while Column (2) adds quadratic control terms. City and year fixed effects are included in both specifications, and city-clustered standard errors are reported in parentheses.

Table 3. Baseline DML estimates: GFRIZ impact on urban supply chain resilience.

Variable	SCR	SCR
GFRIZ	0.003 *** (0.001)	0.005 *** (0.001)
Controls	Yes	Yes
Linear terms	Yes	Yes
Quadratic terms	No	Yes
Year FE	Yes	Yes
City FE	Yes	Yes
N	3705	3705

Note: City-clustered standard errors are reported in parentheses. All specifications incorporate city and year fixed effects. *** $p < 0.01$.

The policy coefficient is positive and significant at the 1% level in both columns. The stability of the point estimate across specifications with and without quadratic controls indicates that the machine learning component adequately absorbs nonlinear confounding.

These results provide empirical support for the paper's central hypothesis: GFRIZ implementation has materially strengthened urban supply chain resilience, consistent with Hypothesis 1.

5.2. Robustness Tests

5.2.1. Alternative Estimation Method

As a first sensitivity check, we re-estimate using a conventional two-way fixed effects (TWFE) model. Column (1) of Table 4 presents the result. The TWFE estimate is 0.005,

significant at the 1% level, matching the DML baseline precisely. This alignment across fundamentally distinct estimation strategies reinforces confidence in the core finding.

Table 4. Robustness I: alternative machine learners and cross-fitting configurations.

Variable	TWFE	Elastic Net	SVM	Lasso	K = 3	K = 7
GFRIZ	0.005 *** (0.001)	0.005 ** (0.001)	0.009 ** (0.004)	0.005 *** (0.001)	0.007 *** (0.002)	0.004 *** (0.001)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Linear terms	Yes	Yes	Yes	Yes	Yes	Yes
Quadratic terms	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
N	3705	3705	3705	3705	3705	3705
Adj. R ²	0.816	—	—	—	—	—

Note: City-clustered standard errors are reported in parentheses. ** $p < 0.05$, *** $p < 0.01$.

5.2.2. Alternative Machine Learning Algorithms

A further robustness exercise replaces the random forest learner with three alternatives: elastic net, support vector machine, and LASSO. Columns (2) through (4) of Table 4 display the resulting estimates.

The GFRIZ coefficient remains positive and statistically significant under all three alternatives: 0.005 (elastic net), 0.009 (SVM), and 0.005 (LASSO), each significant at conventional thresholds. The conclusion does not depend on the specific machine learning algorithm employed.

5.2.3. Alternative Cross-Fitting Folds

Sensitivity to the sample-splitting approach is evaluated by varying the number of cross-fitting folds from the baseline $K = 5$ to $K = 3$ and $K = 7$. Results appear in Columns (5) and (6) of Table 4.

The GFRIZ coefficient stays positive and significant irrespective of the fold count: 0.007 at the 1% significance level for $K = 3$ and 0.004 at the 1% significance level for $K = 7$. The estimated policy effect is not a byproduct of the particular sample-partition scheme.

5.2.4. Interactive Fixed Effects Model

To address potential misspecification bias in the standard difference-in-differences framework and to check robustness against unobserved heterogeneity, an interactive fixed effects model is fitted. This specification accommodates time-varying latent factors with city-specific loadings. Column (1) of Table 5 reports a GFRIZ coefficient of 0.009 at the 1% significance level, confirming that unmodeled heterogeneity does not account for the result.

Table 5. Robustness II: interactive fixed effects, winsorization, and COVID-year removal.

Variable	Interactive FE	Province FE	Winsorized (5–95%)	Excluding 2020
GFRIZ	0.009 *** (0.002)	0.003 *** (0.000)	0.004 *** (0.001)	0.005 *** (0.002)
Controls	Yes	Yes	Yes	Yes
Linear terms	Yes	Yes	Yes	Yes
Quadratic terms	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
N	3705	3705	3705	3420

Note: City-clustered standard errors are reported in parentheses. *** $p < 0.01$.

5.2.5. Inclusion of High-Dimensional Provincial Fixed Effects

Cities located in the same province may be subject to shared macroeconomic conditions, common regional industrial policies, and coordinated development initiatives capable of confounding the estimates. Provincial fixed effects are incorporated to address this concern.

The estimate reported in Column (2) of Table 5, which includes provincial dummies, stands at 0.003 at the 1% significance level. Province-level common shocks do not explain the treatment effect.

To limit the influence of extreme observations, all continuous variables are winsorized at the 5th and 95th percentiles. Column (3) of Table 5 shows a coefficient of 0.004 at the 1% significance level, indicating that outliers are not responsible for the baseline result.

The COVID-19 pandemic may have caused severe disruptions to urban supply chain operations in 2020 that could bias the estimates. To address this, the 2020 observations are dropped. Column (4) of Table 5 shows the coefficient remains 0.005 at the 1% significance level, unchanged from the baseline. The estimated treatment effect is not a pandemic-era artifact.

5.2.6. Placebo Test

To exclude the possibility that the results arise from random variation or sample selection artifacts, both constrained and unconstrained randomization placebo exercises are conducted. In each exercise, treatment status is randomly reassigned across cities 500 times, and the distribution of placebo coefficients under the null hypothesis of no effect is constructed.

Table 6 summarizes the placebo outcomes. The two-sided p -value from the unconstrained procedure is 0.042; from the constrained procedure, it is 0.040. Both values indicate that the observed treatment effect is unlikely to be attributable to chance. Figures 2 and 3 plot the unrestricted and restricted placebo distributions, respectively, with the actual estimate located in the upper tail in each case.

Table 6. Outcomes of randomization-based placebo exercises.

Placebo Method	Two-Sided p	Left-Sided p	Right-Sided p
Unconstrained	0.042	0.968	0.032
Constrained	0.040	0.968	0.032

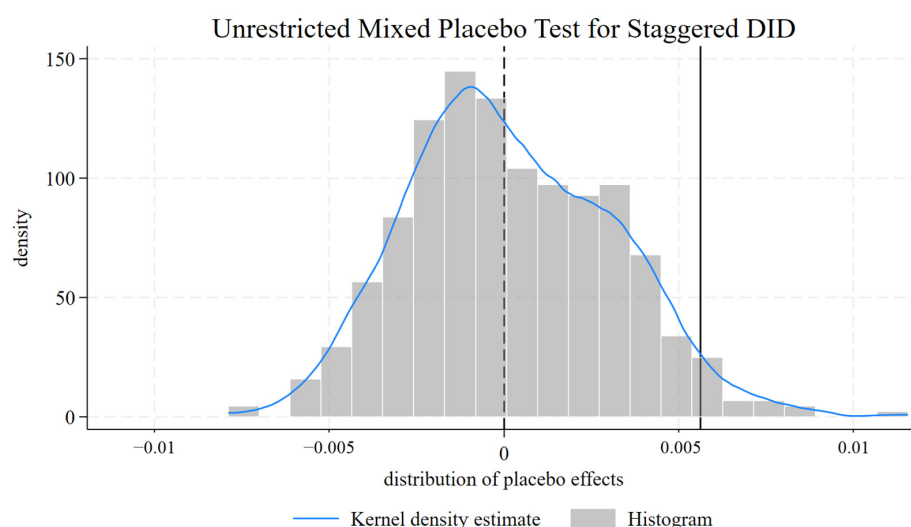


Figure 2. Unrestricted mixed placebo test for staggered DID.

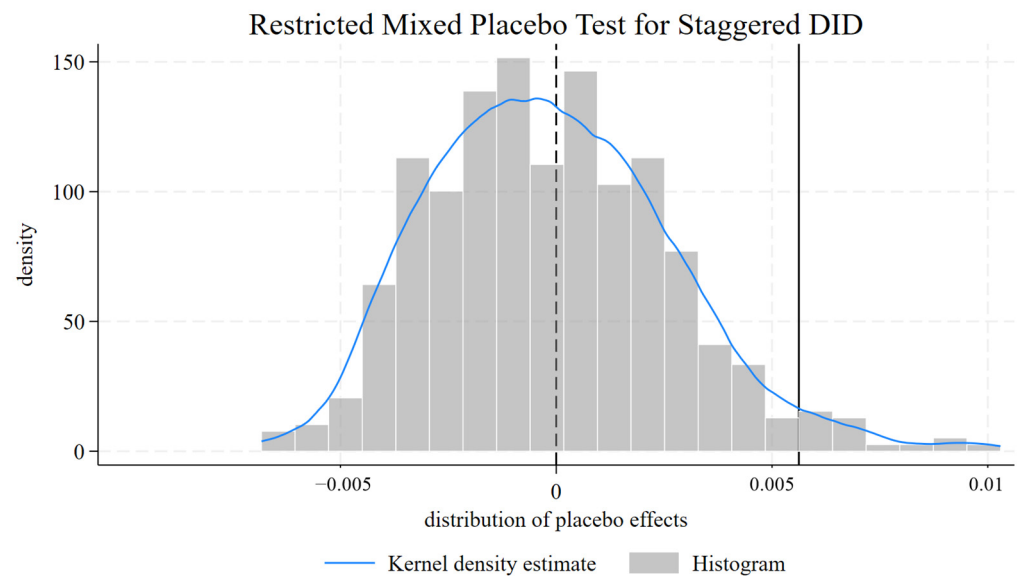


Figure 3. Restricted mixed placebo test for staggered DID.

5.3. Heterogeneity Analysis

5.3.1. Regional Heterogeneity

To examine geographic heterogeneity, cities are split into eastern, central, and western groups using the standard China regional classification, and the model is re-estimated for each subsample.

The GFRIZ generates a large and statistically significant resilience gain in eastern cities and central cities. In western cities, the point estimate is small and not significant. Table 7 reports these regional estimates.

Table 7. Heterogeneity by geographic region.

Variable	Eastern	Central	Western
GFRIZ	0.011 *** (0.004)	0.010 ** (0.004)	0.002 (0.002)
Controls	Yes	Yes	Yes
Linear terms	Yes	Yes	Yes
Quadratic terms	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
N	1105	1027	1105

Note: City-clustered standard errors are reported in parentheses. ** $p < 0.05$, *** $p < 0.01$.

A likely explanation is that eastern China possesses a more developed green finance infrastructure, deeper financial marketization, and denser industrial networks, enabling green finance capital to be translated into resilience improvements with greater efficiency. Central China gains from industrial relocation and policy diffusion emanating from the east, which also facilitates successful implementation.

Western China faces binding constraints, a shallower industrial base, scarcer financial resources, and less mature market institutions, that limit its ability to absorb and productively deploy green finance capital. These structural divergences imply that green finance policies may require complementary foundational support in less developed regions to realize their full potential.

5.3.2. Heterogeneity by City Size

A threshold of one million permanent residents in municipal districts is used to separate large cities from small-to-medium cities. Table 8 shows large cities experiencing a significant positive effect. The estimate for smaller cities is not statistically distinguishable from zero.

Table 8. Heterogeneity by city size and administrative rank.

Variable	Small and Medium	Large	Central Cities	Peripheral Cities
GFRIZ	0.001 (0.001)	0.004 ** (0.002)	0.006 *** (0.002)	0.003 ** (0.001)
Controls	Yes	Yes	Yes	Yes
Linear terms	Yes	Yes	Yes	Yes
Quadratic terms	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
N	2366	1313	455	3224

Note: City-clustered standard errors are reported in parentheses. ** $p < 0.05$, *** $p < 0.01$.

The findings indicate that the Green Finance Reform and Innovation Pilot Zones policy exerts a more pronounced effect on the enhancement of supply chain resilience in large cities. Specifically, the estimated policy coefficient for large cities is 0.004 and is significantly positive at the 10% significance level. In contrast, the estimated coefficient for small- and medium-sized cities is 0.001, but it fails to pass the statistical significance test.

The pattern is consistent with large cities possessing stronger financial agglomeration, more mature digital infrastructure, and greater industrial coordination capacity. These attributes not only attract larger green finance flows but also facilitate the efficient conversion of financial resources into tangible resilience gains.

5.3.3. Heterogeneity by Administrative Hierarchy

A further heterogeneity cut distinguishes central cities from peripheral cities to test whether administrative rank conditions the policy effect.

The GFRIZ significantly raises supply chain resilience in central cities. Peripheral cities also register a positive effect, but of smaller magnitude.

Central cities enjoy deeper financial markets, stronger industrial foundations, richer innovation ecosystems, and more capable institutions for converting green finance policy into resilience outcomes. The gap between central and peripheral cities suggests that administrative hierarchy effects are present in the transmission of green finance.

5.3.4. Heterogeneity by Transportation Conditions

The moderating role of transportation conditions is assessed by classifying cities as transport hubs or non-hubs according to the national comprehensive transportation hub designation.

The GFRIZ significantly enhances resilience in both categories, but the effect is substantially larger in hub cities.

This pattern indicates that a well-developed transport network amplifies green finance's contribution to supply chain resilience. Hub cities are positioned to exploit their connectivity advantages to consolidate supply chain resources and extract greater resilience returns from green finance policies.

5.3.5. Heterogeneity by Industrial Foundation

Heterogeneity linked to industrial heritage is investigated by dividing the sample into old industrial base cities and all remaining cities. Table 9 reports the estimates by transport hub status and industrial heritage.

Table 9. Heterogeneity by transport hub status and industrial heritage.

Variable	Non-Hub	Hub	Non-Old Industrial	Old Industrial Base
GFRIZ	0.003 * (0.002)	0.010 *** (0.003)	0.008 * (0.003)	0.003 *** (0.001)
Controls	Yes	Yes	Yes	Yes
Linear terms	Yes	Yes	Yes	Yes
Quadratic terms	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
N	3432	247	2457	1222

Note: City-clustered standard errors are reported in parentheses. * $p < 0.1$, *** $p < 0.01$.

The GFRIZ significantly bolsters resilience in old industrial bases. Cities without a legacy industrial base also benefit, though the effect is somewhat weaker.

Old industrial bases confront acute transformation pressures and pressing infrastructure renewal needs. Green finance directly targets these demands, and the pre-existing industrial workforce and accumulated production experience in these cities facilitate the absorption and conversion of green finance resources. Cities without a legacy industrial base, characterized by more diversified economies, capture a broader but less concentrated set of resilience improvements.

6. Mechanism Analysis and Spatial Spillovers

6.1. Mechanism Analysis

The mechanism model has been specified in Section 4.1.2. This section reports whether infrastructure upgrading serves as a transmission channel through which the GFRIZ policy affects urban supply chain resilience. The analysis focuses on three mediating variables: digital infrastructure, green infrastructure, and transport infrastructure. Public works infrastructure is not retained in the revised framework because not all public works projects can be clearly classified as green or sustainability-oriented infrastructure.

Columns (1) and (2) of Table 10 report the results for digital infrastructure. Column (1) shows that the GFRIZ policy significantly improves digital infrastructure. In Column (2), digital infrastructure is positively and significantly associated with urban supply chain resilience after controlling for the GFRIZ policy. The coefficient of GFRIZ remains significant, indicating that digital infrastructure plays a partial mediating role. The estimated indirect effect is 0.00007, and the Sobel statistic is 1.67, which is significant at the 10% level. This result provides supplementary evidence for the digital infrastructure channel and supports Hypothesis 2.

Digital infrastructure can strengthen supply chain resilience by improving information exchange, digital coordination, and risk monitoring. Through internet-related employment, telecommunication services, mobile connectivity, and digital inclusive finance, the GFRIZ policy may improve the ability of cities to identify supply chain risks, coordinate production and logistics activities, and respond to disruptions more quickly.

Columns (3)–(4) present the results for green infrastructure. The coefficient of GFRIZ in Column (3) is positive and significant, suggesting that green finance reform promotes green infrastructure investment. In Column (4), green infrastructure has a positive and

significant coefficient in the resilience equation. The GFRIZ coefficient remains significant after green infrastructure is included, indicating partial mediation. The estimated indirect effect is 0.00006, and the Sobel statistic is 3.12, which is significant at the 1% level. This evidence supports Hypothesis 3.

Table 10. Mechanism analysis: infrastructure mediation coefficient estimates.

Variable	Dig	SCR	GII	SCR	TII	SCR
GFRIZ	0.002 *** (0.001)	0.004 *** (0.001)	0.012 *** (0.003)	0.004 *** (0.001)	0.006 *** (0.001)	0.004 *** (0.001)
Dig		0.036 *** (0.012)				
GII				0.005 *** (0.001)		
TII						0.007 *** (0.002)
Indirect effect		0.00007		0.00006		0.00004
Sobel Z		1.67 *		3.12 ***		3.02 ***
Controls		Yes		Yes		Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
N	3705	3705	3705	3705	3705	3705

Note: Dig denotes digital infrastructure, GII denotes green infrastructure, and TII denotes transport infrastructure. Public works infrastructure is excluded from the revised mechanism framework. The indirect effect is calculated as the product of the coefficient of GFRIZ in the mediator equation and the coefficient of the mediator in the resilience equation. Sobel Z statistics are reported as supplementary evidence for the significance of the indirect effects. City-clustered standard errors are reported in parentheses. All specifications include city and year fixed effects. * $p < 0.1$, *** $p < 0.01$.

Green infrastructure contributes to urban supply chain resilience by reducing environmental and resource-related risks. Investments in landscaping, environmental sanitation, waste treatment, and sewage treatment can improve the environmental conditions of production and circulation systems. These improvements may lower ecological pressure, reduce compliance costs, and enhance the long-term stability of supply chain operations.

Columns (5)–(6) examine the transport infrastructure channel. Column (5) shows that the GFRIZ policy significantly promotes transport infrastructure upgrading. Column (6) further shows that transport infrastructure is positively and significantly related to urban supply chain resilience. Since the GFRIZ coefficient remains significant, the results indicate partial mediation through transport infrastructure. The estimated indirect effect is 0.00004, and the Sobel statistic is 3.02, significant at the 1% level. This finding supports Hypothesis 4.

Transport infrastructure strengthens the physical circulation capacity of urban supply chains. Improvements in rail and public transit investment, road investment, and bridge investment can reduce logistics costs, shorten delivery time, and increase route substitutability when disruptions occur. Unlike green infrastructure, transport infrastructure is not treated as a green project by definition. Its contribution lies in improving logistics connectivity and recovery capacity.

Overall, the results suggest that the GFRIZ policy enhances urban supply chain resilience through three infrastructure channels. Digital infrastructure improves information coordination, green infrastructure reduces environmental and resource risks, and transport infrastructure strengthens logistics circulation and recovery capacity. The Sobel tests provide supplementary evidence that the indirect effects through these three mediators are statistically meaningful. Because the GFRIZ coefficient remains significant after each mediator is included, the evidence is more consistent with partial mediation than full mediation.

6.2. Spatial Spillovers

Existing research has largely identified GFRIZ effects within individual city boundaries, leaving the question of whether the policy generates cross-boundary spatial externalities underexplored. Because urban supply chains are interlinked across jurisdictions through factor mobility, industrial connections, and logistics networks, estimates confined to within-city variation risk being biased. This section takes up the spatial dimension.

Spatial dependence in urban supply chain resilience is assessed using the Global Moran's I statistic over the sample period, with a geographic distance-based spatial weight matrix. Annual values are displayed in Table 11.

Table 11. Year-by-year Global Moran's I for urban supply chain resilience.

Year	Moran's I	p-Value
2012	−0.055	0.000
2013	−0.056	0.000
2014	−0.055	0.000
2015	−0.062	0.000
2016	−0.061	0.000
2017	−0.070	0.000
2018	−0.071	0.000
2019	−0.073	0.000
2020	−0.071	0.000
2021	−0.066	0.000
2022	−0.077	0.000
2023	−0.075	0.000
2024	−0.073	0.000

Figures 4–6 present the Moran scatter plots for 2012, 2018, and 2024, respectively. The fitted regression slopes are uniformly negative, and the preponderance of cities lies in the second and fourth quadrants, reinforcing the evidence of negative spatial autocorrelation. The spatial configuration is one of dispersion: high-resilience cities typically have low-resilience neighbors, and vice versa.

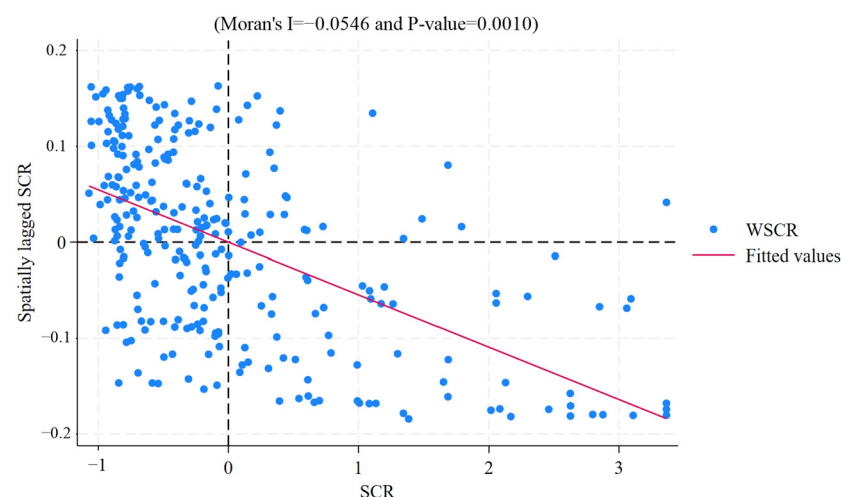


Figure 4. Moran scatter plot of urban supply chain resilience in 2012. Blue circles represent city observations; the red solid line is the fitted regression line; black dashed lines mark zero.

The spatial econometric specification has been introduced in Section 4.1.3. In this section, the LM tests, robust LM tests, Wald tests, and Hausman test are reported as supplementary diagnostic evidence for the appropriateness of the Spatial Durbin Model.

These tests are not used to introduce the spatial model from scratch but to verify whether the selected SDM is consistent with the spatial dependence pattern observed in the data. Table 12 summarizes the diagnostic results.

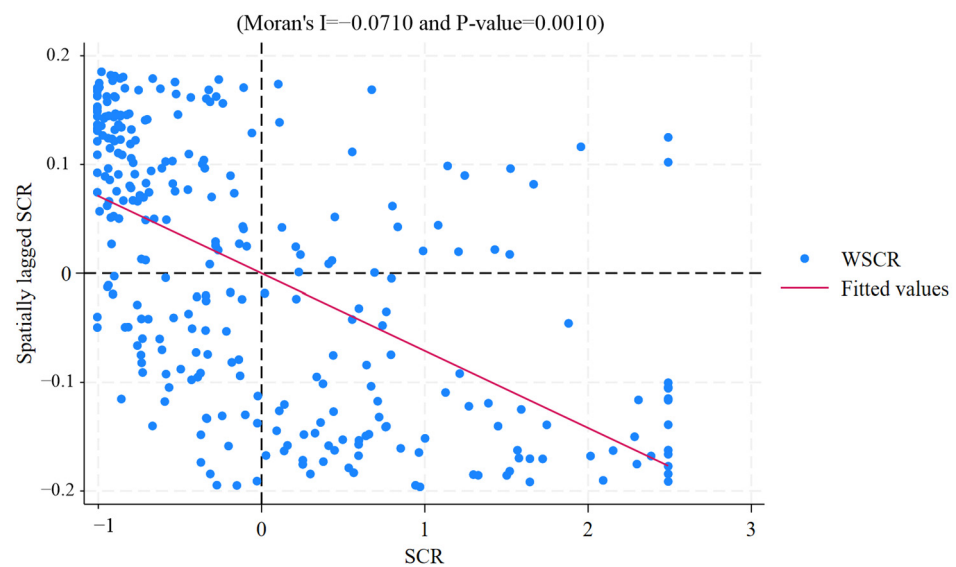


Figure 5. Moran scatter plot of urban supply chain resilience in 2018. Blue circles represent city observations; the red solid line is the fitted regression line; black dashed lines mark zero.

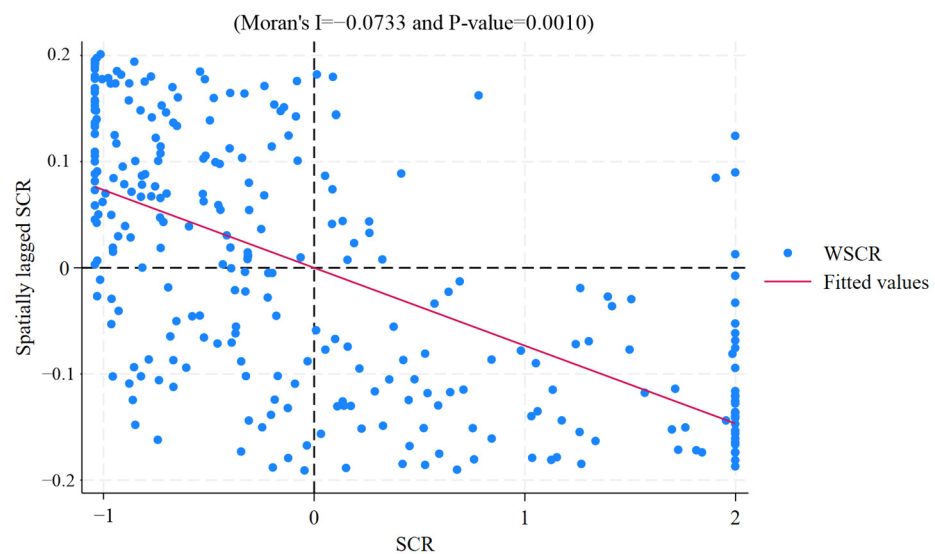


Figure 6. Moran scatter plot of urban supply chain resilience in 2024. Blue circles represent city observations; the red solid line is the fitted regression line; black dashed lines mark zero.

Table 12. Diagnostic tests for the Spatial Durbin Model.

Test	Method	Statistic	<i>p</i> -Value
LM error test	LM_error	76.415	0.000
LM error test (robust)	LM_error_robust	58.902	0.000
LM lag test	LM_lag	55.364	0.000
LM lag test (robust)	LM_lag_robust	43.771	0.000
Wald test (SAR)	Wald	8.61	0.000
Wald test (SEM)	Wald	5.29	0.000
Hausman test	FE vs RE	−10.42	—

The LM and robust LM tests indicate that spatial dependence exists in urban supply chain resilience. Both spatial lag dependence and spatial error dependence are statistically significant, suggesting that a model focusing only on the spatial lag term or only on the spatial error term may be too restrictive. This provides empirical support for using the SDM, which offers a more general framework by incorporating the spatial lag of the dependent variable and the spatial lag of explanatory variables.

The Wald tests further reject the restrictions that would reduce the SDM to either a spatial autoregressive model or a spatial error model. This result indicates that the SDM should not be simplified into SAR or SEM. In addition, the Hausman test supports the use of fixed effects rather than random effects. Taken together, these diagnostic results provide further support for the two-way fixed effects SDM used in the spatial spillover analysis.

Table 13 reports the SDM estimates and effect decomposition. From the decomposition, the direct GFRIZ effect on supply chain resilience stands at 0.002 at the 1% significance level, corroborating the within-city resilience gain documented in the baseline regressions. The indirect effect, representing the spatial externality transmitted to neighboring cities, equals 0.052 at the 1% significance level. This is a striking result: even though the underlying spatial correlation is negative (pointing to inter-city competition), the GFRIZ generates a positive externality for nearby cities, operating through capital flows, industrial coordination, and knowledge diffusion.

Table 13. Spatial Durbin Model estimates and effect decomposition.

Variable	Main	Direct	Indirect	Total
GFRIZ	0.003 *** (0.001)	0.002 *** (0.001)	0.052 *** (0.009)	0.054 *** (0.010)
Spatial ρ	−0.082 *** (0.020)	—	—	—
$W \times \text{GFRIZ}$	0.112 *** (0.015)	—	—	—
σ^2	0.001 *** (0.000)	—	—	—
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
N	3705	3705	3705	3705
R ²	0.178	0.178	0.178	0.178

Note: Standard errors are reported in parentheses. *** $p < 0.01$.

The total effect equals 0.054 and is significantly positive at the 1% level. Once spatial spillovers are accounted for, the regional welfare gain from the GFRIZ substantially outstrips the local effect. Hypothesis 5 is supported.

Figures 7–9 cartographically depict the spatial distribution of urban supply chain resilience in 2012, 2018, and 2024, providing a visual counterpart to the formal spatial econometric results.

The spatial pattern consistently follows an east-high, west-low gradient. The Yangtze River Delta, Pearl River Delta, Beijing–Tianjin–Hebei region, and Shandong Peninsula form the durable high-resilience core. Cities located in interior and western regions systematically register lower resilience values.

Across the 2012–2024 observation window, urban supply chain resilience in China follows a steady upward path. The number of cities classified as high-resilience grows, and spatial diffusion of resilience intensifies. The post-2017 period, synchronous with GFRIZ deployment, displays a notably pronounced improvement trajectory in central and eastern

regions, suggesting that the expansion of green finance, infrastructure upgrading, and regional industrial coordination jointly contributed to strengthening resilience.

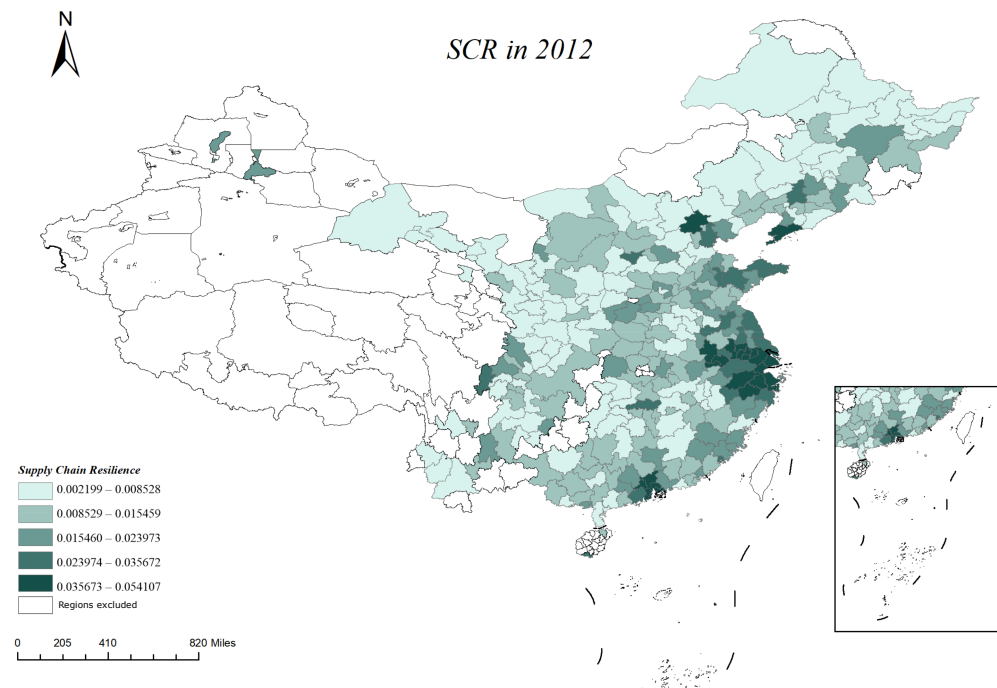


Figure 7. Spatial distribution of urban supply chain resilience in 2012.

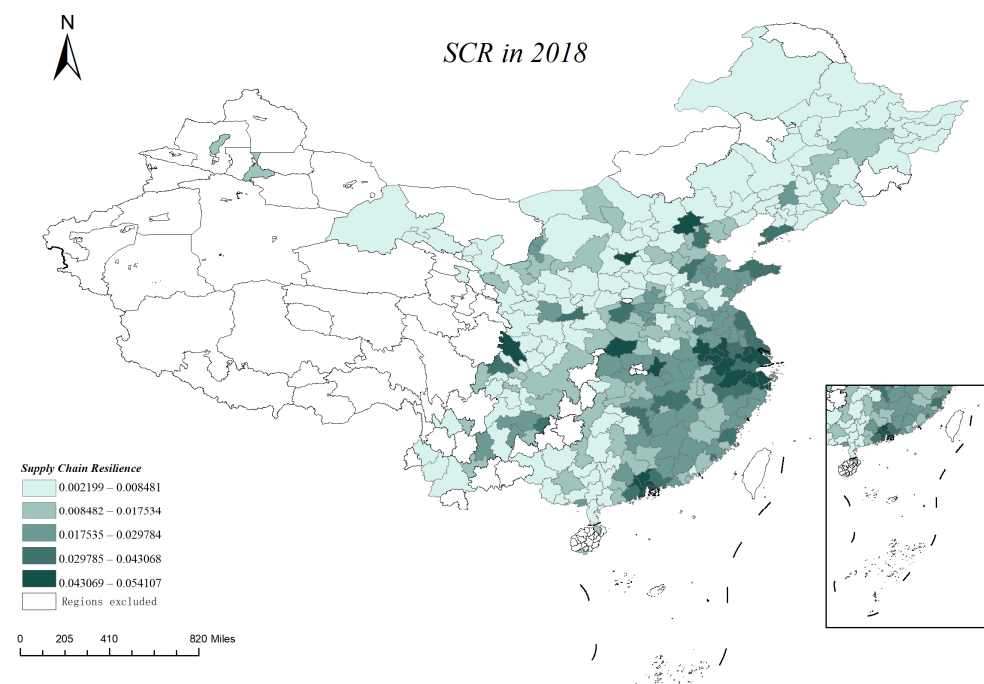


Figure 8. Spatial distribution of urban supply chain resilience in 2018.

Both high-resilience and low-resilience cities exhibit tendencies toward spatial clustering. Cities with comparable resilience levels tend to be geographically proximate, visually corroborating the spatial dependence patterns identified in the Moran and SDM analyses.

Leveraging the GFRIZ as a quasi-natural experiment, this paper combines Double Machine Learning with spatial econometric techniques on a panel of 285 prefecture-level cities

(2012–2024) to produce causal estimates of green finance policy's impact on urban supply chain resilience and to elucidate the mechanisms involved. A set of core findings emerges.

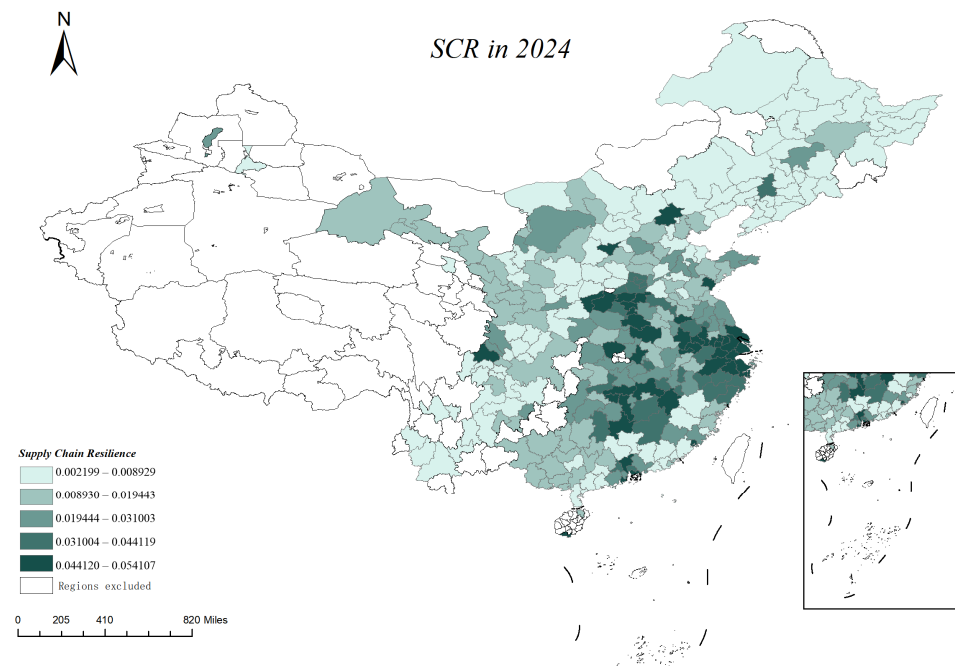


Figure 9. Spatial distribution of urban supply chain resilience in 2024.

The first is that the GFRIZ policy materially elevates urban supply chain resilience. The causal claim rests on verified parallel trends and withstands an extensive set of sensitivity checks: alternative estimators, interactive fixed effects, winsorization, pandemic-year removal, and randomization-based placebo procedures in both constrained and unconstrained formats. Collectively, these checks dispel concerns about model dependency, hidden heterogeneity, outlier influence, and spurious correlation.

Second, the mechanism analysis demonstrates that digital infrastructure, green infrastructure, and transport infrastructure partially mediate the GFRIZ–resilience relationship. Rather than operating through a single dominant channel, green finance exerts its influence through a complementary configuration of infrastructure pathways: digital infrastructure provides the information coordination backbone, green infrastructure reduces environmental and resource-related risks, and transport infrastructure strengthens physical connectivity and recovery capacity.

Third, the GFRIZ effect is heterogeneous across contexts. The strongest impacts concentrate in eastern and central regions, large metropolitan areas, transport hubs, and old industrial bases, settings distinguished by deeper financial markets, stronger industrial coordination, and more developed infrastructure complementarities. Cities with weaker absorptive capacities reap smaller benefits, raising the concern that green finance, if deployed without accompanying support measures, could widen rather than close cross-city resilience gaps.

Fourth, urban supply chain resilience exhibits pronounced negative spatial autocorrelation, a competitive checkerboard pattern. Yet, the GFRIZ nonetheless transmits positive spatial spillovers to neighboring cities via capital mobility, industrial linkages, and technological diffusion. The regional welfare impact of the policy therefore surpasses its direct local effect, highlighting the importance of accounting for spatial externalities in both policy evaluation and policy design.

Several caveats deserve acknowledgment. Although the quasi-experimental design supports credible causal identification, the analysis is conducted at the prefectural city

level and cannot capture within-city heterogeneity or firm-level behavioral mechanisms. The Chinese institutional context, characterized by strong central-state implementation capacity, may produce effect magnitudes that do not directly generalize to market-economy settings with different governance architectures. The data extend only through 2024, limiting the ability to analyze longer-run dynamics as green finance instruments mature and infrastructure investments fully come online.

This study also does not incorporate international firm-level microdata or granular supply chain relationship data, constraining the capacity to detect heterogeneous responses across firm types and supply chain configurations. The external validity of the findings merits testing in a broader range of institutional and economic contexts.

Future research would gain from exploiting firm-level microdata, cross-country comparative designs, and longer temporal spans to deepen the evidence on the green finance–supply chain resilience nexus. Investigations of nonlinear and threshold effects, along with interactions between green finance and adjacent policy instruments, carbon pricing, digital economy programs, and industrial policy, would further strengthen the evidence base for integrated sustainability and resilience governance.

7. Discussion and Policy Implications

Building on the empirical evidence presented above and being mindful of the practical urgency of scaling green finance while securing supply chains globally, the following policy recommendations are offered.

First, national green finance frameworks should be deepened and supply chain resilience should be embedded as an explicit objective in green finance assessment and evaluation systems. Green credit guidelines and green bond taxonomies should recognize supply chain resilience as a valid policy target alongside environmental metrics. Monitoring and disclosure mandates should be strengthened to direct capital more precisely toward resilience-enhancing supply chain infrastructure.

Second, governments should pursue coordinated investment across digital, green, and transport infrastructure. An integrated infrastructure investment framework that aligns green finance flows with information systems, sustainability-oriented environmental facilities, and logistics connectivity can maximize resilience dividends while also supporting environmental and economic objectives.

Third, green finance policy should be differentiated according to cities' and regions' development stages and absorptive capacities. In settings with mature financial systems and dense industrial networks, policy can pursue frontier resilience objectives, intelligent supply chain platforms, AI-optimized logistics, and advanced green logistics systems. In less developed areas, the priority should be foundational support: basic infrastructure financing, technical assistance, risk-sharing mechanisms, and capacity-building programs that equip these areas to absorb and productively deploy green finance capital.

Fourth, international collaboration on green finance and supply chain resilience should be intensified. Countries should work toward harmonized green finance taxonomies, shared supply chain risk monitoring frameworks, and joint green investment platforms that facilitate cross-border capital flows into resilience-enhancing infrastructure. International coordination can help internalize the cross-boundary externalities that national green finance policies inevitably create.

Fifth, the spatial spillover dimension of green finance policy deserves greater attention from policymakers. Regional coordination mechanisms, cross-city green investment platforms, coordinated infrastructure planning, and joint supply chain risk monitoring should be put in place to capture the positive spatial externalities documented here. Such

mechanisms can help convert the current competitive checkerboard pattern of resilience into a more cooperative and spatially balanced configuration.

Author Contributions: Methodology, Y.W.; formal analysis, X.D.; writing—original draft preparation, Y.W.; writing—review and editing, X.L. and Y.W.; project administration, X.L.; funding acquisition, X.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Shandong Provincial Natural Science Foundation of China, with grant number ZR2023QG141.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Data on the dependent variable and control variables were compiled from the China City Statistical Yearbook, China Construction Industry Statistical Yearbook, provincial statistical yearbooks, and the CSMAR database.

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

References

- Shi, D.; Shi, X. Green Finance and High-Quality Economic Development: Mechanisms, Characteristics, and Empirical Evidence. *Stat. Res.* **2022**, *39*, 31–48. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eSHQ8zYcSz-AsGsTE7DQJULTBkmdT1-0MQHUXT0OjZ1SAUezuzDHIXpH1Uc2SbHp3WsKs_XhVRiuhJaSW3JuM28vHszbCH9G9gpwbje-KPy9_6xXmQkrMJLi_fE84bK69U9Rv97nQ_qp-86DHZNdriPPgfCUyUR0fQ=&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese) [CrossRef]
- Lee, C.-C.; Lee, C.-C. How does green finance affect green total factor productivity? Evidence from China. *Energy Econ.* **2022**, *107*, 105863. [CrossRef]
- Liu, C.; Xiong, M. Green finance reform and corporate innovation: Evidence from China. *Financ. Res. Lett.* **2022**, *48*, 102993. [CrossRef]
- Zhang, Z.; Wang, J.; Feng, C.; Chen, X. Do pilot zones for green finance reform and innovation promote energy savings? Evidence from China. *Energy Econ.* **2023**, *124*, 106763. [CrossRef]
- Zhao, X.; Benkraiem, R.; Abedin, M.Z.; Zhou, S. The charm of green finance: Can green finance reduce corporate carbon emissions? *Energy Econ.* **2024**, *134*, 107574. [CrossRef]
- Li, Z.; Song, Z. Green finance reform and innovation pilot zones: A catalyst for green development efficiency in Chinese cities. *J. Clean. Prod.* **2025**, *525*, 146576. [CrossRef]
- Spieske, A.; Birkel, H. Improving supply chain resilience through Industry 4.0: A systematic literature review under the impressions of the COVID-19 pandemic. *Comput. Ind. Eng.* **2021**, *158*, 107452. [CrossRef] [PubMed]
- Belhadi, A.; Kamble, S.; Fosso Wamba, S.; Queiroz, M.M. Building supply-chain resilience: An artificial intelligence-based technique and decision-making framework. *Int. J. Prod. Res.* **2022**, *60*, 4487–4507. [CrossRef]
- Chernozhukov, V.; Chetverikov, D.; Demirer, M.; Duflo, E.; Hansen, C.; Newey, W.; Robins, J. Double/debiased machine learning for treatment and structural parameters. *Econom. J.* **2018**, *21*, C1–C68. [CrossRef]
- Ivanov, D. Supply chain viability and the COVID-19 pandemic: A conceptual and formal generalisation of four major adaptation strategies. *Int. J. Prod. Res.* **2021**, *59*, 3535–3552. [CrossRef]
- Negri, M.; Cagno, E.; Colicchia, C.; Sarkis, J. Integrating sustainability and resilience in the supply chain: A systematic literature review and a research agenda. *Bus. Strategy Environ.* **2021**, *30*, 2858–2886. [CrossRef]
- Yu, C.-H.; Wu, X.; Zhang, D.; Chen, S.; Zhao, J. Demand for green finance: Resolving financing constraints on green innovation in China. *Energy Policy* **2021**, *153*, 112255. [CrossRef]
- Xu, X.; Xie, Y.; Obobisa, E.S.; Sun, H. Has the establishment of green finance reform and innovation pilot zones improved air quality? Evidence from China. *Humanit. Soc. Sci. Commun.* **2023**, *10*, 262. [CrossRef]
- Fan, M.; Liu, W.; Yao, D. The impact of green finance reform and innovation pilot zones on corporate pollution and carbon reduction: From the perspective of dual objective constraints. *J. Environ. Manag.* **2025**, *389*, 126110. [CrossRef] [PubMed]
- Fu, B.; Zhang, Y.; Maani, S.; Wen, L. Green finance and job creation: Analyzing employment effects in China's manufacturing industry within green finance innovation and reform pilot zones. *Energy Econ.* **2025**, *141*, 108090. [CrossRef]
- 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]

17. Wang, J.; Li, X.; Zhang, T.; He, C.; Zhu, L. The impact of green finance reform and innovation policies on green investors in China. *Financ. Res. Lett.* **2025**, *83*, 107709. [CrossRef]
18. Wang, B.; Dong, K.; Taghizadeh-Hesary, F. Can green finance promote high-quality energy development? The case of China. *J. Risk Financ.* **2024**, *25*, 64–79. [CrossRef]
19. Huang, F.; Ren, Y. Harnessing the green frontier: The impact of green finance reform and digitalization on corporate green innovation. *Financ. Res. Lett.* **2024**, *66*, 105554. [CrossRef]
20. Mao, X.; Wang, R. Green Finance and New Quality Productive Forces: Promotion or Inhibition? Evidence from Technological Innovation and Environmental Attention. *J. Shanghai Univ. Financ. Econ.* **2024**, *26*, 30–45. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eRrsuGtrCa82WlhzV6AC8L69HoqL_SM8oe8a-Pp9LFMOeFrYmqDxsp7bSKpRB44UIIdGf-CX2A11q_CK4p3XI2A6OeY98ZOAd1XgsOwEAWs-Cgh9ITHgUA2L0CWIFF9DGleRL8kD7z8rHnMExCv5YRgk0hNvHfmCr-Ae2akk4Pi-Iw==&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese)
21. Ponomarov, S.Y.; Holcomb, M.C. Understanding the concept of supply chain resilience. *Int. J. Logist. Manag.* **2009**, *20*, 124–143. [CrossRef]
22. Sarkis, J. Supply chain sustainability: Learning from the COVID-19 pandemic. *Int. J. Oper. Prod. Manag.* **2021**, *41*, 63–73. [CrossRef]
23. Queiroz, M.M.; Ivanov, D.; Dolgui, A.; Fosso Wamba, S. Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid the COVID-19 pandemic through a structured literature review. *Ann. Oper. Res.* **2022**, *319*, 1159–1196. [CrossRef] [PubMed]
24. Dubey, R.; Bryde, D.J.; Blome, C.; Roubaud, D.; Giannakis, M. Facilitating artificial intelligence powered supply chain analytics through alliance management during the pandemic crises in the B2B context. *Ind. Mark. Manag.* **2021**, *96*, 135–146. [CrossRef]
25. Modgil, S.; Singh, R.K.; Hannibal, C. Artificial intelligence for supply chain resilience: Learning from COVID-19. *Int. J. Logist. Manag.* **2022**, *33*, 1246–1268. [CrossRef]
26. Cai, J.; Sharkawi, I.; Taasim, S.I. How does digital transformation promote supply chain diversification? From the perspective of supply chain transaction costs. *Financ. Res. Lett.* **2024**, *63*, 105399. [CrossRef]
27. Yang, R.; Li, Y.; Meng, S. Enterprise Digital Development, Total Factor Productivity, and Industrial Chain Spillover Effects. *Econ. Res. J.* **2023**, *58*, 44–61. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eShJH1UqUx4QmHsZ0-U1fNDQJIZTPkDwB2BYgLmjv_Rhqm-xRRFBsvufmbMvih6slx-sUBZH311qVvN9doogN6AErpSbyZXZ-FUZckokdU5A0PxK6-ZrwIKBHWUfFESGB4mgUHQ8y6fvPgk1VPZLUxGeHNvwWwsF2g3x92o-gsKK-g==&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese)
28. Kamalahmadi, M.; Shekarian, M.; Mellat Parast, M. The impact of flexibility and redundancy on improving supply chain resilience to disruptions. *Int. J. Prod. Res.* **2022**, *60*, 1992–2020. [CrossRef]
29. Nikoogar, E.; Yanadori, Y. Preparing supply chain for the next disruption beyond COVID-19: Managerial antecedents of supply chain resilience. *Int. J. Oper. Prod. Manag.* **2022**, *42*, 59–90. [CrossRef]
30. El Baz, J.; Ruel, S. Can supply chain risk management practices mitigate the disruption impacts on supply chains' resilience and robustness? Evidence from an empirical survey in a COVID-19 outbreak era. *Int. J. Prod. Econ.* **2021**, *233*, 107972. [CrossRef] [PubMed]
31. Raaymann, S.; Spinler, S. Measuring supply chain resilience along the automotive value chain—A comparative research on literature and industry. *Transp. Res. Part E Logist. Transp. Rev.* **2024**, *192*, 103792. [CrossRef]
32. He, Q.; Gao, X.; Huang, J. Industrial Robot Application and Manufacturing Industrial and Supply Chain Resilience: Evidence from Chinese Firms' Embeddedness in Global Value Chains. *J. Int. Trade* **2024**, *2*, 71–89. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eSAuq3UTlzn-FIID_yvy6y5kGa7Vljin_d5f1e9fkwyDTVz6E0nncTcczeB-FDRHrl-tUaThL2-GilhYX2LbT1cTZvh1GmAXAO1Y9BgahvPgKgwrQZzAbkiVKvAgJyi8TnW9_aGMxus5fckN000_ZN4Dr7Qd5PFTnhU_WeuUAK-xv_A==&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese)
33. Hu, J.; Zhang, H.; Irfan, M. How does digital infrastructure construction affect low-carbon development? A multidimensional interpretation of evidence from China. *J. Clean. Prod.* **2023**, *396*, 136467. [CrossRef]
34. Zhou, X.; Hu, Q.; Luo, H.; Hu, Z.; Wen, C. The impact of digital infrastructure on industrial ecology: Evidence from the Broadband China strategy. *J. Clean. Prod.* **2024**, *447*, 141589. [CrossRef]
35. Chen, S.; Wang, Z.; Du, D.; Kong, Q. How does green-infrastructure investment empower urban sustainable development? Mechanisms and empirical tests. *Sustainability* **2025**, *17*, 5751. [CrossRef]
36. Lin, L.; Yang, Q. Does Green Infrastructure Investment Reduce Carbon Emissions? *Mod. Econ. Res.* **2022**, *12*, 29–37. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eRhTOXNUhJHI-M7zuEM4-OGZ-gDb9kvf8DZCvnHhoMgHlr_jmY3hxl78ybNLmjZ6LkoYkrbilZ9szqM6g36IKM2M3-PIXvH9YqtOTFm4TQxTVbYlhbY-uoGkyRcmTG0zjtVydRbbGoejKov9zcb-Rcrh7xnfZklJj_VZvnB7e6AU7Q==&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese)

37. Yang, Y.; Wu, S.; Zhang, X. Can Expressways Promote Rural Revitalization? Evidence from the “Thousand Villages Survey” of Shanghai University of Finance and Economics. *J. Financ. Econ.* **2024**, *50*, 79–93. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eQuoD2JKYwMhVkwYk9-dQG9k2UaC8TFvjPISFpA1ZB1RFS3iDJiNi0oL3ldMSDxbVymRwn0-IcZ8xtsuL8IrTnGjg362O3jwHLC30zG8BXemezMD1K_UevPLB8ueNwA0Nre-MXYV-mkdWfi1GU9NoBApPQNIXUFovVUBU3-jS0UShg==&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese)
38. Tong, J.; Zhang, C.; Yan, Y. New Infrastructure Construction and High-Quality Economic Development in China. *Manag. Rev.* **2024**, *36*, 81–93. (In Chinese)
39. Li, Q.; Liu, L.; Shao, J. Digital Transformation, Supply Chain Integration, and Firm Performance: The Moderating Effect of Entrepreneurship. *Econ. Manag.* **2021**, *43*, 5–23. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eTGAjs6y84JwLrdNRPaUnh-0cq-d-oRLGNpW45qLdL5fkZvwqwAkQle0Fn1CdhBy_RQHDQ1B3l4E5Ydklv3BX5AU05IJR-jwP2L7rGF84LrqvZ-Z0iUoSdLIXqeJBPAQZY0iCmmFYI9wQDnQoGeh4f_g2nJV664wrXBgmXf7w_Sww==&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese)
40. Yang, R.; Zheng, Y. The Impact of Digital Economy Development on the Evolution and Resilience of Global Value Chain Specialization. *J. Quant. Technol. Econ.* **2023**, *40*, 69–89. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eTwWiADCPXn-WrbLqp5zPLYiInQgqms5pIbS8CdujLZDTa7CEn6r2x4-ZRn6DPeNMSqG9eQSEgu15JoSlosiYjDfOePyg6z-DbMz6QamY6C5Bm6h_ZvVqoNOnQI8b64J3C9AZc1yNtAbjdM1EcppdqFj7wBuc_hARNE=&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese)
41. Lee, C.-C.; Song, H.; An, J. The impact of green finance on energy transition: Does climate risk matter? *Energy Econ.* **2024**, *129*, 107258. [CrossRef]
42. Ping, W.; Pan, F.; Han, Y.; Huang, F.; Shi, H. Climate-resilient city pilot and green economy: A study of local and peer effects. *J. Environ. Manag.* **2025**, *392*, 126812. [CrossRef] [PubMed]
43. Ma, L.; Li, X.; Pan, Y. Global industrial chain resilience research: Theory and measurement. *Systems* **2023**, *11*, 466. [CrossRef]
44. Tao, F.; Wang, X.; Xu, Y.; Zhu, P. Digital Transformation, Industrial and Supply Chain Resilience, and Firm Productivity. *China Ind. Econ.* **2023**, *5*, 118–136. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eRNPwNb84pHMFQ-7aMSN_LI5O53-TdcHyyOMYDCNVlxGm9WDL2x6ii87qpe1FEkzTxyfl0NngQnFCiUSjizM6VyhDzlucfOoqkYPcpoPzZGdjoYlvX-x-djtrqhtDSeKWN1J1g_eR_qPFBR9QQo9T6BBMJjUfBwPFv82mefH3EYjA==&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese)
45. Baron, R.M.; Kenny, D.A. The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *J. Pers. Soc. Psychol.* **1986**, *51*, 1173–1182. [CrossRef] [PubMed]
46. Sobel, M.E. Asymptotic confidence intervals for indirect effects in structural equation models. *Sociol. Methodol.* **1982**, *13*, 290–312. [CrossRef]
47. Zhao, T.; Zhang, Z.; Liang, S. Digital Economy, Entrepreneurial Activity, and High-Quality Development: Empirical Evidence from Chinese Cities. *Manag. World* **2020**, *36*, 65–76. Available online: https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eRVuiskIl4L68pHzmAGg-DxMtiXEXtkrKd-yXcASnTGSCKrHG7JHQADxRzwhirQyADXHvo4rroRxyZzhqxr4e5b0CFtFbZ-8Nu4tAUiIqnmlZ9UAFc9Fs9m_Zkleb2tYjK6mcP626aXDm9AzZBpm0jIg5zt7Ld0-LOpjTg9HAEvQ==&uniplatform=NZKPT&language=CHS (accessed on 11 July 2026). (In Chinese)
48. Liao, M.; Xu, Z.; Hu, C.; Yu, C. Can Infrastructure Investment Still Promote Economic Growth? Evidence from Provincial Panel Data, 1994–2016. *Manag. World* **2018**, *34*, 63–73. Available online: <https://kns.cnki.net/kcms2/article/abstract?v=jit-Bskw5eSltvt2mfefVOOU9ThrntCOapxNBA06tA1nWoIk5Xy8UznkUZAnc8EROP7tGx3JM9rtw60O8d0bjXDl8PjT5cJBKT5QQwh-xruTPpZ0QhGkUOJaekzYVLWkoO94ITD56HOMxQhbbNSWUD-YsLaCje5lYawkdMazn3OvnaYYv9kpKg==&uniplatform=NZKPT&language=CHS> (accessed on 11 July 2026). (In Chinese)

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.