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Configurations for Urban Economic Resilience under the Green Transition: Dynamic QCA Evidence from Core Cities in the Yangtze River Delta

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Research Article

Keywords: urban economic resilience, green transition, resource configuration, TOE framework, dynamic QCA, core cities of the Yangtze River Delta

Posted Date: March 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9139140/v1

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Additional Declarations: No competing interests reported.

Abstract

Amid increasingly stringent carbon reduction imperatives and the rising incidence of compound shocks, urban economic resilience has become a crucial benchmark for evaluating the effectiveness of green transformation and the capacity of cities to withstand and adapt to external disturbances. Using panel data for 27 central cities in the Yangtze River Delta from 2014 to 2023, this study develops a Technology–Organization–Environment (TOE) analytical framework and incorporates six key antecedent conditions, namely digital finance, green innovation, green finance, innovative human capital, green governance capacity, and green policy signals. On this basis, a dynamic qualitative comparative analysis (dynamic QCA) is employed to identify the multiple configurational pathways through which high urban economic resilience is achieved and to examine their intertemporal evolutionary patterns. The findings reveal that no single condition constitutes a stable and universally necessary prerequisite for high urban economic resilience across cities and periods. Instead, high resilience emerges from the joint effects of multiple factors operating in combination. Moreover, several equifinal configurations can lead to high resilience, while the relative explanatory power of different pathways shifts across stages of green transformation and exhibits a degree of convergence in the later sample period. By adopting a configurational perspective, this study enriches the understanding of how urban economic resilience is shaped under green transformation and provides empirical evidence for the design of differentiated and stage-specific policy mixes.

1. Introduction

Against the backdrop of intensifying global climate change, disruptive events such as extreme heat, floods, typhoons, and environmental pollution have become increasingly frequent and complex in their impacts on urban systems [1]. Although countries have continued to advance institutional arrangements aimed at carbon reduction, energy transition, and green development, the effects of external shocks on urban economic systems have not substantially diminished. Owing to the cumulative and lagged nature of climate impacts, together with the high spatial concentration of critical factors such as population, capital, and infrastructure within cities, such shocks are instead more likely to propagate through industrial linkages, spatial connections, and factor flows, thereby evolving into systemic risks that cut across sectors and regions [2]. Under these circumstances, how to enhance cities' capacity to maintain essential functions, absorb external disturbances, restore economic activity, and achieve adaptive adjustment amid the dual pressures of deepening green transformation and rising external uncertainty has become a central concern in both climate governance and urban governance. This issue is not only highly consistent with the climate adaptation and risk governance agenda emphasized in the Paris Agreement [3], but also closely aligned with China's 14th Five-Year Plan, which places resilience-oriented urban development high on the policy agenda [4]. Therefore, identifying the formative conditions and realization pathways of urban economic resilience from the perspective of green transformation carries both substantial theoretical significance and practical value.

The concept of resilience was originally used to describe a system's ability to maintain structural stability and recover after disturbance, and was later introduced into regional economics, where it gradually evolved into the research domain of economic resilience [5]. Building on this foundation, urban economic resilience is generally understood as the capacity of an urban economic system to maintain its basic functions, buffer risks, and restore growth when confronted with external shocks, as well as its ability to achieve functional recovery, structural optimization, and path renewal through adaptive adjustment during medium- and long-term structural change [6]. This conceptualization suggests that urban economic resilience is reflected not only in recovery from short-term disturbances, but also in the longer-term process of reconfiguring resource allocation and enhancing systemic adaptability during structural transformation. As one of the most economically dynamic regions in China, with the highest concentration of innovation resources and some of the most advanced progress in green transformation, the 27 central cities of the Yangtze River Delta provide a highly representative setting for examining the formation mechanisms of urban economic resilience in the context of green transformation. Most of these cities occupy critical positions in national regional development strategies, industrial and supply chain division systems, innovation networks, and financial resource allocation systems. As such, they are not only more vulnerable to the transmission and amplification of external shocks, but also more likely to pioneer resilience-enhancing pathways with broader demonstration effects [7]. At the same time, substantial heterogeneity exists across cities within the region in terms of industrial foundations, innovation capacity, the development of digital finance, the provision of green finance, and governance environments. This indicates that a similar macro-institutional context does not necessarily produce homogeneous resilience outcomes [8]. Accordingly, the formation of high urban economic resilience is more likely to result from the context-specific matching and synergistic interaction of multiple categories of resource factors, rather than from the independent and linear effect of any single factor.

Existing studies have examined urban economic performance and the foundations of resilience under green transformation from multiple perspectives. First, with respect to the economic effects of green transformation, prior research has shown that green transformation is not only associated with emissions reduction performance and ecological improvement, but also exerts profound influences on the quality of urban economic growth, industrial upgrading, resource allocation efficiency, and the transition from old to new growth drivers, thereby further shaping the stability and sustainability of urban economic systems [9–10]. Second, regarding the formation mechanisms of urban economic resilience, the existing literature has analyzed the issue from technological, organizational, and environmental dimensions, suggesting that factors such as digital finance, green innovation, green financial provision, innovative human capital, governance capacity, and policy support can affect cities' abilities to absorb risks, restore functions, and adjust their structures by improving financing conditions, facilitating knowledge diffusion, enhancing organizational absorptive capacity, and optimizing the institutional environment [11–12]. Third, with the development of configurational approaches to complex causality, some recent studies have begun to investigate the realization paths of complex outcomes such as green development, regional innovation, and high-quality development from a configurational perspective. These studies argue that high-performance outcomes in reality rarely depend on a single dominant factor, but instead exhibit the characteristics of conjunctural causation, equifinality, and causal asymmetry. In this context, although traditional regression analysis is capable of identifying the average net effects of individual variables, it is less well suited to addressing a question that is more consistent with real-world decision logic, namely, which combinations of conditions can lead to the same outcome [13–14]. Overall, the existing literature provides an important foundation for understanding the formation of urban economic resilience in the context of green transformation, yet it still lacks a more integrated explanatory framework for how different resource factors combine effectively under specific urban contexts and stages of transformation.

A closer review suggests that the current literature can be further extended in at least three respects. First, most empirical studies still rely predominantly on regression-based frameworks to identify the average net effects of single factors, making it difficult to capture the conjunctural causation, equifinality, and causal asymmetry that are widespread in reality. As a result, the literature has yet to provide a systematic answer to the question of what types of resource structures and capability foundations different cities should rely on, and through what combinations of conditions they can achieve relatively high levels of economic resilience [15–16]. Second, although prior studies have considered multidimensional conditions such as technology, organization, and environment, insufficient attention has been paid to the synergistic, complementary, and substitutive relationships among these conditions. Consequently, an integrated analytical framework capable of systematically explaining the generative logic of high urban economic resilience remains underdeveloped [17–18]. Third, green transformation should not be regarded as a static background, but rather as a dynamic process with clear stage-specific characteristics. As China's dual-carbon strategy continues to advance, digital finance deepens, green financial systems improve, and the cross-regional mobility of innovation factors evolves, the advantageous configurations and core conditions underpinning high urban economic resilience may shift over time. If identification relies solely on static cross-sectional data or long-term averages, the transition patterns of effective pathways across stages may easily be obscured, making it difficult to accurately capture the intertemporal evolution of high urban economic resilience [19–20].

In response to these practical concerns and research gaps, this study uses panel data for 27 central cities in the Yangtze River Delta from 2014 to 2023 to construct a resource-allocation analytical framework for urban economic resilience from the perspective of the Technology–Organization–Environment (TOE) framework, and employs dynamic qualitative comparative analysis (dynamic QCA) to identify the formation paths of high urban economic resilience and their intertemporal evolutionary characteristics. The TOE framework is adopted because it allows the simultaneous incorporation of technological conditions, organizational absorptive capacity, and the external institutional environment, thereby providing a more comprehensive perspective for explaining the formation logic of urban economic resilience in the context of green transformation. Dynamic QCA is employed because it not only identifies multiple equifinal paths under complex causality, but also makes it possible to examine changes in pathway structures and their core conditions over time. Rather than focusing solely on the net effects of individual variables, this study places greater emphasis on the circumstances under which different resource factors form effective configurations and on how such configurations persist, strengthen, or shift across stages.

The contributions of this study are threefold. First, at the theoretical level, this study interprets urban economic resilience from a configurational rather than a single-factor perspective, conceptualizing it as the outcome of the synergistic interaction of multiple categories of resource factors within specific institutional contexts. In doing so, it advances the literature from explaining resilience in terms of the net effects of isolated variables toward explaining it through configurational generative mechanisms. Second, at the methodological level, this study introduces dynamic QCA to identify conjunctural causation, equifinality, and causal asymmetry, while further revealing the stage-specific evolutionary patterns in the formation mechanism of high urban economic resilience. This provides dynamic analytical evidence for understanding how urban resilience is shaped in the context of green transformation. Third, at the practical level, this study identifies multiple realization paths leading to high urban economic resilience on the basis of different configuration types, and accordingly proposes more targeted policy approaches differentiated by type and stage, thereby offering empirical support for optimizing resilience-enhancement pathways for central cities in the Yangtze River Delta during green transformation.

2. Theoretical Foundations and Analytical Framework

2.1 Applicability of the TOE Framework

To explain the formation logic of high urban economic resilience in the context of green transformation, this study introduces the TOE framework [21]. Originally developed to explain the multidimensional determinants of technology adoption and organizational change, the TOE framework is particularly valuable because it incorporates technological conditions, organizational absorptive capacity, and external environmental constraints within a unified analytical perspective, thereby enabling the identification of the multiple conditional structures underlying complex outcomes. Compared with analytical approaches that focus solely on the effect of individual factors, the TOE framework places greater emphasis on the synergistic interactions among different conditions and their contextual dependence. This is highly consistent with the characteristics of urban economic resilience, which is typically shaped by multiple sources of influence, embedded in structural conditions, and manifested through heterogeneous developmental pathways.

From the perspective of the actual process of green transformation, the formation of urban economic resilience depends not only on technological progress itself, but also on the capacity of organizational systems to absorb and integrate factors such as capital, talent, and knowledge, while being continuously shaped by policy orientation, governance capacity, and the broader institutional environment [22–23]. The technological dimension determines whether a city possesses the endogenous drivers needed to advance green transformation and improve resource allocation efficiency. The organizational dimension concerns whether technology, capital, and human resources can be translated into effective capacities for adjustment and renewal. The environmental dimension, in turn, influences the direction of factor flows, the intensity of institutional implementation, and the efficiency of resource coordination [24–25]. Accordingly, urban economic resilience is better understood as a configurational outcome arising from the joint effects of technological, organizational, and environmental conditions, rather than as the linear result of any single factor operating in isolation over time.

In this study, the TOE framework serves two main purposes. First, it provides a unified theoretical basis for condition variables such as digital finance, green innovation, green financial provision, innovative human capital, green governance capacity, and green policy signals, allowing resource factors from different dimensions to be incorporated into a single explanatory system. Second, it highlights that different conditions may exhibit complementary, substitutive, or reinforcing relationships under different contexts, thereby offering a theoretical foundation for explaining why different cities can achieve relatively high levels of resilience through differentiated pathways. On this basis, this study adopts the TOE framework as the core theoretical lens for analyzing the formation mechanism of urban economic resilience in the context of green transformation.

2.2 Configurational Mechanisms of the Conditional Factors

2.2.1 Technological Dimension: Digital Finance and Green Innovation

The technological dimension is primarily reflected in the empowering role of digital finance and green innovation in enhancing urban economic resilience. As a product of the deep integration of digital technologies and financial services, digital finance expands the boundaries of financial service provision, reduces information asymmetry and transaction costs, and improves the efficiency with which capital is allocated across sectors, firms, and projects [26]. For cities undergoing green transformation, digital finance not only helps alleviate financing constraints faced by green projects and emerging industries, but also strengthens the capacity of the economic system to provide liquidity support and mitigate risks in the face of external shocks [27]. Its role, therefore, extends beyond improving access to finance; more importantly, by enhancing factor-matching efficiency and increasing resource liquidity, digital finance provides urban economic systems with greater adaptive space and adjustment flexibility.

Unlike digital finance, which primarily improves the efficiency of resource allocation, green innovation more directly relates to the technological substitution capacity and long-term transformation capacity of urban economic systems. By promoting the development of low-carbon technologies, the diffusion of cleaner production, and the upgrading of green industries, green innovation not only improves resource-use efficiency and environmental performance, but also reshapes industrial structures and cultivates new growth drivers [28]. In a context of increasingly stringent environmental regulation and frequent external shocks, cities with higher levels of green innovation typically possess stronger capacities for technological upgrading and greater room for structural adjustment, making them more likely to absorb and reconstruct in response to shocks through industrial reorganization and developmental path transformation [29]. In this sense, green innovation constitutes not only the technological foundation of green transformation, but also an important and enduring source of urban economic resilience.

2.2.2 Organizational Dimension: Green Financial Provision and Innovative Human Capital

The organizational dimension mainly reflects a city's absorptive capacity to translate technological conditions and external support into actual resilience performance, which is specifically manifested in green financial provision and innovative human capital. Green transformation is usually accompanied by industrial substitution, technological upgrading, and infrastructure restructuring, all of which require sustained, stable, and clearly oriented capital support. Green financial provision not only captures a city's ability to provide financial support for green industries and green projects, but also reflects its organizational capacity in resource screening, capital allocation, and risk sharing. In the absence of a financial supply system compatible with green transformation, even cities with a certain degree of innovative capacity and policy support may still see their resilience formation weakened by financing constraints and insufficient investment continuity.

Innovative human capital, in turn, serves as the key carrier linking technological inputs to their effective transformation within the organizational dimension. The formation of urban economic resilience depends not only on whether a city possesses technology and capital, but also on whether it has a high-quality talent base capable of absorbing knowledge, transforming technology, and promoting organizational learning [30]. A higher level of innovative human capital helps strengthen cities' capacities to absorb, diffuse, and further innovate on the basis of green technologies, while also enhancing the coordination capacity, responsiveness, and institutional learning ability of firms and government departments under shock conditions [31]. In other words, innovative human capital determines not only whether technology and capital can be effectively translated into actual productive forces, but also whether a city possesses the capacity for continuous adjustment and regeneration during processes of functional recovery and structural reorganization.

2.2.3 Environmental Dimension: Green Governance Capacity and Green Policy Signals

The environmental dimension is mainly reflected in the shaping role of green governance capacity and green policy signals in influencing the direction of resource allocation and the efficiency of coordination. Green governance capacity reflects the overall capability of local governments in environmental regulation, pollution control, policy implementation, and risk response [32]. Green transformation is not the spontaneous outcome of market forces alone; rather, it is the result of the joint action of governments, markets, and society. In this process, stronger green governance capacity helps reduce institutional frictions, enhance cross-departmental coordination and policy implementation efficiency, and improve a city's ability to coordinate and respond under conditions where environmental pressures and economic risks overlap [33]. Thus, the role of green governance capacity is reflected not only in improved environmental performance, but also in its support for resource integration efficiency and the stability of system operation.

Whereas governance capacity emphasizes institutional implementation, green policy signals act more directly on development expectations and the direction of resource flows. Clear, sustained, and credible policy signals can guide capital, technology, and talent toward green sectors, strengthen the stability of market expectations regarding the direction of green transformation, and improve the coordination efficiency among different resource conditions [34]. Especially during critical stages of green transformation, policy signals often mobilize resources through agenda setting, target constraints, and incentive guidance, thereby influencing investment intensity, technological choices, and the speed of organizational response in urban green development projects [35]. Accordingly, green policy signals not only constitute an important component of the external institutional environment, but also represent a crucial external condition shaping the formation of urban economic resilience at specific stages.

2.3 Analytical Framework

Based on the foregoing theoretical analysis, this study argues that the formation of relatively high urban economic resilience in the context of green transformation is essentially the result of the synergistic interaction of technological, organizational, and environmental conditions. Among these, digital finance and green innovation constitute the technological foundation for improving resource allocation efficiency and promoting structural transformation; green financial provision and innovative human capital determine whether cities can translate technological potential and capital support into actual capacities for adjustment and regeneration; and green governance capacity together with green policy signals influence the coordination efficiency among different conditions through institutional implementation, directional guidance, and resource mobilization. These three categories of conditions are not

isolated from one another; rather, they combine in differentiated ways across specific urban contexts and stages of transformation, jointly shaping the capacities of urban economic systems for resistance and recovery, adaptation and adjustment, and transformation and regeneration.

On this basis, this study develops an analytical framework linking the TOE framework, resource-allocation conditions, and urban economic resilience, as illustrated in Figure 1. The core implication of this framework is that relatively high resilience does not depend on the continued presence of any single condition; instead, it is more likely to emerge from effective configurations of multiple categories of resource factors under specific institutional environments and developmental stages. Guided by this analytical framework, the study further employs dynamic QCA to identify and compare the formation pathways of relatively high urban economic resilience and their intertemporal evolutionary characteristics.

3. Research Design

3.1 Research Method

This study employs dynamic QCA to identify the configurational pathways through which central cities in the Yangtze River Delta achieve high urban economic resilience in the context of green transformation, and to characterize their intertemporal evolutionary features [36]. Grounded in set theory and Boolean algebra, QCA is well suited to explaining complex socioeconomic phenomena within an analytical framework that emphasizes conjunctural causation, equifinality, and causal asymmetry, and is particularly effective in uncovering configurational mechanisms through which different conditions may exhibit complementary, substitutive, or compensatory relationships across distinct combinations [37]. Compared with regression-based approaches, which primarily focus on identifying the average net effect of individual variables on outcomes, QCA is more concerned with determining which combinations of conditions are sufficient to produce a given outcome. It therefore aligns more closely with the theoretical expectation of this study that high urban economic resilience is jointly generated by the configuration of multiple categories of resource factors.

However, conventional QCA is typically based on static cross-sectional data or pooled samples over the study period, making it difficult to further identify the temporal stability, reinforcement, and migration patterns of effective configurations. As a result, it may obscure the emergence, evolution, and relative convergence of advantageous pathways under the stage-specific progression of green transformation [38]. Under the continuous advancement of carbon-reduction constraints, changes in the penetration of digital finance, the development of green financial systems, the diffusion of green innovation, and shifts in governance capacity jointly reshape patterns of resource allocation and the pace of industrial adjustment, thereby rendering the formation mechanism of urban economic resilience distinctly temporal and stage-dependent. Against this background, this study incorporates dynamic QCA within the TOE framework and conducts phased identification, intertemporal comparison, and overall synthesis of both necessary-condition relationships and sufficient configurations, so as to capture more accurately the intertemporal evolution of complex causal relationships.

More specifically, the dynamic QCA analysis in this study is conducted at three levels: annual identification, intertemporal comparison, and overall synthesis. First, at the annual level, truth tables are constructed separately for each year to identify sufficient configurations, while necessity tests are performed for each individual condition and its absence. Second, at the intertemporal comparison level, the consistency, coverage, and changing trends of the same pathway across different years are compared in order to identify the reinforcement, weakening, migration, and relative convergence of dominant configurations. Third, at the overall synthesis level, the results from each year are integrated, and both the between-group consistency-adjusted distance and the within-group consistency-adjusted distance are used to examine, respectively, the stability and variation of configurational explanatory power across years and across cities [39]. Among these, the between-group consistency-adjusted distance is mainly used to identify the degree of fluctuation over time, whereas the within-group consistency-adjusted distance is primarily used to capture heterogeneity at the case level. To ensure the reproducibility and robustness of the findings, this study sets the relevant thresholds in accordance with the sample size and panel structure, and further conducts robustness tests by raising these thresholds.

3.2 Sample Selection

This study selects 27 central cities in the Yangtze River Delta as the research sample. Compared with ordinary cities, central cities generally possess stronger advantages in the provision of green financial instruments, the agglomeration of science and technology innovation resources, and the allocation of governance capacity, and are therefore better positioned to reflect the typical features of urban economic resilience in the context of green transformation. According to the scope of central cities defined in the Development Plan for the Yangtze River Delta Urban Agglomeration, the selected sample exhibits a relatively high degree of comparability in terms of regional development hierarchy, while still retaining sufficient variation in industrial structure, the foundation of green finance development, technological innovation capacity, and governance environment. This makes the sample well suited to configurational analysis, which requires both internal heterogeneity and the possibility of identifying multiple pathways.

With regard to the temporal scope, this study focuses on the period 2014–2023. During this period, China's green development orientation was continuously strengthened, digital finance expanded rapidly, the green finance policy system was gradually improved, and green technological innovation continued to diffuse. These developments provide an appropriate window for examining the intertemporal migration of the pathways leading to urban economic resilience and their stage-specific changes. Accordingly, the sample period from 2014 to 2023 offers a solid basis for identifying the configurational logic of TOE factors and their evolutionary patterns from the perspective of dynamic QCA.

3.3 Measurement of Variables and Data Sources

3.3.1 Outcome Variable

This study takes urban economic resilience as the outcome variable. Given the multidimensional nature of economic resilience, a single indicator is insufficient to capture its full connotation. Drawing on the composite evaluation approach adopted in the relevant literature [40], this study constructs an

index system for urban economic resilience from three dimensions—resistance and recovery capacity, adaptation and adjustment capacity, and transformation and regeneration capacity (see Table 1). Based on this framework, the level of urban economic resilience of central cities in the Yangtze River Delta over the period 2014–2023 is measured (see Figure 2). This index system is intended to reflect, from the perspective of overall capability, the comprehensive performance of cities in maintaining functions, adjusting structures, and forming new development paths under conditions of external shocks and green transformation.

Table 1. Design and Measurement of the Outcome Variable

Variable type	Primary dimension	Secondary indicator	Indicator description
Outcome variables	Resistance and recovery capacity	Economic development	GDP per capita
		Employment	Registered urban unemployment rate
		Income level	Disposable income of residents
		Household savings	Urban–rural household savings / permanent population
		Openness	Actual utilized foreign direct investment / GDP
	Adaptive andadjustment capacity	Upgrading of industrial structure	Value added of tertiary industry / value added of secondary industry
		Fixed-asset investment	Fixed-asset investment / permanent population
		Financial quality	Balance of loans of financial institutions / GDP
		Fiscal balance	Fiscal revenue / fiscal expenditure
		Income distribution	Urban Gini coefficient
		Consumption capacity	Total retail sales of consumer goods / GDP
	Transformative and renewal capacity	Urbanization rate	Urban permanent population / permanent population
		Science and education input	Science and education expenditure as a share of GDP
		Science and education capacity	Number of university students enrolled
		R&D capacity	Number of patent applications per 10,000 people

In terms of data sources, the relevant indicators are primarily drawn from urban statistical yearbooks, provincial statistical yearbooks, and the National Bureau of Statistics of China database. Selected financial and economic indicators are further supplemented and cross-validated using the CSMAR database to ensure data continuity and comparability. All indicators are first adjusted to ensure consistency in directional attributes and then standardized. The entropy weight method is subsequently applied to assign objective weights and aggregate the indicators into a composite index of urban economic resilience. It should be noted that the entropy weight method is used to construct a comparable composite resilience index, whereas the subsequent QCA calibration further maps this composite index into set membership scores. The two procedures serve different purposes—namely, index construction and set-theoretic analysis—and therefore do not involve repeated weighting.

3.3.2 Condition Variables

Based on the TOE analytical framework developed above, this study selects six conditional variables: digital finance, green innovation, green financial provision, innovative human capital, green governance capacity, and green policy signals (see Table 2).

Digital finance is measured using the Peking University Digital Financial Inclusion Index. This index reflects the level of urban digital finance development in terms of coverage breadth, depth of use, and degree of digitalization, and is therefore able to capture the foundations and intensity of digital finance development at the city level in a relatively comprehensive manner. The data are obtained from the Peking University Digital Financial Inclusion Index database.

Green innovation is measured by the number of green patents per 10,000 people, which is used to reflect the level of technological innovation output oriented toward green transformation. The relevant data are obtained from patent statistics and urban statistical yearbooks.

Green financial provision is measured by a green finance index, which is used to capture the level of supply of green financial instruments and the availability of green capital at the city level. The data are compiled and calculated on the basis of statistical materials and publicly available data from the National Bureau of Statistics of China, the Ministry of Science and Technology, the People's Bank of China, and other relevant sources.

Innovative human capital is measured by the number of R&D personnel per 10,000 people, which reflects the supply of urban R&D and innovation talent. The data are drawn from urban statistical yearbooks, science and technology statistical yearbooks, and relevant databases.

Green governance capacity is measured by the share of environmental governance investment in general public budget expenditure, which is used to capture the level of local government investment in ecological and environmental governance and its governance foundation. The relevant data are obtained from urban statistical yearbooks, fiscal statistics, and environmental statistical materials.

Green policy signals are measured by the standardized frequency of green- and environmental-related keywords in annual government work reports, which is used to reflect the intensity and continuity of local governments' green development agenda. The data are collected from publicly available texts of local government work reports and standardized by the total word count of each report.

Table 2. Design and Measurement of the Conditional Variables

Variable type	Primary dimension	Secondary indicator	Indicator description
Condition variables	Technology	Digital finance	Peking University Digital Inclusive Finance Index
		Green innovation	Green patents per 10,000 people
	Organization	Green finance supply	Composite score of the Green Finance Index evaluation
		Innovative human capital	R&D personnel per 10,000 people
	Environment	Green governance capacity	Environmental governance investment / general public budget expenditure
		Green policy signals	Total frequency of environmental keywords in the annual Government Work Report

3.3.3 Variable Calibration

After completing the organization of the raw data and the measurement of indicators, this study further calibrates both the outcome variable and all condition variables into fuzzy sets in order to obtain the set-membership scores required for QCA. Given that the sample consists of a balanced panel of 27 central cities in the Yangtze River Delta over the period 2014–2023, the 75th percentile, 50th percentile, and 25th percentile are selected as the calibration anchors to reduce the potential interference of scale differences and extreme values in configurational identification. These thresholds correspond to full membership, the crossover point, and full non-membership, respectively. To ensure the comparability of configurational results across different years, this study adopts uniform calibration anchors based on the distribution of all city-year observations in the full sample, rather than setting calibration thresholds separately for each year. The specific calibration results for all variables are reported in Table 3.

Table 3. Calibration results of variables

Variable type	Variable	Calibration		
		Full membership	Crossover point	Full non-membership
Outcome variable	Urban economic resilience	0.434	0.3675	0.2994
Condition variable	Digital finance	313.4309	272.6308	220.9618
	Green innovation	2058.25	962	390.5
	Green finance supply	0.4372	0.3992	0.2981
	Innovative human capital	340.8718	233.2935	136.8209
	Green governance capacity	0.0111	0.0082	0.0057
	Green policy signals	202	171	144

4. Empirical Analysis

4.1 Necessity Analysis of Individual Conditions

According to the conventional criterion in QCA, a condition can be regarded as necessary for the occurrence of an outcome when its consistency with the outcome reaches or exceeds 0.90 [41]. On this basis, this study conducts necessity tests for the six condition variables under the TOE framework, together with their absence states, and further examines the stability of these necessity relationships across both the temporal dimension and the case dimension by incorporating the between-group consistency-adjusted distance and the within-group consistency-adjusted distance [42].

As reported in Table 4, the aggregate consistency values of all individual conditions and their absence states with respect to high urban economic resilience are below 0.90, indicating that there is no single condition that can independently constitute a stable necessary condition for high urban economic resilience. This finding suggests that the formation of high urban economic resilience cannot be adequately explained by any single resource factor alone, but is more likely to depend on the configurational matching and synergistic interaction among technological, organizational, and environmental conditions. A closer examination further shows that some conditions exhibit relatively large between-group consistency-adjusted distances or within-group consistency-adjusted distances, implying that even if certain conditions approach the threshold of necessity in particular years or individual cities, their necessity relationships still lack stability across time or across cases.

Table 4. Results of necessary condition analysis

Condition variable	High Urban Economic Resilience			
	Overall consistency	Overall coverage	Between-group consistency adjustment distance	Within-group consistency adjustment distance
High digital finance	0.701	0.709	1.119	0.131
Low digital finance	0.401	0.404	1.387	0.272
High green innovation	0.775	0.793	0.121	0.305
Low green innovation	0.351	0.349	0.356	0.465
High green finance supply	0.731	0.703	0.203	0.302
Low green finance supply	0.392	0.416	0.779	0.432
High innovative human capital	0.767	0.771	0.132	0.305
Low innovative human capital	0.340	0.345	0.291	0.534
High green governance capacity	0.621	0.633	0.269	0.236
Low green governance capacity	0.483	0.482	0.433	0.287
High green policy signals	0.510	0.515	0.603	0.327
Low green policy signals	0.584	0.589	0.526	0.287

For condition pairings characterized by relatively large between-group consistency-adjusted distances and by consistency values approaching or reaching the necessity threshold in certain individual years, this study further conducts period-specific necessity tests, the results of which are reported in Table 5. Overall, with the exception of a few pairings—such as high digital finance and high urban economic resilience and non-high digital finance and high urban economic resilience—that exhibit consistency values above 0.90 in certain individual years, most condition–outcome pairings fail to meet the necessity criterion in the majority of years. Even for these few pairings that approach or reach the level of necessity in specific years, such patterns are mainly concentrated in isolated stages of the sample period and do not display sustained stability over time. It is therefore evident that neither high digital finance nor non-high digital finance can be regarded as a stable necessary condition for high urban economic resilience. Taken together, the necessity analysis further indicates that the formation of economic resilience in the central cities of the Yangtze River Delta is characterized by marked complexity and configurationality, such that no single factor can provide a temporally robust explanation. This also provides empirical support for the subsequent sufficiency analysis from the perspective of multi-condition configurations.

Table 5. Inter-group analysis of conditions with large consistency-adjusted distances

Causal Combination Case			Year				
			2014	2015	2016	2017	2018
Case 1	High digital finance and high urban economic resilience	Between-group consistency	0.014	0.054	0.133	0.43	0.67
		Between-group coverage	1	0.97	0.907	0.875	0.805
Case 2	High green innovation and high urban economic resilience	Between-group consistency	0.783	0.776	0.793	0.68	0.806
		Between-group coverage	0.849	0.825	0.847	0.899	0.752
Case 3	High green finance supply and high urban economic resilience	Between-group consistency	0.595	0.652	0.616	0.64	0.816
		Between-group coverage	0.614	0.711	0.653	0.694	0.673
Case 4	High green governance capacity and high urban economic resilience	Between-group consistency	0.426	0.69	0.54	0.652	0.607
		Between-group coverage	0.543	0.552	0.563	0.523	0.68
Case 5	High green policy signals and high urban economic resilience	Between-group consistency	0.758	0.718	0.889	0.614	0.647
		Between-group coverage	0.405	0.52	0.445	0.505	0.448
Case 6	Not-high digital finance and high urban economic resilience	Between-group consistency	0.998	0.983	0.95	0.769	0.541
		Between-group coverage	0.28	0.359	0.413	0.497	0.468

As shown in Figure 3, the consistency of the condition variables over the period 2014–2023 exhibits a relatively clear pattern of differentiation. Specifically, the consistency of high digital finance shows an overall upward trend; high green policy signals remain relatively strong in the earlier stage but gradually weaken over time; high green innovation and high green financial provision display relatively higher consistency in the middle stage of the sample period; high innovative human capital remains at a generally high level with fluctuations; and high green governance capacity presents a pattern of stage-specific fluctuation with an overall upward tendency. These patterns indicate that the strength of association between any single condition and high urban economic resilience is not stable across different stages, and that its effect is more likely to be jointly shaped by temporal context and inter-city heterogeneity. In other words, although the changing consistency of individual conditions can provide useful clues for understanding stage-specific differences in conditional effects, it is still insufficient to offer a full explanation for high urban economic resilience. These findings further support the necessity of identifying the

realization paths of high urban economic resilience from the perspective of resource-factor configurations, and also provide an empirical basis for the subsequent sufficiency analysis.

4.2 Sufficiency Analysis of Conditional Configurations

4.2.1 Overall Results

Building on the necessity analysis, this study further identifies the sufficient configurations leading to high urban economic resilience. The thresholds for consistency, PRI consistency, and frequency are set at 0.75, 0.70, and 1, respectively. Under the assumption of no directional expectations, effective pathways are identified by combining the intermediate solution with the parsimonious solution [43]. The results show that four conditional configurations can lead to high urban economic resilience. The overall solution consistency, overall PRI, and overall coverage are 0.913, 0.892, and 0.624, respectively, indicating that the identified configurations possess strong explanatory power (Table 6).

Table 6. Results of configurational sufficiency analysis

Condition variable	Configurations leading to high urban economic resilience			
	Configuration 1	Configuration 2	Configuration 3	Configuration 4
Digital finance	Ä	●	●	●
Green innovation	●	●		●
Green finance supply			●	
Innovative human capital	●	●	●	●
Green governance capacity				●
Green policy signals	●	Ä	Ä	
Consistency	0.938	0.91	0.89	0.909
PRI	0.901	0.881	0.853	0.886
Coverage	0.201	0.289	0.27	0.351
Unique coverage	0.032	0.015	0.028	0.002
Between-group consistency adjustment distance	0.132	0.088	0.093	0.082
Within-group consistency adjustment distance	0.142	0.153	0.171	0.16
Overall consistency	0.913			
Overall PRI	0.892			
Overall coverage	0.624			

Note: ●and Ä indicate the presence and absence of a core condition, respectively; ● and Ä indicate the presence and absence of a peripheral (auxiliary) condition, respectively; blank cells indicate that the condition may be either present or absent.

Overall, the sufficiency analysis yields three important findings. First, there is no single optimal pathway to high urban economic resilience; rather, the outcome exhibits a clear pattern of equifinality. Different cities can achieve high resilience through differentiated combinations of factors under varying resource endowments, institutional environments, and stages of development. Second, innovative human capital appears in all four configurations, indicating that it plays a cross-path supporting role in the formation of high urban economic resilience and serves as a critical capability carrier linking financial resources, technological inputs, and structural transformation. Third, digital finance, green innovation, green financial provision, green governance capacity, and green policy signals do not display fixed or invariant ranks of importance. Instead, they assume different functions across configurations, including core driving, complementary support, and synergistic reinforcement. This further suggests that the formation logic of high resilience is strongly configuration-dependent.

Based on the structure of the core conditions, this study classifies the four configurations into four typical patterns: the innovation–policy synergy pattern, the digital innovation–human capital driven pattern, the digital finance–human capital supported pattern, and the governance-empowered reinforcement pattern. It should be noted that these four types of pathways are not mutually isolated; rather, they exhibit a certain hierarchical relationship in their underlying logic. In particular, the digital innovation–human capital driven pattern and the governance-empowered reinforcement pattern share a similar foundational structure, with the latter being understood as an extended form of the former under the strengthened condition of governance capacity. By contrast, the innovation–policy synergy pattern and the digital finance–human capital supported pattern represent two distinct realization mechanisms dominated respectively by policy–innovation synergy and finance–human capital synergy. This indicates that, although all four pathways lead to high urban economic resilience, the dominant conditional structures on which they rely are not the same.

4.2.2 Intertemporal Evolution of Configurations and Case Heterogeneity

To further examine the stability of the configurational pathways, this study compares the intertemporal variation and case heterogeneity of the four configurations from three dimensions: between-group consistency, within-group consistency, and their corresponding adjusted distances. The results show that both the between-group consistency-adjusted distance and the within-group consistency-adjusted distance for all four configurations are below the empirical threshold of 0.20, indicating that the configurations remain generally valid and broadly applicable, without losing explanatory power due to temporal progression or deviations in individual cases.

From the temporal perspective (Figure 4), all four configurations remain effective throughout the period 2014–2023, although their explanatory power exhibits some stage-specific variation. Configuration 1 shows a pattern of initial decline followed by recovery and eventual stabilization in the later period, suggesting that the pathway dominated by green innovation, innovative human capital, and green policy signals becomes more likely to translate into high-resilience performance in the later stage of the sample period. Configuration 2, although maintaining a relatively high level of consistency overall, shows some decline in the later period, indicating that the synergistic effects of digital finance, green innovation, and human capital may face a certain reduction in discriminating power or increasing constraints in institutional coordination over time. Configurations 3 and 4, by contrast, exhibit relatively strong persistence, suggesting that pathways characterized by financial support or governance reinforcement remain comparatively stable throughout the sample period. Overall, differences across pathways are reflected more in the dynamic adjustment of their explanatory strength than in any fundamental change in their validity. This implies that the formation mechanism of urban economic resilience in the context of green transformation displays considerable continuity, while the relative importance of dominant conditions may be reordered as the transformation process unfolds.

From the case dimension (Figure 5), each configuration exhibits relatively high consistency in most cities, with lower consistency observed only in a small number of cases. Compared with between-group differences, the within-group consistency-adjusted distance is generally higher, indicating that variation in the explanatory power of configurations for high urban economic resilience stems less from temporal change and more from the structural heterogeneity across cities in terms of industrial structure, innovation foundations, financial conditions, and governance environments. In other words, the same combination of conditions does not possess exactly the same applicability across all cities; rather, its effects remain contingent upon local developmental foundations and institutional contexts. This finding suggests that, when identifying the pathways to high resilience, attention should be paid not only to whether a given pathway is effective, but also to the specific boundaries and application scenarios under which different pathways hold.

5. Discussion

5.1 Discussion of Configurations

To further enhance the real-world interpretive power of the configurational findings, this study builds on the identification of sufficient pathways and the dynamic comparative analysis by incorporating the practical experiences of representative cities in green transformation, digital empowerment, financial allocation, and governance coordination to discuss the four pathways leading to high urban economic resilience. It should be noted that the purpose of the case discussion is not to replace the configurational results with the experience of individual cities, but rather to use locally grounded practices with strong real-world representativeness to further validate the underlying logic of resource coordination, the contextual boundaries of applicability, and the dynamic evolutionary characteristics associated with each configuration. Overall, the four pathways correspond to four typical mechanisms: policy–innovation coupling, digital finance–technology–human capital linkage, financial provision–human capital support, and governance-enhanced coordination. This indicates that high urban economic resilience does not arise from the continuous accumulation of a single advantageous condition, but from the formation of contextually adaptive combinations of multiple resource factors under specific institutional environments and developmental stages.

First, the innovation–policy synergy pattern suggests that, when the direction of green transformation is clearly defined and policy signals are released in a sustained manner, strong reinforcing relationships can emerge among green innovation, innovative human capital, and policy orientation. The core of this pathway does not lie in policy directly creating resilience per se, but in the way policy signals stabilize expectations, reduce coordination costs, and shape the direction of resource flows, thereby providing sustained institutional support for green innovation activities and the agglomeration of high-end talent. The practices of Shanghai and Wuxi illustrate this mechanism well. In the former, the *Shanghai 2035* master plan and subsequent key dual-carbon work arrangements have incorporated the construction of an international science and technology innovation center, green development constraints, and industrial upgrading into a unified strategic framework, gradually forming a linkage pattern of policy orientation–innovation advancement–factor agglomeration. In the latter, the city established a net-zero carbon city target at an early stage and progressively developed a “1+1+N+X” dual-carbon policy system, embedding green transformation requirements into technological research, the commercialization of scientific achievements, and the cultivation and attraction of new-energy talent. Together, these cases show that Configuration 1 does not capture policy support in a generic sense, but rather the synergistic effect between sustained, clear, and transmissible green policy signals and a convertible innovation capacity base. It is precisely for this reason that the explanatory power of this pathway increases in the later stage of the sample period, suggesting that as the institutional environment of green transformation moves from an advocacy phase into a deepening phase, the coupling between policy orientation and the innovation system is more likely to be translated into resilience performance.

Second, the digital innovation–human capital driven pattern reveals that, even when policy signals do not consistently occupy a dominant position, cities may still achieve high resilience through the synergy among digital finance, green innovation, and innovative human capital. The key to this pathway lies in the fact that digital finance does not merely provide financing convenience; rather, by improving information identification, reducing transaction frictions, and enhancing the efficiency of resource allocation, it creates a more effective support environment for green technological innovation and the growth of innovative actors. Innovative human capital, in turn, ensures that capital, technology, and industrial application scenarios can be effectively coupled. The experiences of Suzhou and Ningbo illustrate this mechanism particularly well. Suzhou has formed strong linkages among digital financial infrastructure, flexible regulatory innovation, and talent supply for key industries through integrated financial service platforms such as “Surongtong” and “Yidaima,” pilot programs in financial technology innovation regulation, and leading-talent initiatives, thereby simultaneously improving financing accessibility, risk

manageability, and innovation continuity. Ningbo, by contrast, has connected digital platforms, policy constraints, and firms' green transformation needs through "Yongjintong," energy-saving and carbon-reduction action plans, the "heroes per mu" performance system, and green technological upgrading financial instruments, demonstrating the amplifying effect of digital financial capacity once embedded in governance and industrial upgrading systems. Compared with Configuration 1, this pathway is less dependent on formal policy signals and places greater emphasis on the endogenous synergy between digitalized resource allocation capacity and innovative absorptive capacity. However, the decline in its explanatory power in the later period also suggests that as foundational conditions such as digital finance gradually diffuse and become more widespread, their marginal role in distinguishing cities' resilience levels may weaken. In such circumstances, without more stable institutional coordination and scenario-conversion mechanisms, the configuration of digital finance + innovation + human capital alone may not be sufficient to maintain a lasting advantage.

Third, the digital finance–human capital supported pattern indicates that, during the deepening stage of green transformation, the synergy between the structural supply capacity of the financial system and innovative human capital plays an important role in enhancing resilience. Compared with the previous pathway, this configuration places greater emphasis on the medium- and long-term supporting function of green financial provision, highlighting that only when the efficiency advantages of digital finance are combined with the directional supply of green finance, and when innovative human capital completes the processes of absorption, transformation, and diffusion, can financial resources be genuinely converted into capacities for industrial upgrading and shock recovery. The case of Hangzhou provides a relatively clear real-world illustration of this mechanism. As one of China's first low-carbon pilot cities and a leading hub of the digital economy, Hangzhou has not relied solely on policy appeals to advance green transformation. Instead, it has gradually embedded pollution and carbon reduction goals into emissions data acquisition, accounting rule construction, digital platform governance, and green credit support systems, forming a coordinated structure of data availability–credible accounting–usable finance–closed-loop governance. In this process, digital finance has improved the efficiency of green project identification and financing matching, green financial provision has enhanced capital availability for medium- and long-term transformation projects, and innovative talent together with industrial clusters has ensured the continuous iteration of monitoring, accounting, modeling, and governance tools. Thus, Configuration 3 does not simply imply that "more financial investment leads to greater resilience"; rather, it highlights the coupling relationship among the directionality of financial provision, the efficiency of digital tools, and the transformative capacity of human capital. This also explains why this pathway exhibits relatively strong explanatory power in the middle stage of the sample period: when green transformation shifts from conceptual advocacy toward project implementation, capital reallocation, and institutional deepening, the synergy between financial support and human capital absorption becomes especially critical.

Finally, the governance-empowered reinforcement pattern suggests that, although green governance capacity may not constitute an independent dominant condition in all pathways, under specific circumstances it can significantly enhance the stability and efficiency with which existing resource combinations are translated into resilience outcomes. Put differently, the role of governance capacity in this configuration is closer to that of an amplifier than an engine. The experience of Hefei reflects this feature particularly well. Through policy arrangements involving digital economy development planning, new infrastructure construction, the expansion of digital finance application scenarios, and pilot programs for a chief data officer system, Hefei has gradually developed a resource-organization capacity supported by data platforms. More specifically, the Hefei High-Tech Zone has embedded green innovation, research platforms, and collaborative enterprise innovation into a stronger institutional implementation and feedback loop through a pollution and carbon reduction evaluation index system, smart energy platforms, industrial carbon points, and linkage mechanisms connecting policy implementation with financial products. In this context, digital finance, green innovation, and innovative human capital constitute the foundational driving structure, while green governance capacity, by enhancing rule implementation, reducing institutional frictions, and strengthening platform coordination, enables this structure to be translated more stably into high-resilience performance. Configuration 4 can therefore be understood as an upgraded version of Configuration 2 under strengthened governance capacity. Its theoretical significance lies in showing that, for cities that already possess a certain foundation in digital finance, green innovation, and human capital, further improving green governance capacity is not merely an optional add-on, but often a key condition determining whether existing advantages can be continuously amplified.

Taken together, the four pathways and their representative cases suggest that the formation of high urban economic resilience is characterized by strong configuration dependence, stage specificity, and contextual embeddedness. On the one hand, there is no single resource factor that can stably play a decisive role across all cities and all periods. On the other hand, the different pathways are not completely disconnected from one another; rather, they exhibit certain hierarchical and substitutive relationships. Policy signals can strengthen innovation coordination during periods of institutional stabilization, digital finance can improve the efficiency of resource allocation in marketized and platform-based environments, green financial provision can offer directional capital support in the deepening stage of transformation, and green governance capacity can enhance existing resource foundations by improving effectiveness and providing stabilizing support. In practical terms, this means that cities seeking to enhance economic resilience should not mechanically replicate any single "successful experience," but should instead identify more context-appropriate combinations of factors based on their own stage of development, resource endowments, and institutional foundations. From a theoretical perspective, the case discussion further validates the core argument of this study that high urban economic resilience is jointly generated by multiple resource factors, and also shows that within the TOE framework, technological, organizational, and environmental conditions do not operate in a static manner, but are reordered and recombined under different transformation contexts.

5.2 Robustness Tests

Following the existing literature, this study conducts robustness tests by raising the thresholds for consistency, PRI consistency, and frequency. Specifically, the consistency threshold is increased from 0.75 to 0.80, the PRI threshold from 0.70 to 0.75, and the frequency threshold from 1 to 2. The results show that, under these more stringent identification criteria, the resulting configurations still exhibit a clear subset relationship with the benchmark results, and the core conditional structures of each pathway remain unchanged, with only minor differences in a few peripheral conditions. Overall, the robustness tests do not alter the central conclusions of this study—namely, that high urban economic resilience is achieved through multi-factor configurations, that multiple equifinal pathways exist, and that different pathways display stage-specific variation—thereby confirming the strong robustness of the findings.

6. Conclusions and implications

6.1 Conclusions

Based on a dynamic QCA analysis of panel data for 27 central cities in the Yangtze River Delta from 2014 to 2023, this study systematically examines the generative mechanism of high urban economic resilience in the context of green transformation from three dimensions: necessity testing, identification of sufficient configurations, and intertemporal comparative analysis. The findings are as follows. First, no single condition constitutes a stable necessary condition across periods and cities, indicating that no individual resource factor can, in an overall sense, serve as the prerequisite for the formation of high resilience. This empirically supports the theoretical argument that urban economic resilience is configurationally generated. Second, the sufficiency analysis identifies four equifinal pathways leading to high urban economic resilience, which can be summarized as the innovation–policy synergy pattern, the digital innovation–human capital driven pattern, the digital finance–human capital supported pattern, and the governance-empowered reinforcement pattern. This demonstrates that high resilience is not the result of a single pathway, but can be realized through multiple combinations of resource factors. Third, the dynamic comparison further shows that the explanatory power of different pathways shifts across stages of green transformation, exhibiting an overall pattern of stage-specific differentiation and a certain degree of relative convergence in the later period of the sample. As foundational conditions such as digital finance become increasingly widespread, differences in high urban economic resilience are more likely to depend on the quality of coordination among factors such as green innovation, green financial provision, governance implementation, and policy expectations.

6.2 Policy Implications

Based on the above findings, this study argues that enhancing urban economic resilience requires attention to both common capacity building and path-differentiated configuration. At the general level, a resilience capacity assessment and configurational diagnostic mechanism centered on TOE factors should be established to dynamically identify the most proximate advantageous pathway for each city and the corresponding missing conditions. At the same time, innovative human capital should be treated as a foundational cross-path capability, with stable systems for talent supply, cultivation, and transformation to improve the absorptive and transformative efficiency of various resource inputs. At the differentiated level, cities characterized by the innovation–policy synergy pattern should focus on strengthening the continuity and predictability of policy signals, so as to improve collaborative governance efficiency through more stable goal systems and implementation agendas. Cities following the digital innovation–human capital driven pattern should prioritize the improvement of data governance and digital financial infrastructure in order to enhance the matching efficiency of capital allocation toward green and high-growth sectors. Cities characterized by the digital finance–human capital supported pattern should focus on improving the system of green financial instruments and cross-cycle risk-sharing mechanisms so as to strengthen the stability of medium- and long-term capital supply. Cities exhibiting the governance-empowered reinforcement pattern, in turn, should prioritize improvements in governance implementation and regulatory coordination, and enhance the credibility and executability of project advancement through public data provision and digital governance, thereby amplifying the synergistic effects among technological, organizational, and environmental factors.

Declarations

Author Contributions:M.D.: Writing—review and editing, Methodology, Conceptualization. J.L.: Writing—original draft, Data curation, Visualization. M.D.: Writing—review and editing, Validation, Supervision. All authors have read and agreed to the published version of the manuscript.

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Funding:This study was supported by the Major Project of Philosophy and Social Science Research in Jiangsu Higher Education Institutions, Research on the Synergistic Mechanism between the Achievement of Jiangsu’s Dual-Carbon Goals and the Enhancement of Economic Resilience (Grant No. 2023SJZD059).

Data Availability Statement:Data will be made available on request.

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

Declarations: Ethical approval not applicable

Consent to Participate : not applicable

Consent to Publish : All authors consent to publish

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Figures

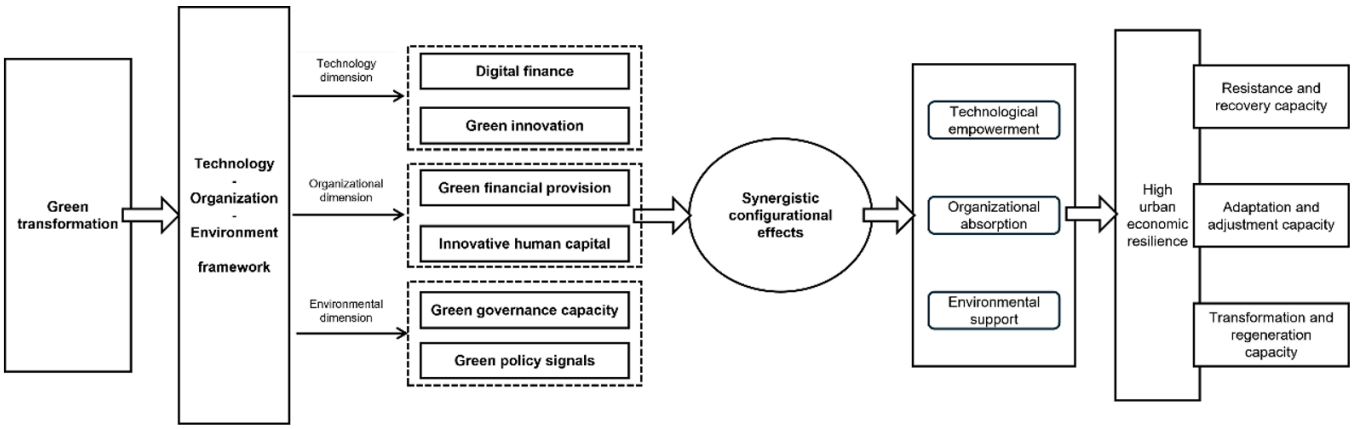


Figure 1

Analytical framework of high urban economic resilience under green transformation

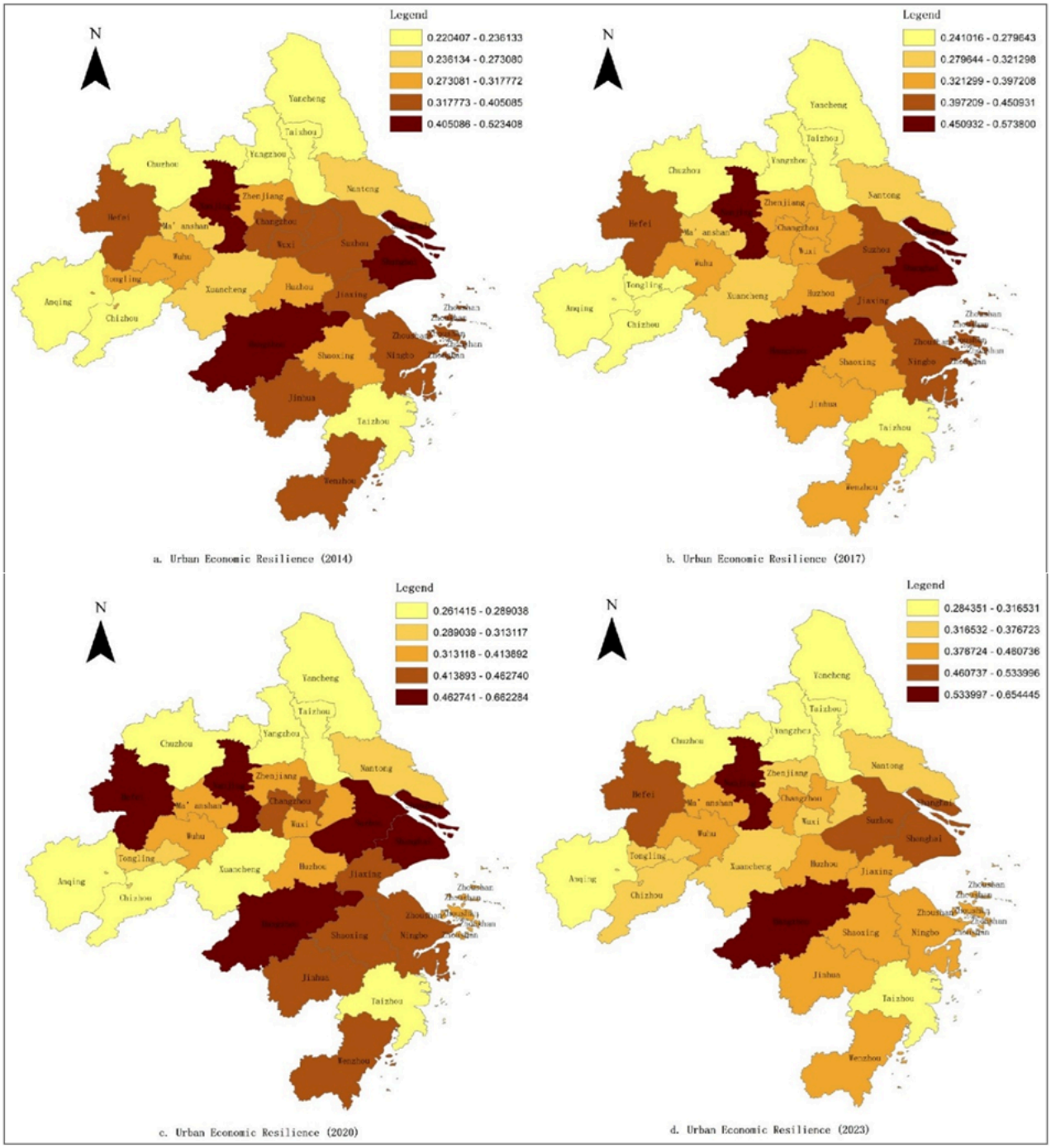


Figure 2

Spatial pattern of economic resilience development in core cities of the Yangtze River Delta

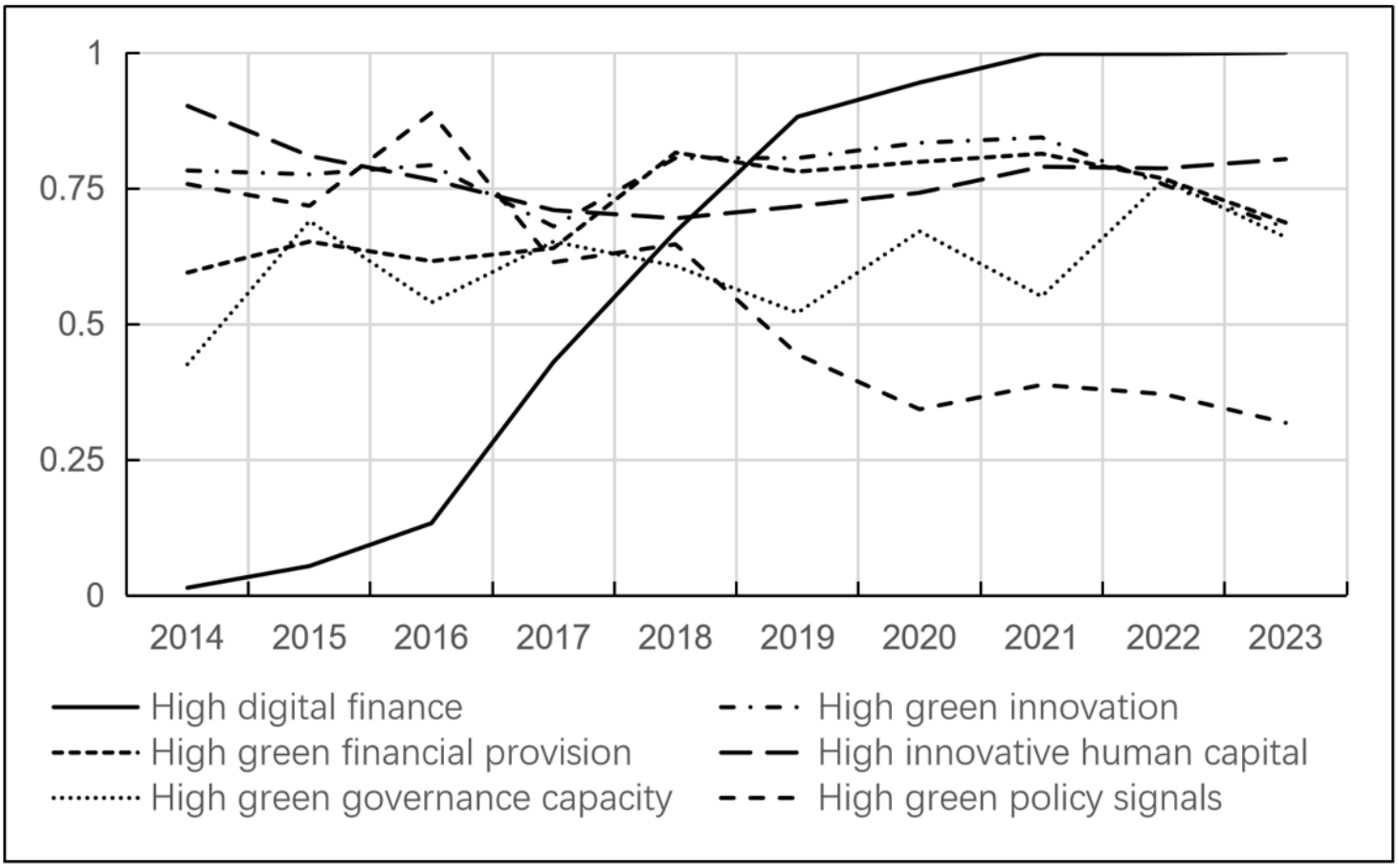


Figure 3

Consistency changes of the condition variables

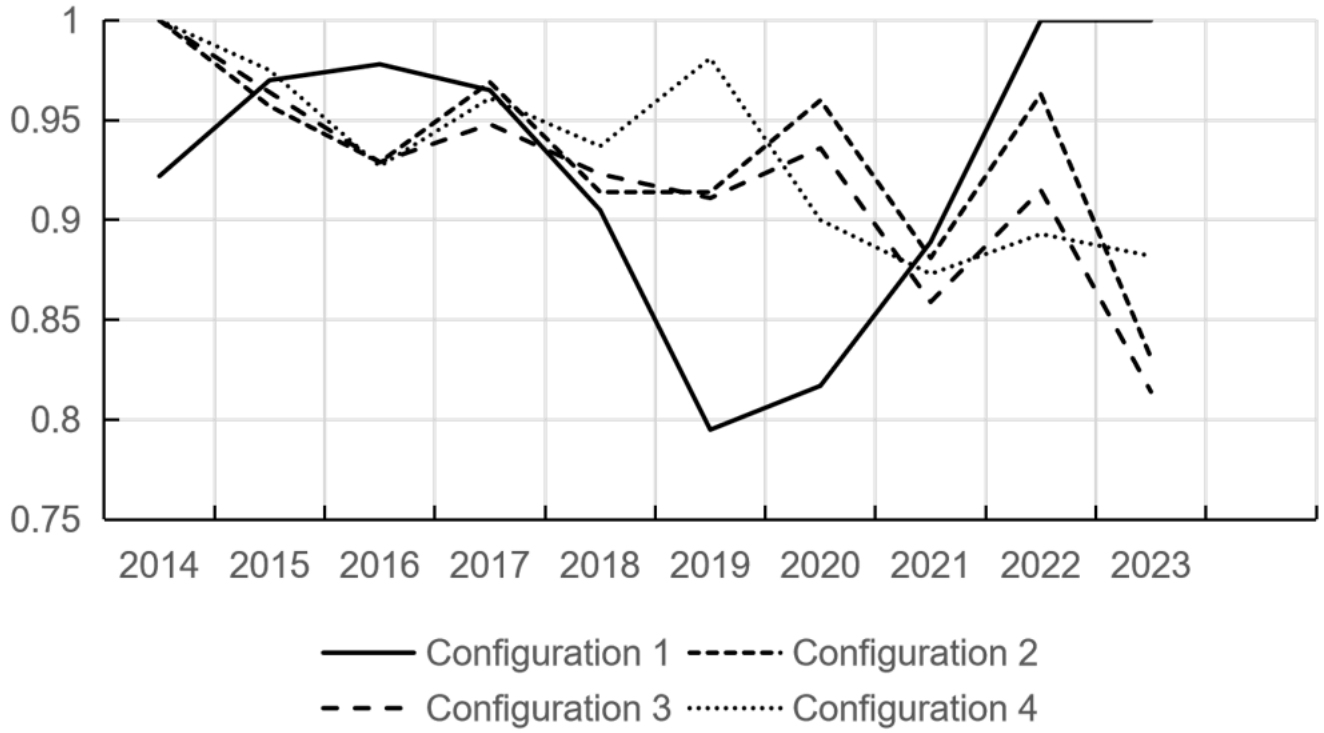


Figure 4

Trends in between-group consistency across configurations

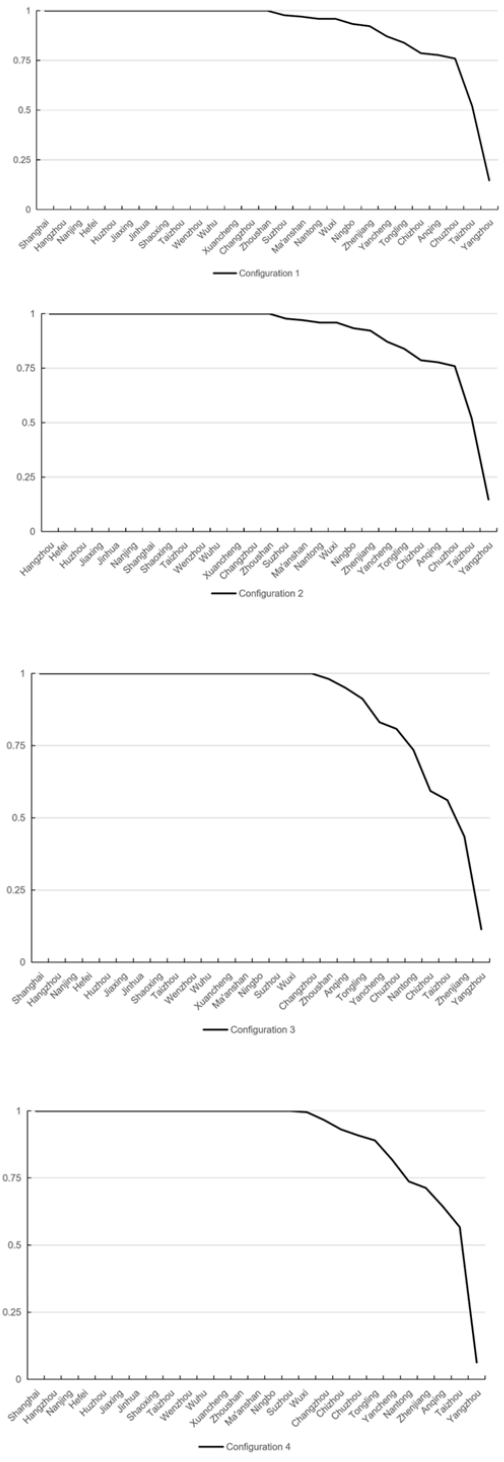


Figure 5

Within-group consistency across configurations