frontiers | Frontiers in Environmental Science

TYPE Community Case Study
PUBLISHED 29 August 2025
DOI 10.3389/fenvs.2025.1636479

OPEN ACCESS

EDITED BY
Xingwei Li,
Sichuan Agricultural University, China

REVIEWED BY
Haoxiang Zhao,
Chinese Academy of Sciences, China
Yilin Zheng,
Tianjin University of Commerce, China
Han Hu,
Hunan University, China

*CORRESPONDENCE
Zhongfeng Pan,
328113921@qq.com

RECEIVED 29 May 2025
ACCEPTED 12 August 2025
PUBLISHED 29 August 2025

CITATION
Li Y, Pan Z and Shen Y (2025) Regional integration policies and ecological resilience: a case study of urban agglomeration planning policies in China.
Front. Environ. Sci. 13:1636479.
doi: 10.3389/fenvs.2025.1636479

Regional integration policies and ecological resilience: a case study of urban agglomeration planning policies in China

Yuanzhu Li[1], Zhongfeng Pan[2]* and Yang Shen[3]

[1]School of Land Resources and Environment, Jiangxi Agricultural University, Nanchang, China, [2]Wuhan City Polytechnic, Wuhan, China, [3]Institute of Quantitative Economics and Statistics, Huaqiao University, Xiamen, China

Facing the severe challenges of global climate change, cities must transition to regenerative, equitable, and adaptive systems, which serves as the cornerstone of urban sustainable development. This study employs a multi-period difference-in-differences approach as a quasi-natural experiment to investigate how regional integration policies (RIP) shape urban ecological resilience (UER), with a particular concentration on the underlying mechanisms. The findings demonstrate that Regional integration significantly enhances urban ecological resilience. Heterogeneity analysis reveals that RIP exerts a pronounced positive effect on UER in eastern cities, whereas its impact is statistically insignificant in central and western regions. Moreover, the policy exerts a substantially stronger influence on provincial capitals compared to non-capital cities. RIP affects UER primarily through industrial structure upgrading and technological innovation. These analysis demonstrate the critical role of inter-city interactions and interdependencies in cross-administrative ecological governance, providing a scientific foundation for optimizing regional governance frameworks and enhancing ecological security.

KEYWORDS

urban ecological resilience, regional integration policies, multi-period difference-in-differences model, urban agglomeration, upgrading of industrial structure, technological innovation

1 Introduction

Since the 20th century, global population growth and accelerated industrialization have led to an unprecedented expansion in the intensity and scope of human disturbances to ecosystems (Lloren and McCune, 2024). The world's ecosystems are undergoing unprecedented perturbations and degradation, posing existential threats to human societies and development. Concurrently, influenced by climate change, urban uncertainties and risks are escalating (Contreras and Platania, 2019; Shen et al., 2023; Liu et al., 2024), while the declining resilience of regional ecosystems has become a critical factor constraining sustainable development and jeopardizing regional ecological security. Under the dual pressures of intensifying global climate change and rapid urbanization, the vulnerability of urban ecosystems has become increasingly pronounced (Almulhim et al., 2024; Haque and Sharifi, 2024). China's rapid urbanization has precipitated severe ecological challenges, with urban ecological resilience (UER) construction confronting the dual dilemmas of ecosystem degradation and inadequate risk response (Li and Wang, 2023). Strengthening urban ecological governance and enhancing UER have thus emerged as core imperatives for urban development (Afriyanie et al., 2020; Han et al., 2023).

UER refers to the ability of an ecosystem to maintain its structural and functional integrity following disturbances, or to reorganize and adapt to new environmental conditions (Asghar et al., 2025). Traditional urban ecological studies have predominantly focused on isolated elements, whereas resilience-oriented governance emphasizes a systems-thinking approach (Zhang et al., 2025). Regional integration demonstrates to significantly enhance UER by fostering cross-jurisdictional collaboration and collective governance mechanisms (Yin et al., 2024). Under a regional coordination framework, urban agglomerations employ ecological compensation mechanisms and joint environmental regulation to dismantle administrative barriers, thereby optimizing the allocation of ecological resources and reinforcing the holistic stability of ecosystems (Wang et al., 2022; Wang and Shao, 2025).

UER is a critical component of the multidimensional spatial construction of resilient cities. It encompasses the inherent ability of urban ecosystems to resist, rebound from, and adjust to various external disturbances (Feng et al., 2024). UER plays a vital role in ensuring urban ecological security (Yang et al., 2024). Regional integration policies (RIP), with city clusters as spatial carriers, shape urban spatial organization forms that align with high-quality development by leveraging agglomeration, multiplier, and spillover effects. Furthermore, RIP promotes regional green development synergy through coordinated policy planning, industrial collaboration, management integration, and ecological and environmental protection efforts (Yin et al., 2024). Simultaneously, RIP enhances environmental and ecological governance in peripheral regions by optimizing industrial spatial allocation and facilitating technology spillover. This serves as an operational foundation for integrated regional joint prevention and control efforts aimed at improving overall ecological quality (Lv et al., 2024a; Zhao et al., 2024).

Urban agglomeration represents the primary spatial manifestation of RIP (Feng et al., 2023). The synergistic effect of RIP on the environment is of great significance. Consequently, policy evaluation models are widely employed to assess the environmental impacts of RIP. Existing studies have primarily utilized the differences-in-differences (DID) model (Tan et al., 2022) and the multi-period DID method (Jiang et al., 2022) to examine the positive effects of RIP. These effects include promoting green innovation (Li et al., 2022), reducing carbon emissions (Ai and Xu, 2023), and improving energy efficiency (Wang and Shao, 2025). Given its strong network properties, RIP reshapes the spatial patterns of regional resources and environments, thereby influencing surrounding areas (He et al., 2018). However, some studies reveal that RIP may also exacerbate the spread of risks and degrade environmental quality by facilitating the free flow of factors (Bloise and Tancioni, 2021).

Despite these findings, there is a scarcity of research examining the impact of RIP on UER. While some studies have investigated the impact of RIP on UER within a single-stage framework (Yin et al., 2024), they have largely neglected the multi-period effects of urban agglomeration planning. To fill this research gap, this study empirically analyzes the effects of RIP implementation on UER by employing a multi-period DID model, using 11 national-level urban agglomerations in China as case studies. The contributions of this paper are twofold. First, it transcends the limitations of conventional ecological resilience research that relies predominantly on cross-sectional data or case-study analyses by employing the application of a multi-period DID method. This methodological innovation effectively controls for unobserved temporal trends and individual heterogeneity, thereby providing more robust empirical evidence for assessing the causal effects of policy interventions on UER. Second, the study investigates the cross-administrative boundary mechanisms of ecological governance through RIP and its heterogeneous impacts on UER. By elucidating how inter-city dependencies shape ecological governance outcomes, the findings offer a substantive foundation for formulating differentiated regional ecological governance policies.

2 Literature review

2.1 Comprehensive analysis of urban ecological resilience

Holling (1973) initially proposed the concept of resilience in ecology, defining it as the capacity of an ecosystem to sustain or revert to a stable condition. As a critical dimension of urban resilience assessment, UER is often evaluated using the ecological quality index (Feng et al., 2024). UER represents the dynamic ability of urban ecosystems to manage exogenous environmental shocks (McCloy et al., 2024). Through these mechanisms, it enables ecosystems to recover typically to their original state through defense mechanisms, timely responses, and continuous learning and innovation (Yin et al., 2024). Scholars have investigated the development processes and spatio-temporal patterns of UER across various spatial scales, including countries (Asghar et al., 2025), city clusters (Li et al., 2025), and watersheds (Wang and Pan, 2024). These studies typically employ indicator systems and methodologies such as the entropy weighting method (Xu et al., 2024), comprehensive evaluation method (Yang et al., 2024), and the UERM method (Shamsipour et al., 2024). The enhancement of UER is profoundly influenced by the dynamic interaction between natural and social elements. Natural factors, like topography, vegetation, and water resources, significantly affect UER (Huang et al., 2023). Similarly, social factors, including environmental regulation (Zhang et al., 2024), green infrastructure (Wu et al., 2020), and green finance (Le et al., 2024), also significantly contribute to UER enhancement.

2.2 Urban agglomeration and regional integration

Regional integration (RI) originally refers to the cooperative integration among countries aimed at establishing mutually beneficial relationships and achieving common development (Rakhimov, 2010). Over time, this concept has been adapted to the context of urban agglomeration development (Feng et al., 2023). Notable examples of RI include organizations such as the European Union, ASEAN, and APEC (Krieger-Boden and Soltwedel, 2013).

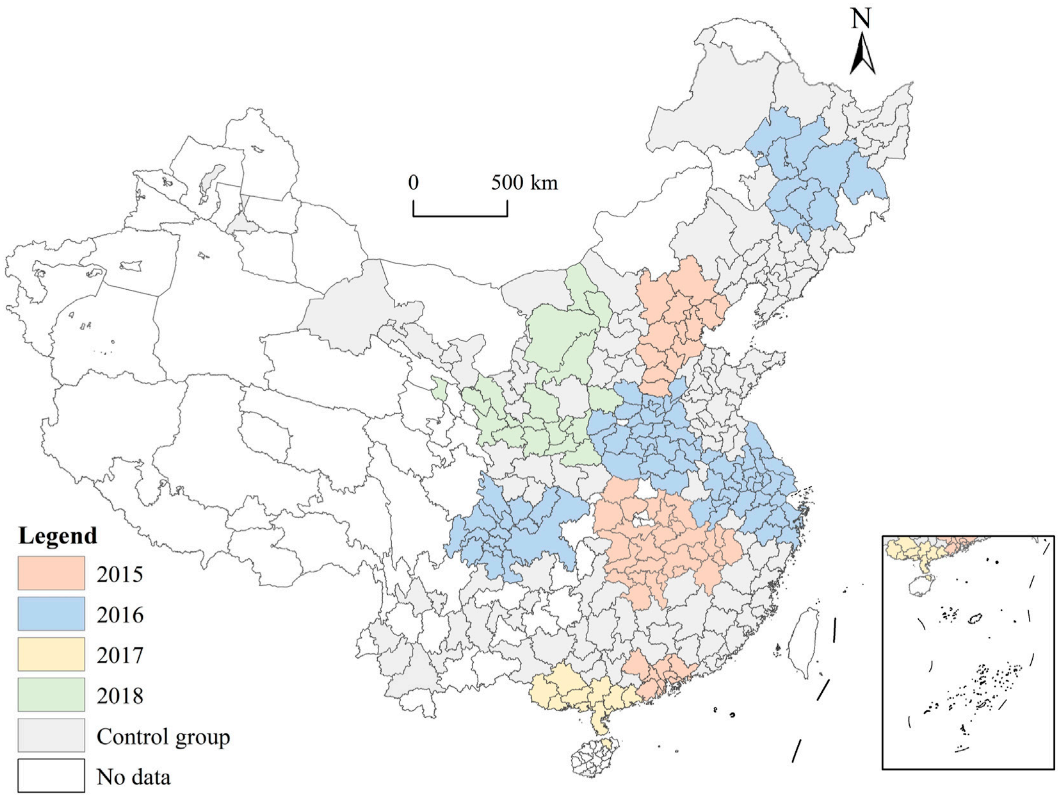

FIGURE 1
Approval time and distribution of RIP.

The impacts of urban agglomeration on economic development (Lv et al., 2024b), sustainable development (Ullah et al., 2024), foreign trade and exports (Mamba et al., 2024), and social interactions (Israel et al., 2017) have been extensively studied. In China, urban agglomeration primarily manifests in two forms: block type and channel type (Tian et al., 2023). Among these, the integration process driven by urban agglomerations has garnered significant attention from researchers. It is noteworthy that rapid urbanization has led to a widening development gap, thereby exacerbating challenges like uneven social development (Sulemana et al., 2019). Urban agglomerations are widely recognized as a crucial mechanism for promoting social equity (Tan et al., 2022), enhancing economic performance (Shen et al., 2022), and leveraging regional locational endowments (Feng et al., 2018).

2.3 RIP and UER

UER represents a concentrated manifestation of the comprehensive effects of the urban environment. The urban environmental impacts induced by RIP have garnered significant academic attention, although research outcomes vary due to differences in policy implementation targets and pollutant selection. Empirical studies have demonstrated that RIP enhance the efficiency of urban green development (Wang et al., 2022), reduce urban carbon emissions (Zhao et al., 2024), lower energy intensity (Ding et al., 2022), and improve air quality (Zhang et al., 2023) through mechanisms such as promoting green innovation (Li et al., 2022), and enhancing the carrying capacity of land resources (Shen et al., 2022). However, Sun et al. (2024) identified an inverted U-shaped correlation between RIP and CO_2 emissions, where emissions initially increase before declining. Similarly, Lv et al. (2024b), through a case study of the Yangtze River Delta region and the application of the DID model, found that RIP has an insignificant effects on CO_2 reduction in China. Furthermore, owing to the common traits of the same region, RIP exhibit negative spillover effects on environmental pollution control (Jiang et al., 2022). For instance, Wang and Shao (2025) observed that, whereas RIP considerably boosts energy efficiency inside cities, it simultaneously suppresses energy efficiency improvements in adjacent regions.

3 Theoretical analysis

3.1 Policy background

The primary objective of China's establishment of national-level urban agglomerations is to optimize resource allocation through spatial reorganization, address regional development imbalances, and tackle ecological challenges arising from rapid urbanization. As of 2023, China has officially approved 11 national-level urban agglomerations (Figure 1). With the expansion of large-scale urban agglomerations, issues such as insufficient environmental carrying capacity and ecological fragmentation have become increasingly prominent. The traditional ecological governance model, which relies on individual cities acting independently, struggles to address regional environmental pollution and ecosystem fragmentation. In contrast, urban agglomerations function as environmental communities, capable of breaking administrative barriers and fostering collaborative construction and governance. Through coordinated cooperation, they enhance the quality and stability of the ecosystems, effectively mitigating regional ecological security risks and laying a solid ecological foundation for sustainable urban development.

3.2 Research hypothesis

3.2.1 Direct effect

3.2.1.1 Collaborative governance

RIP enhances the institutional resilience of urban ecosystems by establishing cross-jurisdictional governance mechanisms. As a classic non-excludable public resource, the ecological environment is subject to significant externalities and spillover effects (Dzwigol et al., 2023), leading to fragmented ecological governance. RIP promotes the convergence and unification of environmental regulatory standards by formulating uniform environmental criteria and establishing cross-jurisdictional management bodies (Lv et al., 2024b). This creates a multi-tiered, networked governance system. Additionally, RIP leverages digital regulatory platforms and joint law enforcement systems to strengthen the coordination of governance actions. The collaborative transformation of this governance model not only optimizes governance costs and information transmission mechanisms but also enhances the ecological system's adaptive capacity to withstand human interference through a clearly defined system of responsibility allocation. This provides institutional support for improving UER.

3.2.1.2 Collective defense

RIP enhances the overall resilience of urban clusters in responding to ecological crises through mechanisms of shared risk and joint defense. The core of UER lies in the system's ability to maintain dynamic stability when facing external disturbances (Shamsipour et al., 2024). A single city, constrained by resource limitations and geographical boundaries, faces challenges in effectively combating cross-domain and complex ecological threats. RIP addresses this issue by establishing a multi-city collaborative prevention and control network (Wang and Shao, 2025). In the face of environmental pressures, this network enables a paradigm shift from fragmented governance to holistic coordination through real-time information exchange and joint response strategies (Jiang and Jiang, 2024). This collective defense system integrates isolated urban defense units into a cohesive and organically connected whole. By leveraging shared risks and resource complementarities, it mitigates the localized destructive effects of ecological shocks and thereby strengthens the overall resilience of the ecological system.

3.2.1.3 Collective development

RIP fosters the long-term sustainable development of UER through the flow of factors and industrial collaboration. The institutional divisions created by traditional administrative boundaries have hindered the cross-regional allocation of production factors, putting more pressure on the ecological environment's bearing capacity. By dismantling administrative restrictions, RIP establishes a market-oriented mechanism for resource allocation, leading to an overall improvement in resource utilization efficiency (Shen et al., 2022). Furthermore, through the deepening of regional division of labor and cooperation, regional integration aligns industrial layouts with ecological carrying capacities (Ding et al., 2022), avoiding resource waste and environmental pressures caused by homogeneous competition. This collective development, by establishing a virtuous interaction between industrial ecosystems and natural ecosystems, optimizes the structural resilience of urban ecosystems (Feng et al., 2023), providing dynamic adaptation and self-repair capabilities that offer systematic support for UER.

H1: *RIP has a positive direct effect on UER.*

3.2.2 Indirect effect

3.2.2.1 Industrial structure upgrading

In the process of integration, the expansion of market breadth and the evolution of the division of labor drive cities within the region to reshape their industrial layouts based on comparative advantages (Feng et al., 2023). High-environment-sensitivity industries gradually shift to regions with the capacity to support them, while knowledge-intensive industries concentrate in areas rich in innovation factors, thereby forming an industrial system of gradient development. This reallocation of factors accelerates the high-level evolution of the industrial structure, thereby driving the transformation from resource-dependent industries to technology-driven industries. As the share of emerging industries increases, the regional economy significantly reduces its dependence on natural resources, effectively alleviating the issue of ecological overload under traditional development models. The dynamic adaptation of industrial layouts to ecological carrying capacity avoids the environmental pressure overload caused by industrial agglomeration, reserving sufficient space for ecosystem restoration. Moreover, the optimization of industrial structure promotes a shift toward a circular economy model, lowering the environmental impact per unit of output through the closure of industrial chains and the efficient recycling of resources, thereby enhancing the ecosystem's buffering capacity against external shocks (Yin et al., 2024).

3.2.2.2 Technological innovation

RIP fosters technological innovation by establishing cross-domain innovation collaboration networks, breaking spatial constraints on the flow of innovation factors, and providing systemic impetus for technological advancements (Wang and Shao, 2025). During the integration process, the cross-regional integration of research and development resources promotes the efficient fusion of knowledge, talent, and capital (Li et al., 2022),

TABLE 1 Evaluation indicator system of UER.

Dimension	Indicators	Nature
Resistance	Population density	-
	The proportion of built-up area to urban area	-
	Unit GDP industrial sulfur dioxide emissions	-
	Unit GDP industrial wastewater emissions	-
Adaptability	Comprehensive utilization rate of industrial solid waste	+
	Centralized treatment rate of sewage treatment plants	+
	Sewage treatment rate	+
	Harmless treatment rate of domestic waste	+
Resilience	Per capita water availability	+
	Park green space *per capita*	+
	Greening coverage of built-up areas	+
	Number of parks	+

thereby reducing the marginal costs of innovation activities. Technological innovation driven by RIP enhances UER by strengthening the ecosystem's adaptive and regulatory capacities. In terms of ecological restoration, technological innovation optimizes ecological engineering methods, accelerating the recovery of damaged ecosystems, and improving resource productivity and environmental governance effectiveness. At the same time, the application of intelligent monitoring and early warning technologies allows for the precise identification and dynamic alerting of ecological risks, enhancing the system's adaptive regulation capacity. Furthermore, technological innovation drives the transformation of production functions and consumption patterns, fostering a positive feedback loop between socio-economic systems and natural ecosystems, reinforcing societal consensus on ecological protection (Jiang et al., 2022), and providing a profound social foundation for UER.

H2: *RIP enhances UER through industrial structure upgrading and technological innovation.*

4 Methods and data

4.1 Empirical method

4.1.1 DID method

A multi-period DID model was used to test the effect of RIP on UER:

$$UER_{it} = \alpha + \beta_1 DID_{it} + \gamma x_{it} + \mu_t + \nu_i + \varepsilon_{it} \quad (1)$$

In Equation 1, UER_{it} is urban ecological resilience; DID_{it} is dummy variable identifying city agglomeration planning policies; β is the coefficient of the impact of policies on UER; x_{it} is control variable; μ_t is time fixed effect; ν_i is a city fixed effect; and ε_{it} is random error term.

4.1.2 The mediating effect model

A mediated effects model was used to explore the mechanism of RIP's effect on UER, modeled as follows:

$$M_{it} = \alpha + \beta_1 DID + \gamma x_{it} + \mu_t + \nu_i + \varepsilon_{it} \quad (2)$$

$$UER_{it} = \alpha + \beta_1 DID + \beta_2 M_{it} + \gamma x_{it} + \mu_t + \nu_i + \varepsilon_{it} \quad (3)$$

In Equations (2) and (3), M_{it} is the mediating variable.

4.2 Variables

4.2.1 Explained variable

UER is divided into three main characteristics: resistance, adaptability, and resilience (Table 1), on the basis of which the indicator system is constructed with reference to existing studies (Chen and Wang, 2022; Zhang et al., 2025; Yin et al., 2024). (1) Resistance is the fundamental guarantee of UER, reflecting the capacity of the urban ecosystem to preserve its structural and functional stability in the face of external disturbances. Cities employ buffering mechanisms to withstand shocks and reduce the loss of core functions. Strong resistance effectively prevents the spread of disturbances, minimizing the extent of the ecosystem damage. This dimension quantifies human activity intensity and pollution load, reflecting the system's stability threshold under the dual pressures of industrialization and urbanization. (2) Adaptability is the key support for UER, embodying the capacity of ecosystems to modify their structure and function over time to adapt to changes. Good adaptability allows the ecosystem to dynamically align with environmental changes, preventing collapse due to prolonged maladaptation and ensuring that the ecosystem continues to provide services in a non-steady-state environment. This dimension captures resource recycling efficiency and pollution control levels, determining the system's dynamic balance capacity under continuous disturbances. High resource utilization and treatment rates can effectively buffer environmental pressures and delay functional degradation, serving as key regulatory mechanisms for maintaining resilience. (3) Resilience is the ability of the urban environment to restore its pre-disturbance state of structure and function after a disturbance ends. Strong resilience allows urban ecosystems to self-repair rapidly after damage, minimizing the long-term negative effects of disturbances and safeguarding the sustainability of the urban ecological system. This dimension quantifies the ecological space supply capacity, reflecting the speed and efficiency with which the system rebuilds its steady state. Subsequently, the entropy method is used to measure UER (Jiang and Jiang, 2024).

4.2.2 Explanatory variable

The sample cities are divided into an experimental group (which implements RIP) and a control group (which does not implement RIP). Based on the four phases of policy pilot implementation between 2015 and 2018, a time dummy variable is constructed. The explanatory variable is the interaction term between the policy group and the time group.

4.2.3 Mediating variables

4.2.3.1 Industrial structure upgrading (ISU)

RIP optimizes resource allocation through industrial gradient planning, promoting the relocation of high-environment-sensitivity industries and the clustering of knowledge-intensive industries. This reduces the economic system's dependence on natural resources, establishing a dynamic equilibrium between industrial layout and ecological carrying capacity, and fostering the transition to a circular economy, thereby enhancing UER. This is represented by the ratio of the output value of the tertiary sector to that of the secondary sector (Yin et al., 2024).

4.2.3.2 Technological innovation (TI)

RIP not only facilitates the cross-regional integration of innovation factors, lowers R&D costs, and promotes the upgrading of ecological restoration technologies and the improvement of intelligent monitoring systems, but also strengthens the ecosystem's adaptability and regulatory capacity. It optimizes production and consumption patterns, creating a positive feedback loop between the socio-economic system and the natural ecology, thus systematically enhancing UER. This is represented by the number of patents granted *per capita* (Dai et al., 2022).

4.2.4 Control variables

Based on existing research, the factors affecting UER mainly include the following aspects.

1. Economic development (lnGDP): ECO provides the material capital necessary for ecological infrastructure construction, directly enhancing the physical buffering capacity and disturbance resistance threshold of urban ecosystems through ecological restoration projects, pollution control facilities, and green space development. This is measured by GDP *per capita* (Jiang et al., 2022).
2. Infrastructure development (INF): INF enables ecosystems to maintain overall structural stability during localized disturbances by providing functional complementarities, reducing the risk of resilience decay caused by spatial fragmentation. This is measured by road density (Luo et al., 2018).
3. Financial development (FIN): The price discovery mechanism in financial markets facilitates the allocation of ecological factors, guiding resources towards environmentally friendly industries and strengthening the dynamic adaptive capacity of urban ecosystems. This is represented by the ratio of the total deposits and loans of regional financial institutions to GDP (Feng et al., 2023).
4. Government intervention (GOV): Through budget allocations and special bonds, the government provides financial support for ecological projects, ensuring the dynamic alignment between ecosystem functions and urban development needs. This is measured by the proportion of public budget expenditure to GDP (Wang and Shao, 2025).
5. Urbanization level (URB): Urbanization, through coordinated land use planning, integrates ecological, residential, and production space requirements, enhancing the self-regulation capacity of natural ecosystems, improving grassroots ecological governance, and strengthening the perception and response capabilities to ecological risks. This is measured by the urbanization rate (Wang and Shao, 2025).

4.3 Data

This study collected balanced panel data of 276 cities in China from 2009 to 2023. The sample comprises 155 cities within city clusters and 121 non-pilot cities. Data were collected from the China Urban Statistical Yearbook and the China Urban and Rural Construction Statistical Yearbook. For missing data, linear interpolation was applied to fill the gaps. Descriptive statistics for the variables are presented in Table 2.

5 Empirical results

5.1 Baseline regression result

Column (1) of Table 3 reports the results after further controlling for city trend terms based on the inclusion of control variables. Column (2) of Table 3 presents the results of the city-time joint fixed effects. The results show that the estimated coefficients of RIP in both columns (1) and (2) are significantly positive, indicating that RIP significantly promotes the improvement of UER, which preliminarily verifies hypothesis H1. First, RIP breaks down administrative divisions to form a collaborative governance system, reduces disaster prevention costs for individual cities through scale effects, and significantly enhances the overall resilience of the ecosystem. Second, the industry gradient transfer and green technology diffusion driven by integration accelerate the co-construction and sharing of ecological facilities, stimulate the sharing of low-carbon technologies, and facilitate the establishment of circular economy networks, achieving a virtuous coupling between economic development and ecological protection.

TABLE 2 Descriptive statistics.

Type	Variable	Obs	Mean	Std.Dev	Min	Max
Explained variable	*UER*	4140	0.183	0.059	0.080	0.479
Explanatory variables	*DID*	4140	0.302	0.459	0.000	1.000
Control variables	*lnGDP*	4140	10.728	0.632	4.595	13.056
	INF	4140	1.057	0.496	0.047	3.061
	FIN	4140	1.477	0.627	0.371	5.314
	GOV	4140	0.193	0.097	0.020	0.871
	URB	4140	0.551	0.156	0.151	1.000

TABLE 3 Benchmark regression results.

Variable	(1)	(2)
DID	0.015*** (0.004)	0.013** (0.005)
lnGDP	0.037*** (0.005)	0.015** (0.007)
INF	0.023** (0.010)	0.019* (0.010)
FIN	0.020*** (0.004)	0.002 (0.006)
GOV	0.014 (0.025)	0.061*** (0.022)
URB	0.004 (0.014)	0.018 (0.022)
Cons	−0.276*** (0.047)	−0.038 (0.079)
Time Fixed	No	Yes
City Fixed	Yes	Yes
Obs	4140	4140
R^2	0.360	0.442

***, **, and * indicate that the estimates are significant at the 0.01, 0.05, and 0.1 levels; robust standard errors obtained by clustering to cities are in parentheses, below.

5.2 Parallel trend test

To ensure the validity of the impact assessment of RIP on UER, this study first examines the parallel trends assumption. Utilizing an event study approach to evaluate the dynamic effects of policy implementation, Figure 2 demonstrates that, prior to the policy intervention, the disparities in UER between the treatment and control groups were statistically insignificant at all observed time points, thereby satisfying the fundamental prerequisite for the DID model. Following policy implementation, the estimated coefficients became significantly positive, indicating a measurable treatment effect. These findings confirm both the robustness of the multi-period DID model specification and the reliability of subsequent policy impact assessments.

5.3 Robustness tests

5.3.1 Placebo test

To systematically evaluate the robustness of the baseline regression results, we conducted a placebo test by randomly reassigning the policy treatment variable across the sample. Through 500 iterations of random sampling, we generated a distribution of simulated treatment effects under the null hypothesis of no policy impact. As illustrated in Figure 3, the resulting coefficients exhibit a symmetric distribution centered around zero, with their kernel density estimate closely aligning with a normal distribution curve. Crucially, the actual estimated coefficient of 0.013 (denoted by the red dashed line) falls within the extreme tail of the simulated distribution, demonstrating statistically significant divergence from random outcomes. These findings confirm the absence of systematic bias in the baseline regression, thereby substantiating the reliability of core conclusions.

5.3.2 PSM-DID estimation

This study employs PSM-DID to systematically refine the sample composition. Using the control variables from the baseline regression as matching covariates, we implemented a kernel density matching algorithm to achieve precise pairing between treatment and control groups. Following confirmation of satisfactory matching quality through balance tests, we proceeded to estimate a PSM-DID model. As presented in Column (1) of Table 4, the DID coefficient remains statistically significant and positive, demonstrating that the promoting effect of RIP on UER persists even after rigorously controlling for sample self-selection issues.

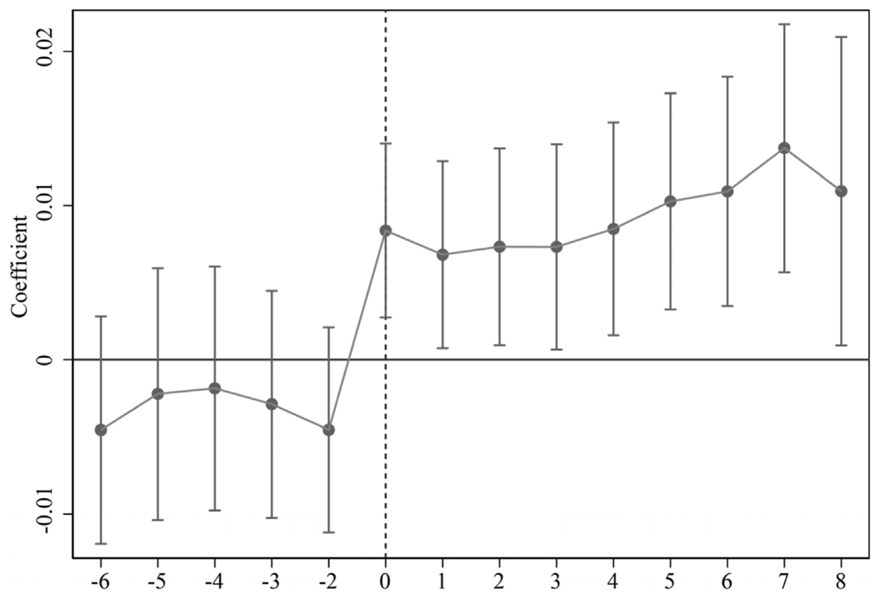

FIGURE 2
Parallel trend test.

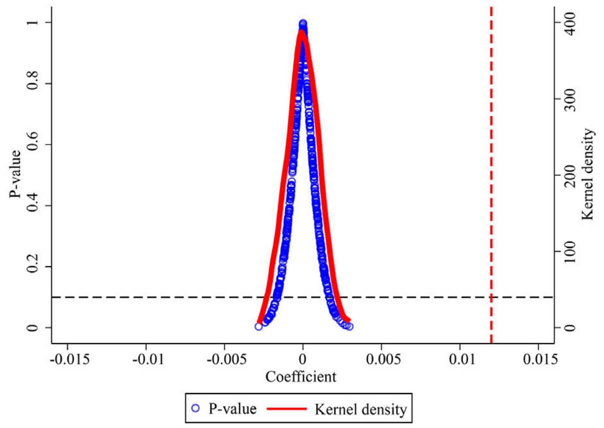

FIGURE 3
Placebo test.

These results confirm the robustness of our baseline regression findings.

5.3.3 Policy confounding effects

In the regression estimation, a critical inquiry arises as to whether other policies might interfere with the promoting effect of the RIP on UER. To address this concern, we excluded the prefecture-level cities where the Yangtze River Economic Belt's regional integration strategy overlaps with the urban agglomeration planning policies examined in this study. We designated the remaining cities within the urban agglomeration planning scope as the experimental group and conducted benchmark regression. Column (2) of Table 4 illustrates that, after excluding the influence of the Yangtze River Economic Belt strategy, RIP still exerts a positive and significant promoting effect on UER, not impeded by interference from other policies.

5.3.4 Other robustness tests

5.3.4.1 Excluding the municipalities

Considering the potential systemic biases that may arise from the unique administrative hierarchy, policy prerogatives, and resource allocation mechanisms of these municipalities, which could skew the estimation results, this study conducted a robustness test by excluding samples from the four municipalities directly under the central government. Given that these municipalities possess provincial-level administrative authority and more comprehensive environmental governance frameworks, their UER performance might not accurately reflect the policy impact of RIP on ordinary prefecture-level cities. The regression results presented in column (3) of Table 4 demonstrate that the DID estimator remains significantly positive, thereby confirming the robustness of RIP's enhancing effect on UER for samples excluding municipalities directly under the central government.

5.3.4.2 Endogeneity

To address potential endogeneity issues, this study draws on the approach employed by published literature (Jiang and Jiang, 2024), utilizing ancient Ming Dynasty post stations as instrumental variables for the RIP. Firstly, post stations occupied pivotal positions within the ancient transportation network, and their spatial distribution has long shaped economic interactions and social connections across regions. Areas with a dense network of post stations are more prone to develop modern urban agglomeration spatial structures, thereby satisfying the relevance condition. Secondly, the siting and construction of Ming Dynasty post stations primarily served strategic needs such as military defense and the efficient transmission of imperial edicts, with no direct connection to contemporary ecological policies, thus meeting

TABLE 4 Robustness test.

Variable	(1)	(2)	(2)	(4)
DID	0.015*** (0.002)	0.011* (0.006)	0.013** (0.005)	0.383*** (0.115)
CV	Yes	Yes	Yes	Yes
Time Fixed	Yes	Yes	Yes	Yes
City Fixed	Yes	Yes	Yes	Yes
Kleibergen-Paaprk LM stat				11.997 [0.000]
Kleibergen-Paap rk Wald F stat				26.809 <16.38>
Cons	0.167*** (0.044)	−0.248*** (0.052)	0.011 (0.058)	
Obs	3420	3030	4080	
R^2	0.780	0.315	0.437	

P values in [ ]; critical values at the Stock-Yogo test 10% level in < >.

TABLE 5 Heterogeneity test.

Variable	Region		Administrative level	
	Eastern cities	Central and western cities	Provincial capital cities	Non-provincial capital cities
	(1)	(2)	(3)	(4)
DID	0.022** (0.009)	0.009 (0.006)	0.030*** (0.006)	0.011* (0.006)
CV	Yes	Yes	Yes	Yes
Cons	−0.191 (0.160)	0.052 (0.060)	0.048 (0.132)	0.011 (0.071)
Time Fixed	Yes	Yes	Yes	Yes
City Fixed	Yes	Yes	Yes	Yes
Obs	1,695	2445	450	3690
R^2	0.445	0.465	0.630	0.438

the exogeneity requirement. Following Wang and Shao's (2025) methodology, the interaction term between Ming Dynasty post stations and time dummy variables is employed as the IV, with estimation conducted using the 2SLS method. As indicated in column (4) of Table 4, the Kleibergen-Paap rk LM statistic passes the significance test, indicating no issue of under-identification. Moreover, the Kleibergen-Paap rk Wald F statistic exceeds the critical value at the 10% level in the Stock-Yogo weak identification test, suggesting the absence of a weak instrument problem. Furthermore, the estimated coefficient for the DID remains significantly positive, demonstrating that after eliminating endogeneity-related biases in the model estimation, RIP continues to exert a positive and significant promoting effect on UER.

5.4 Heterogeneity test

1. Leveraging their solid economic foundations and well-established environmental governance mechanisms, eastern cities have secured a pioneering advantage in the realm of ecological development. In contrast, while central and western cities possess relatively weaker ecological bases, they have received substantial policy support due to the preferential treatment. These disparities in regional endowments and policy orientations have led to significant divergence in the ecological effects of the RIP. Columns (1)–(2) of Table 5 reveal that RIP exerts a significantly positive impact on UER in eastern cities, whereas its influence on central and western cities remains statistically insignificant. The eastern region, bolstered by its highly mature market mechanisms, comprehensive industrial ecosystems, and efficient factor circulation networks, has laid an institutional foundation for the effective translation of policy efficacy. Through robust resource synergy capabilities and innovation diffusion effects, this region has successfully transformed regional collaboration advantages into tangible ecological governance performance. Conversely, central and western regions, constrained by their developmental stages and factor endowment limitations, have failed to witness substantial improvements in resource allocation efficiency concurrent with the dissolution of administrative barriers. Structural

TABLE 6 Mechanism test.

Variable	(1) *IS*	(2) *UER*	(3) *TI*	(4) *UER*
DID	0.005*** (0.002)	0.011** (0.005)	0.027*** (0.008)	0.010** (0.005)
IS		0.387** (0.155)		
TI				0.120*** (0.046)
CV	Yes	Yes	Yes	Yes
Cons	0.026 (0.018)	0.003 (0.055)	−0.062 (0.087)	0.021 (0.051)
Time Fixed	Yes	Yes	Yes	Yes
City Fixed	Yes	Yes	Yes	Yes
Obs	4140	4140	4140	4140
R^2	0.747	0.481	0.933	0.516

deficiencies in their innovation systems further impede the absorption and transformation efficiency of technological diffusion, resulting in a lack of necessary transmission media for policy incentives. Consequently, the promoting effect of RIP on UER is difficult to fully manifest in these regions.

2. As regional cores, provincial capital cities possess distinct advantages in terms of financial discretion and environmental regulatory capacity, resulting in structural disparities in policy implementation efficacy compared to non-provincial capital cities. Columns (3)–(4) of Table 5 demonstrate that the impact of the RIP on UER is more pronounced in provincial capital cities than in their non-provincial counterparts. Provincial capitals leverage their strengths in fiscal resource allocation, aggregation of high-end factors, and innovation platform construction to translate these resource endowment advantages into enhanced policy conversion capabilities. This enables them to internalize the externalities of regional synergy into tangible ecological governance performance. Concurrently, through institutional innovations such as leading the design of ecological compensation mechanisms and optimizing industrial spatial layouts, provincial capitals effectively dissolve administrative boundary constraints and establish efficient policy implementation channels. However, non-provincial capital cities, due to their geographical distance from provincial capitals or inadequate transportation accessibility, encounter physical barriers to factor mobility and exhibit lower initiative in regional collaboration. These structural disadvantages pose significant challenges for non-provincial cities in converting integration opportunities into momentum for enhancing UER, ultimately manifesting as hierarchical disparities in policy responsiveness.

5.5 Mechanism testing

1. Column (1) of Table 6 reveals that the RIP significantly promotes ISU, and ISU exerts a positive influence on UER, thereby constituting a positive contributing factor in RIP's promotion of UER. On one hand, RIP, by reshaping factor allocation and optimizing industrial division, guides the clustered development of low-environmental-load industries in core urban agglomerations, reducing the intensity of resource consumption in overall regional industrial development. On the other hand, the elevation of industrial ecological levels substantially enhances the service supply capacity of urban ecosystems, enabling a dynamic match between the intensity of economic activities and regional ecological carrying capacity, thereby avoiding structural overloads on environmental carrying capacity.
2. Columns (3) and (4) of Table 6 demonstrate that the regression results of both model types are significantly positive, indicating that TI exerts a relatively pronounced positive mediating effect on the enhancement of UER. Consequently, TI also constitutes a positive mediating effect in RIP's promotion of UER. In terms of ecological restoration, TI strengthens the self-repairing capabilities of ecosystems by breaking through barriers in resource recycling and pollution source control, thereby expanding the buffer space for ecosystems to respond to external shocks. In terms of technology diffusion, RIP facilitates the widespread dissemination of advanced environmental technologies, elevating the level of refinement in urban ecosystem management and enabling early warning and dynamic regulation of ecological risks.

6 Discussion

Enhancing UER is crucial for realizing high-quality urban development, and RIP based on urban agglomerations plays an important role in enhancing UER (Jiang and Jiang, 2024; Yin et al., 2024). Previous studies have mostly focused on evaluating the spatio-temporal evolution characteristics and influencing factors of UER (Huang et al., 2023; Feng et al., 2024; Xu et al., 2024), with less attention paid to exploring the influence of policy factors on UER. Based on the measurement of UER, this paper uses a multi - period DID model to explore the influence of RIP on UER, which broadens the research perspective of UER and provides reference for improving RIP and building resilient cities. The results indicate that RIP has significantly enhanced UER by breaking down administrative barriers and facilitating resource synergy, with this effect being particularly pronounced in eastern cities and provincial capital cities. This finding provides robust empirical evidence supporting the effectiveness of regional collaborative governance in the ecological domain.

The significantly positive impact of RIP on UER fundamentally stems from the establishment of regional collaborative governance systems following the removal of administrative barriers (Jiang and Jiang, 2024; Lv et al., 2024b), which aligns with the theoretical proposition that RIP enhances systemic resilience of ecosystems. Heterogeneity analysis reveals differential effects shaped by regional endowments and policy orientations. Eastern cities, leveraging well-developed market mechanisms and advanced industrial ecosystems, demonstrate superior capacity in translating policy dividends into ecological governance outcomes. In contrast, central and western regions, constrained by factor endowment limitations and underdeveloped innovation systems, exhibit weaker policy responsiveness due to inadequate transmission mechanisms. Existing literature has established that RIP facilitates green technology innovation (Li et al., 2022; Tan et al., 2022) and industrial structure upgrading (Dai et al., 2022). Our mechanism analysis further demonstrates that RIP, by dismantling administrative fragmentation, promotes industrial gradient transfer and green technology diffusion, thereby reducing regional disaster prevention costs while enhancing UER. Moreover, the mediating effect of technological innovation indicates that RIP fosters low-carbon technology sharing and circular economy network development, strengthening the geographical proximity effect in technology diffusion. This process consequently elevates the precision of ecological governance, a finding that resonates with the work of Yin et al. (2024).

Departing from conventional single-city scale analyses of UER, this study elucidates the enhancement effect of regional coordination on UER, thereby enriching empirical evidence for multi-scale ecological governance (Huang et al., 2023; Feng et al., 2024; Asghar et al., 2025). The identified heterogeneity in policy effects resolves academic debates regarding differential policy responsiveness between eastern and central-western regions and provincial capital *versus* non-capital cities, while explicating how administrative hierarchies and developmental foundations constrain policy transmission. These findings underscore the necessity of synchronizing RIP with local capacity building initiatives. The study makes two substantive academic contributions: First, it expands the evaluative dimensions of RIP by incorporating UER into the analytical framework of policy effectiveness. Second, it provides empirical validation for collaborative governance theory, demonstrating that cross-jurisdictional institutional designs can effectively address ecological challenges. Therefore, eastern regions should intensify regional coordination to accelerate ecological technology diffusion; central-western areas must prioritize infrastructure development and institutional capacity building to establish prerequisite conditions for RIP implementation; and resource allocation between provincial capitals and non-capital cities requires optimization to mitigate hierarchical disparities in policy implementation.

7 Conclusion

RIP is a crucial initiative for fostering coordinated regional development, and it plays a significant role in enhancing UER. This study utilizes data from 276 prefecture-level cities in China from 2009 to 2023, employing a multi-period DID model and a mediating effect model to investigate the influence of RIP on UER and its underlying mechanisms. RIP demonstrates statistically significant enhancement effects on UER, though with notable spatial heterogeneity in implementation outcomes. Empirical results reveal substantially stronger policy effects in eastern regions compared to statistically insignificant impacts in central-western areas, while provincial capitals exhibit greater responsiveness than non-capital cities. Mechanism analysis confirms that RIP primarily facilitates UER improvement through two synergistic pathways: industrial structure upgrading and technological innovation diffusion. The policy implications are as follows:

1. It is imperative to formulate cross-regional environmental law enforcement standards and establish a unified ecological and environmental monitoring network. Led by central cities within urban agglomerations, initiatives should be taken to explore the establishment of ecological compensation mechanisms, implementing differentiated compensation based on regional ecological contributions to incentivize active participation in ecological conservation across regions. Environmental monitoring data from various cities should be integrated to enable real-time sharing and coordinated early warning responses. Central cities should take the lead in formulating ecological protection plans for urban agglomerations, clearly delineating the roles and responsibilities of each city in ecological restoration, joint prevention and control of pollution, and the layout of green industries. Meanwhile, surrounding cities should proactively align with the ecological governance standards set by central cities, jointly constructing ecological corridors, sharing environmental monitoring data, and collaborating on cross-border pollution control initiatives.
2. For the central and western regions, it is essential to intensify support for ecological conservation and restoration projects, improve transportation networks and energy supply systems, attract the clustering of green industries, and enhance the contribution rate of the ecological economy. Simultaneously, for non-provincial capital cities, targeted support should be provided for the cultivation of green industries and the introduction of advanced technologies to narrow the gap in UER with provincial capital cities. Furthermore, it is crucial to strengthen inter-regional exchanges of experience in ecological governance, organize mutual visits among cities for ecological governance purposes, facilitate the dissemination of advanced concepts and technologies, and promote an overall elevation in the level of regional ecological governance.
3. Promote the ecological transformation of industrial structures through industrial chain collaboration, with the eastern region fostering low-carbon industrial clusters and the central and western regions developing resource recycling industries. Establish regional environmental technology promotion

centers to conduct joint research and development efforts in areas such as pollution control, ecological restoration, and resource recycling. We advocate that government departments pay attention to green technological innovation and low-carbon technological innovation. Provide policy support, including patent protection and tax incentives, for green technological innovation achievements to stimulate corporate innovation vitality. Strengthen the construction of platforms for the transformation of ecological technology achievements, facilitating the rapid application of scientific research outcomes and driving the shift of industrial structures towards a green model, thereby significantly enhancing the resilience and sustainability of ecosystems.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YL: Methodology, Project administration, Investigation, Conceptualization, Visualization, Writing – original draft. ZP: Methodology, Supervision, Project administration, Investigation, Software, Visualization, Writing – review and editing. YS: Data curation, Validation, Writing – review and editing, Methodology, Software.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by the Project commissioned by Huanggang (grant number: HXXMA2025031).

Conflict of interest

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

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Afriyanie, D., Julian, M. M., Riqqi, A., Akbar, R., Suroso, D. S. A., and Kustiwan, I. (2020). Re-framing urban green spaces planning for flood protection through socio-ecological resilience in Bandung City, Indonesia. *Cities* 101, 102710. doi:10.1016/j.cities.2020.102710

Ai, K., and Xu, N. (2023). Does regional integration improve carbon emission performance? a quasi-natural experiment on regional integration in the Yangtze River Economic Belt. *Sustainability* 15, 15154. doi:10.3390/su152015154

Almulhim, A. I., Kafy, A. A., Ferdous, M. N., Fattah, Md. A., and Morshed, S. R. (2024). Harnessing urban analytics and machine learning for sustainable urban development: a multidimensional framework for modeling environmental impacts of urbanization in Saudi Arabia. *J. Environ. Manage.* 357, 120705. doi:10.1016/j.jenvman.2024.120705

Asghar, M., Ayaz, M., and Ali, S. (2025). Ecological resilience in crisis: analyzing the role of urban land use and institutional policies. *Land Use Policy* 151, 107492. doi:10.1016/j.landusepol.2025.107492

Bloise, F., and Tancioni, M. (2021). Predicting the spread of COVID-19 in Italy using machine learning: do socio-economic factors matter? *Struct. Change Econ. Dyn.* 56, 310–329. doi:10.1016/j.strueco.2021.01.001

Chen, Y., and Wang, H. (2022). Industrial structure, environmental pressure and ecological resilience of resource-based cities-based on panel data of 24 prefecture-level cities in China. *Front. Environ. Sci.* 10, 885976. doi:10.3389/fenvs.2022.885976

Contreras, G., and Platania, F. (2019). Economic and policy uncertainty in climate change mitigation: the London Smart City case scenario. *Underst. Smart Cities Innov. Ecosyst. Technol. Adv. Soc. Chall.* 142, 384–393. doi:10.1016/j.techfore.2018.07.018

Dai, S., Zhang, W., Wang, Y., and Wang, G. (2022). Examining the impact of regional development policy on industrial structure upgrading: quasi-experimental evidence from China. *Int. J. Environ. Res. Public. Health* 19, 5042. doi:10.3390/ijerph19095042

Ding, R., Zhou, T., Yin, J., Zhang, Y., Shen, S., Fu, J., et al. (2022). Does the urban agglomeration policy reduce energy intensity? Evidence from China. *Int. J. Environ. Res. Public. Health* 19, 14764. doi:10.3390/ijerph192214764

Dzwigol, H., Kwilinski, A., Lyulyov, O., and Pimonenko, T. (2023). Renewable energy, knowledge spillover and innovation: capacity of environmental regulation. *Energies* 16, 1117. doi:10.3390/en16031117

Feng, Y., Wu, S., Wu, P., Su, S., Weng, M., and Bian, M. (2018). Spatiotemporal characterization of megaregional poly-centrality: evidence for new urban hypotheses and implications for polycentric policies. *Land Use Policy* 77, 712–731. doi:10.1016/j.landusepol.2018.06.022

Feng, Y., Lee, C.-C., and Peng, D. (2023). Does regional integration improve economic resilience? Evidence from urban agglomerations in China. *Sustain. Cities Soc.* 88, 104273. doi:10.1016/j.scs.2022.104273

Feng, X., Zeng, F., Loo, B. P. Y., and Zhong, Y. (2024). The evolution of urban ecological resilience: an evaluation framework based on vulnerability, sensitivity and self-organization. *Sustain. Cities Soc.* 116, 105933. doi:10.1016/j.scs.2024.105933

Han, S., Wang, B., Ao, Y., Bahmani, H., and Chai, B. (2023). The coupling and coordination degree of urban resilience system: a case study of the Chengdu–Chongqing urban agglomeration. *Environ. Impact Assess. Rev.* 101, 107145. doi:10.1016/j.eiar.2023.107145

Haque, Md. N., and Sharifi, A. (2024). Who are marginalized in accessing urban ecosystem services? A systematic literature review. *Land Use Policy* 144, 107266. doi:10.1016/j.landusepol.2024.107266

He, W., Wang, B., and Wang, Z. (2018). Will regional economic integration influence carbon dioxide marginal abatement costs? Evidence from Chinese panel data. *Energy Econ.* 74, 263–274. doi:10.1016/j.eneco.2018.06.010

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* 4, 1–23. doi:10.1146/annurev.es.04.110173.000245

Huang, J., Zhong, P., Zhang, J., and Zhang, L. (2023). Spatial-temporal differentiation and driving factors of ecological resilience in the Yellow River Basin, China. *Ecol. Indic.* 154, 110763. doi:10.1016/j.ecolind.2023.110763

Israel, S., Buttler, F., Ingensiep, C., and Reimann, C. (2017). Connected Europe (ans): does economic integration foster social interaction? *J. Contemp. Eur. Stud.* 25, 88–106. doi:10.1080/14782804.2016.1198687

Jiang, N., and Jiang, W. (2024). How does regional integration policy affect urban resilience? Evidence from urban agglomeration in China. *Environ. Impact Assess. Rev.* 104, 107298. doi:10.1016/j.eiar.2023.107298

Jiang, N., Jiang, W., Zhang, J., and Chen, H. (2022). Can national urban agglomeration construction reduce PM2.5 pollution? Evidence from a quasi-natural experiment in China. *Urban Clim.* 46, 101302. doi:10.1016/j.uclim.2022.101302

Krieger-Boden, C., and Soltwedel, R. (2013). Identifying European economic integration and globalization: a review of concepts and measures. *Reg. Stud.* 47, 1425–1442. doi:10.1080/00343404.2013.834319

Le, X., Ding, X., Zhang, J., and Zhao, L. (2024). Has green finance enhanced the ecological resilience level in the Yangtze River Economic Belt? *Sustainability* 16, 2926. doi:10.3390/su16072926

Li, G., and Wang, L. (2023). Study of regional variations and convergence in ecological resilience of Chinese cities. *Ecol. Indic.* 154, 110667. doi:10.1016/j.ecolind.2023.110667

Li, L., Ma, S., Zheng, Y., Ma, X., and Duan, K. (2022). Do regional integration policies matter? Evidence from a quasi-natural experiment on heterogeneous green innovation. *Energy Econ.* 116, 106426. doi:10.1016/j.eneco.2022.106426

Li, Q., Ge, J., Zhang, X., Wu, X., Fan, H., and Yang, L. (2025). Assessment of the interaction between digital infrastructure and ecological resilience: Insights from Yangtze River Delta urban agglomeration in China. *J. Clean. Prod.* 486, 144364. doi:10.1016/j.jclepro.2024.144364

Liu, Y., Zhang, X., and Shen, Y. (2024). Technology-driven carbon reduction: Analyzing the impact of digital technology on China's carbon emission and its mechanism. *Technol. Forecast. Soc. Change* 200, 123124. doi:10.1016/j.techfore.2023.123124

Lloren, J. I., and McCune, J. (2024). Testing for synergistic effects of natural and anthropogenic disturbance on ecological communities at a landscape scale. *Landsc. Ecol.* 39, 40. doi:10.1007/s10980-024-01844-w

Luo, Z., Wan, G., Wang, C., and Zhang, X. (2018). Urban pollution and road infrastructure: a case study of China. *China Econ. Rev.* 49, 171–183. doi:10.1016/j.chieco.2017.04.008

Lv, K., Fan, Y., and Cheng, Y. (2024a). How does regional integration affect CO2 emission intensity? A natural experiment based on the expansion of the Yangtze River Delta, China. *Ann. Reg. Sci.* 73, 493–519. doi:10.1007/s00168-024-01264-3

Lv, X., Zhu, Y., and Du, J. (2024b). Can regional integration policies enhance the win–win situation of economic growth and environmental protection? New evidence for achieving carbon neutrality goals. *Sustainability* 16, 1647. doi:10.3390/su16041647

Mamba, E., Wonyra, K. O., and Evlo, K. (2024). Regional (economic) integration, political stability uncertainty and (intra-African) exports. *Econ. Syst.* 49, 101266. doi:10.1016/j.ecosys.2024.101266

McCloy, M. W. D., Andringa, R. K., Maness, T. J., Smith, J. A., and Grace, J. K. (2024). Promoting urban ecological resilience through the lens of avian biodiversity. *Front. Ecol. Evol.* 12, 1302002–1302024. doi:10.3389/fevo.2024.1302002

Rakhimov, M. (2010). Internal and external dynamics of regional cooperation in Central Asia. *Discip. Reg. Trends Russ. Eurasian Stud. Retrosp. Glances New Steps* 1, 95–101. doi:10.1016/j.euras.2010.04.002

Shamsipour, A., Jahanshahi, S., Mousavi, S. S., Shoja, F., Ansari Golenji, R., Tayebi, S., et al. (2024). Assessing and mapping urban ecological resilience using the loss-gain approach: a case study of Tehran, Iran. *Sustain. Cities Soc.* 103, 105252. doi:10.1016/j.scs.2024.105252

Shen, L., Cheng, G., Du, X., Meng, C., Ren, Y., and Wang, J. (2022). Can urban agglomeration bring "1 + 1 > 2Effect"? A perspective of land resource carrying capacity. *Land Use Policy* 117, 106094. doi:10.1016/j.landusepol.2022.106094

Shen, Y., Yang, Z., and Zhang, X. (2023). Impact of digital technology on carbon emissions: evidence from Chinese cities. *Front. Ecol. Evol.* 11, 1166376. doi:10.3389/fevo.2023.1166376

Sulemana, I., Nketiah-Amponsah, E., Codjoe, E. A., and Andoh, J. A. N. (2019). Urbanization and income inequality in Sub-Saharan Africa. *Sustain. Cities Soc.* 48, 101544. doi:10.1016/j.scs.2019.101544

Sun, A., He, Q., Xiao, C., Hua, Y., and Zhang, J. (2024). The spatial spillover effects of regional integration on carbon emissions. *Int. Rev. Econ. Finance* 95, 103447. doi:10.1016/j.iref.2024.103447

Tan, F., Gong, C., and Niu, Z. (2022). How does regional integration development affect green innovation? Evidence from China's major urban agglomerations. *J. Clean. Prod.* 379, 134613. doi:10.1016/j.jclepro.2022.134613

Tian, Y., Sun, C., Ren, Y., Liu, K., and Zuo, Z. (2023). Tax competition, spatial correlation and regional integration development——evidence from the Yangtze River Delta. *Energy Policy* 181, 113715. doi:10.1016/j.enpol.2023.113715

Ullah, A., Nobanee, H., Ullah, S., and Iftikhar, H. (2024). Renewable energy transition and regional integration: Energizing the pathway to sustainable development. *Energy Policy* 193, 114270. doi:10.1016/j.enpol.2024.114270

Wang, Y., and Pan, J. (2024). Landscape-based ecological resilience and impact evaluation in arid inland river basin: a case study of Shiyang River Basin. *Appl. Geogr.* 167, 103299. doi:10.1016/j.apgeog.2024.103299

Wang, L., and Shao, J. (2025). How does regional integration policy affect urban energy efficiency? A quasi-natural experiment based on policy of national urban agglomeration. *Energy* 319, 135003. doi:10.1016/j.energy.2025.135003

Wang, Z., Zhang, X., Zhang, C., and Yang, Q. (2022). How regional integration affects urban green development efficiency: evidence from urban agglomeration in the middle reaches of the Yangtze River. *Int. J. Environ. Res. Public. Health* 19, 7937. doi:10.3390/ijerph19137937

Wu, X., Zhang, J., Geng, X., Wang, T., Wang, K., and Liu, S. (2020). Increasing green infrastructure-based ecological resilience in urban systems: a perspective from locating ecological and disturbance sources in a resource-based city. *Sustain. Cities Soc.* 61, 102354. doi:10.1016/j.scs.2020.102354

Xu, C., Huo, X., Hong, Y., Yu, C., de Jong, M., and Cheng, B. (2024). How urban greening policy affects urban ecological resilience: quasi-natural experimental evidence from three megacity clusters in China. *J. Clean. Prod.* 452, 142233. doi:10.1016/j.jclepro.2024.142233

Yang, Z., Cui, X., Dong, Y., Guan, J., Wang, J., Xi, Z., et al. (2024). Spatio-temporal heterogeneity and influencing factors in the synergistic enhancement of urban ecological resilience: evidence from the Yellow River Basin of China. *Appl. Geogr.* 173, 103459. doi:10.1016/j.apgeog.2024.103459

Yin, S., Zhou, Y., Zhang, C., and Wu, N. (2024). Impact of regional integration policy on urban ecological resilience: a case study of the Yangtze River Delta region, China. *J. Clean. Prod.* 485, 144375. doi:10.1016/j.jclepro.2024.144375

Zhang, W., Cui, R., Li, C., Ge, H., Zhang, Z., and Tang, X. (2023). Impact of urban agglomeration construction on urban air quality–empirical test based on PSM–DID model. *Sci. Rep.* 13, 15099. doi:10.1038/s41598-023-42314-8

Zhang, W., Wang, Z., and Wang, S. (2024). The impact of land-use carbon efficiency on ecological resilience—the moderating role of heterogeneous environmental regulations. *Sustainability* 16, 9842. doi:10.3390/su16229842

Zhang, T., Wang, C., and Duan, D. (2025). Pilot climate resilient cities and ecological resilience: evidence from double machine learning method. *Front. Environ. Sci.* 13, 1530104–1532025. doi:10.3389/fenvs.2025.1530104

Zhao, R., Sun, J., and Wang, X. (2024). Synergistic impact of digital finance and urban agglomeration policy on carbon emission reduction. *Int. Rev. Econ. Finance* 96, 103685. doi:10.1016/j.iref.2024.103685