

Impact Mechanism of Four-Chain Integration on Regional Economic Resilience

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Abstract: Regional economic resilience has become increasingly important as economies face external disruptions and structural change. This study investigates how the integration of innovation, industry, capital, and talent relates to regional economic resilience, using panel data for 30 Chinese provinces from 2013 to 2022. An entropy-weighted coupling coordination degree model measures four-chain integration, while the system Generalized Method Of Moments (GMM) and threshold models examine persistence, nonlinear relationships, and regional heterogeneity. The results indicate a positive integration-resilience association, with a full-model coefficient of 0.214 and a lagged resilience coefficient of 0.387. The estimated threshold is 0.523, with a stronger association above this value. The eastern coefficient is larger than the central-western coefficient. Mechanism regressions suggest innovation investment and industrial structure upgrading as potential channels, although they do not directly identify knowledge spillovers or mediate the effect. The study combines multi-chain measurement, dynamic relationships, threshold patterns, and regional comparisons in a common empirical framework. It provides a basis for differentiated integration strategies and for coordinating project appraisal, financial support, and workforce development. The Industrial Internet of Things (IIoT) offers a possible implementation context for cross-chain information sharing, rather than a separately tested driver. The numerical findings depend on index construction and identification assumptions; applications to other countries require locally comparable indicators and re-estimation.

Keywords: Four-chain integration; regional economic resilience; coupling coordination degree model; dynamic panel; industrial internet of things (IIoT).

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1. Introduction

With the rapid development of digital technology and increasing economic volatility, strengthening regional economic resilience is necessary to respond to disruptions and support long-term development. Four-chain integration refers to close coordination among innovation activities, industrial production, financial resources, and human capital. These functions connect technological development with commercialization, financing, and implementation, offering a way to improve resource allocation and regional adjustment capacity (Ma et al., 2025; Tang et al., 2024). External financial instability, trade disputes, public health crises and domestic industrial restructuring can impose distinct pressures on these interconnected resources. In China, integration initiatives combine government coordination with enterprise participation to support industrial modernization. However, policy interest alone does not establish how coordination relates to regional resilience, how the relationship changes as integration develops, or why provinces may benefit differently. Addressing these questions is necessary for differentiated regional planning. It also helps clarify the relevance of the Industrial Internet of Things (IIoT), which may facilitate information exchange across chains but is not directly measured in the present provincial analysis. Existing research offers several complementary perspectives on four-chain integration. Wang (2025) examines how digital technology supports integration in manufacturing, linking digitalization to the coordination of production resources. Lan and Luo (2025) use Guangxi as a case study to develop a knowledge-management perspective on four-chain economic development, emphasizing the organization and circulation of knowledge. Tang et al. (2024) discuss integration pathways for innovation, industry, capital, and talent in Xi'an. These contributions clarify the institutional and organizational foundations of integration, while leaving room for a common quantitative assessment of its relationship with regional economic resilience over time. Quantitative and sectoral studies further broaden this foundation. Gan et al. (2025) apply a neutrosophic Brownian framework to the development of high-quality manufacturing in the Chengdu–Chongqing economic circle. Shuang et al. (2025) examine data-element marketization and quadruple-chain integration in equipment manufacturing, highlighting enterprise capabilities and the policy environment. Their working-paper evidence concerns the formation of integration itself; the present study instead treats coordination as an explanatory variable for regional resilience. Wan et al. (2024) evaluate the coupling coordination of manufacturing innovation, industry,

capital, and talent in Jilin Province, providing a closely related measurement application. These studies motivate the examination of both the development of individual chains and their coordinated functioning. Related work also shows that the composition of a multi-chain framework depends on the research setting. Li et al. (2023) investigate industry-education consortia, while Li et al. (2025) discuss the cultivation of applied innovative talent in industrial colleges. Both connect education with industry, talent, and innovation rather than treating capital as a separate chain. Zhao (2023) evaluates industrial, innovation, service, and capital chains in venous industrial parks. Ding et al. (2021) apply a four-chain perspective to cultural derivative design. These applications illustrate the breadth of coordination approaches, but their indicators and subsystem definitions cannot be transferred mechanically to an innovation-industry-capital-talent index. A further strand links technological development with regional adjustment. Zhao et al. (2024) discuss industrial coordination in secondary urban agglomerations under a low-carbon framework. Hu et al. (2024) examine innovative-province construction, artificial intelligence development, and innovation-ecosystem resilience using spatial and machine-learning approaches. Mi et al. (2025) connect digital industrial clusters, talent aggregation, and high-quality development. These studies motivate consideration of institutional conditions, spatial differences, and human-capital channels alongside technology. Economic resilience, however, remains distinct from industrial coordination, innovation-ecosystem resilience, and high-quality development, so the outcome and proposed mechanisms require explicit definition.

Building on this literature, the present study combines three analytical elements. First, a dynamic panel model accounts for persistence in resilience and addresses potential endogeneity under specified moment restrictions, rather than assuming that current integration is independent of earlier economic performance. Second, threshold analysis examines whether the integration-resilience relationship varies across coordination regimes, allowing resource bottlenecks and complementarities to have different implications at different levels of development. Third, entropy weighting and coupling coordination measurement combine the four subsystems within a transparent index framework. Data-based weighting reduces reliance on discretionary indicator weights but does not eliminate choices regarding indicators, normalization, and chain-level weights. The contribution lies in integrating these perspectives for a provincial resilience analysis, rather than claiming that the individual methods are new. In summary, the literature supports the relevance of multi-chain coordination but leaves scope for joint examination of resilience persistence, potential transmission channels, nonlinear patterns, and regional differences. This study, therefore, links coupling coordination measurement to dynamic panel and threshold analysis using a common provincial sample. It also considers how the findings can inform regional agencies, industrial parks, and project managers. The application discussion distinguishes evidence at the provincial level from proposed practices in individual organizations and from broader IIoT-enabled industrial development.

1.1. Research Questions

RQ1: How is four-chain integration associated with regional economic resilience after accounting for persistence and observed regional characteristics?

RQ2: How do innovation investment and industrial structure upgrading relate to the association between four-chain integration and regional economic resilience?

RQ3: How does the integration-resilience relationship vary across coordination regimes, and what threshold separates these regimes in the sample?

RQ4: How does the integration-resilience relationship differ between eastern and central-western provinces in China?

2. Theoretical Basis and Research Hypotheses

2.1. Definition of Core Concepts

2.1.1. Coupling coordination degree of four-chain integration

Four-chain integration signifies coordinated development through the circulation of resources and complementary roles among innovation, industry, capital, and talent. From a systems-management perspective, progress in one subsystem depends partly on conditions in the others. An innovation requires industrial demand, financing, and skilled personnel before it can become commercially useful. IIoT can support information exchange and cooperative management, although adoption is not measured here. Coupling and coordination distinguish interaction among chains from their overall development level. Coupling degree measures interaction and relative balance among the four chain scores. Balance indicates whether development in one chain is disconnected from the others, but does not show whether the subsystems have sufficient resources. The numerical range depends on the specific expression in Eq. (5). Coordination degree combines coupling with the development levels of the four chains. This avoids treating a balanced but uniformly weak system as equivalent to one with strong complementary capabilities. Its interpretation requires consistent normalization; the scale limitation is discussed in Section 5.5.

2.1.2. Regional economic resilience

Following Martin (2012), regional economic resilience is the capacity to withstand external disruption or internal structural change, recover economic activity, and adapt through structural and functional reorganization. Adaptation may involve new industries and resource combinations rather than a return to the previous development path. Table 1 evaluates resistance, recovery, and transformation capacities; it does not trace recovery from a single identified shock.

2.2. Theoretical Mechanisms and Research Hypotheses

Four-chain integration may relate to resilience through direct coordination benefits and indirect channels for innovation and upgrading. System-synergy theory suggests that improved information exchange can reduce fragmentation between

production, research, finance, and workforce decisions. IIoT-enabled interconnection provides one possible supporting infrastructure. Complementary resources may then allow a region to adjust production and investment more effectively when conditions change. These mechanisms motivate the following hypotheses.

2.2.1. Direct effects

A higher degree of coupling coordination can improve resource allocation between chains. Technological achievements from the innovation chain can be converted into competitive products through the industrial chain; the capital chain provides liquidity for Research and Development (R&D) and industrial expansion; and the talent chain supplies the skills required for innovation and upgrading. Coordination among technology, industry, capital, and talent can reduce delays between these stages and the disruption caused by a shortage in one subsystem. When a shock changes demand or interrupts production, access to financing, alternative technologies, and adaptable workers may support faster adjustment. These complementary capabilities provide the direct theoretical link between four-chain integration and regional resistance and recovery.

2.2.2. Indirect effects

Innovation investment and knowledge diffusion provide the first potential indirect channel. Four-chain integration can facilitate the concentration and circulation of innovative resources, encourage enterprise R&D expenditure, and support the application of technological results. Regions with stronger innovation capabilities may adapt products and processes more rapidly and reduce dependence on established activities. Knowledge exchange may also allow firms to learn from technological advances elsewhere. The empirical proxy used here is R&D expenditure as a share of Gross Domestic Product (GDP), which measures the intensity of innovation investment. It does not directly measure cross-regional knowledge flows; the analysis therefore evaluates an investment-related channel rather than identifying technological spillovers themselves. Industrial structure upgrading provides the second potential channel. Four-chain integration can support the shift toward higher-value activities by connecting new technologies to finance, skilled labor, and production demand. A region with a broader range of viable activities may be less dependent on a single vulnerable industry, while upgrading can strengthen its capacity to transform in the aftermath of disruption. The empirical measure is the ratio of tertiary-sector output to secondary-sector output. This ratio captures changes in industrial composition but does not, by itself, establish higher productivity, greater diversification, or an improvement in the quality of every service-sector activity. These distinctions guide the interpretation of the mechanism regressions.

2.2.3. Nonlinear characteristics

The integration-resilience relationship may be nonlinear. Below a coordination threshold, weak inter-chain links can constrain the use of otherwise available resources. For example, the capital chain may not meet the financing needs of innovation and production, or the talent chain may lack the skills needed to implement new technologies. The contribution of an isolated improvement can then remain limited. As these constraints ease, complementary investment across chains may strengthen the association with resilience. Threshold regression evaluates whether the data display such a change in slope. The estimated boundary is interpreted as a sample-specific feature, rather than a universal stage of regional development.

Based on these mechanisms, this study proposes the following research hypotheses:

H1: Four-chain integration is positively associated with regional economic resilience.

H2: Innovation investment and industrial upgrading are channels consistent with the positive integration-resilience relationship.

H3: The integration-resilience relationship is stronger above a coordination threshold.

H4: The integration-resilience relationship is stronger in eastern than in central-western provinces.

3. Research Design

3.1. Model Specification

3.1.1. Coupling coordination degree model

Indicator normalization and entropy weighting: The entropy method measures innovation (I), industrial (P), capital (F), and talent (H) development. Related applications separate subsystem development from coordination (Wan et al., 2024; Zhao, 2023). Entropy weights reflect indicator variation and reduce discretionary weighting, while indicator selection and normalization remain substantive choices. Standardization removes differences in units. Eq. (1) applies to positive indicators, where larger raw values represent higher development.

$$x^*_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

In Eq. (1), x_{ij} is the raw observation for indicator j ; $\min(x_j)$ and $\max(x_j)$ are its extrema in the normalization sample, and x^*_{ij} is dimensionless. Eq. (2) reverses the scale for negative indicators.

$$x^*_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

In Eq. (2), higher standardized values consistently indicate better performance. Constant indicators require separate treatment to avoid division by zero. Eq. (3) defines shares, entropy, and weights.

$$p_{ij} = \frac{x_{*ij}}{\sum_{i=1}^m x_{*ij}}, \quad e_j = -\frac{\sum_{i=1}^m p_{ij} \ln p_{ij}}{\ln m}, \quad w_j = \frac{1 - e_j}{\sum_l (1 - e_l)} \quad (3)$$

In Eq. (3), m is the observation count, p_{ij} is the indicator share, e_j is normalized entropy, and w_j is the weight. The convention $p \ln p = 0$ at $p = 0$ follows by continuity. The weight denominator sums within each chain. Eq. (4) aggregates standardized indicators.

$$S_k = \sum_j \in J_k w_j x_{*j}, \quad k \in \{I, P, F, H\} \quad (4)$$

In Eq. (4), J_k denotes the set of indicators assigned to chain k , and S_k is the resulting development score. The scores are denoted I , P , F , and H for the four subsystems. Their interaction is summarized by the coupling expression in Eq. (5).

$$C = \left(\frac{I \times P \times F \times H}{(I + P)(P + F)(F + H)(H + I)} \right)^{1/4} \quad (5)$$

In Eq. (5), nonnegative scores I , P , F , and H enter the numerator, while the denominator combines adjacent pairs. C summarizes relative balance. Eq. (6) combines this measure with overall development.

$$D = \sqrt{C \times T} \quad (6)$$

In Eq. (6), T summarizes chain development. Eq. (7) defines its weighted sum.

$$T = 0.3I + 0.3P + 0.2F + 0.2H \quad (7)$$

In Eq. (7), T is the comprehensive development score, with weights of 0.3, 0.3, 0.2, and 0.2 for innovation, industry, capital, and talent. Equal weighting is examined in Section 4.7. In Eq. (6), D is the coordination index and the core explanatory variable. Section 5.5 discusses consistency between the formula and the observed index range.

3.1.2. Dynamic panel model

System generalized method of moments (GMM) estimation accounts for persistence and potential feedback between integration and resilience, subject to appropriate moment restrictions (Blundell and Bond, 1998). Stronger economies may invest more in the four chains and benefit from coordination. Eq. (8) specifies the dynamic model.

$$Y_{it} = \rho Y_{it-1} + \theta D_{it} + \lambda' X_{it} + \mu_i + \varepsilon_{it} \quad (8)$$

In Eq. (8), Y_{it} denotes resilience in province i and year t , Y_{it-1} is its lag, and ρ captures persistence. D_{it} is coordination, θ its short-run coefficient, and X_{it} contains controls with coefficients λ . The province effect μ_i captures time-invariant characteristics, and ε_{it} is the disturbance. Causal interpretation additionally requires valid identifying assumptions. System GMM requires valid instrument orthogonality, additional level-moment conditions, and the absence of second-order serial correlation in the differenced disturbances. First- and second-order serial-correlation tests, AR(1) and AR(2), and the Sargan test provide diagnostics, not proof of instrument validity. Instrument proliferation and finite-sample behavior require particular attention in the case of 30 provinces (Roodman, 2009).

3.1.3. Threshold regression model

To examine H3, the model allows the coefficient on four-chain coordination to differ below and above a single threshold. D serves as both the explanatory and threshold variable. Eq. (9) incorporates this change in slope while retaining the lagged outcome and controls.

$$Y_{it} = \rho Y_{it-1} + \theta_1 D_{it} \mathbb{1}(D_{it} \leq \gamma) + \theta_2 D_{it} \mathbb{1}(D_{it} > \gamma) + \lambda' X_{it} + \mu_i + \varepsilon_{it} \quad (9)$$

In Eq. (9), γ is the threshold, $\mathbb{1}(\cdot)$ indicates whether its condition holds, and θ_1 and θ_2 are the lower- and upper-regime coefficients. Testing a threshold differs from testing individual slopes. The lagged outcome and potentially endogenous threshold variable require the assumptions of dynamic threshold analysis (Seo and Shin, 2016). The reported threshold tests use 500 bootstrap replications to compare the single-threshold specification against the no-threshold and additional-break specifications. The boundary and confidence interval characterize this sample and index scale, rather than a common threshold for all countries.

3.2. Variable Definitions and Data Sources

3.2.1. Dependent variable

Nine indicators across resistance, recovery, and transformation from the resilience index through standardization and entropy weighting. Table 1 lists their definitions, directions, and units. Overlap with income, innovation, and industrial-structure variables is considered when interpreting the regressions.

3.2.2. Core explanatory variable

Table 2 presents the innovation, industrial, capital, and talent indicators. Standardized indicators are aggregated within each chain; the resulting scores are then used to input the coupling coordination model. This construction considers both subsystem development and coordination.

Table 1. Regional economic resilience indicators

First-level dimension	Secondary indicators	Indicator Nature	Unit
Resistance	Per capita GDP	Positive	Ten thousand yuan per person
	The proportion of the tertiary industry	Positive	%
	Fiscal self-sufficiency rate	Positive	%
Recovery ability	GDP growth rate	Positive	%
	Growth rate of fixed asset investment	Positive	%
	Unemployment rate(urban)	Negative	%
Transformation ability	The proportion of R&D expenditure to GDP	Positive	%
	The proportion of output value of high-tech industries	Positive	%
	The number of authorized invention patents per 10,000 people	Positive	Patents per 10,000 people

Table 2. Indicators of four-chain integration

Chain type	Secondary Indicators	Indicator Nature	Unit
Innovation (I)	Internal expenditure on R&D funding	Positive	Billion yuan
	Full-time equivalent R&D personnel	Positive	Person-years
	Number of high-tech enterprises	Positive	Number
Industry (P)	Value-added of industrial enterprises above designated size	Positive	Billion yuan
	Manufacturing output as a percentage of GDP	Positive	%
	Industrial agglomeration (locational entropy)	Positive	-
Capital (F)	Balance of deposits and loans in financial institutions	Positive	Billion yuan
	Government science and technology funding	Positive	Billion yuan
	Total social financing	Positive	Billion yuan
Talent (H)	Number of university graduates per 10,000 population	Positive	Per 10,000 people
	Number of professional and technical personnel	Positive	Ten thousand people
	Expenditure on talent recruitment	Positive	Billion yuan

3.2.3. Control variables

Drawing on the research framework, the following variables control for observed regional characteristics that may also relate to resilience:

Per capita GDP (PGDP): GDP per person, measured in ten thousand yuan per person.

Government intervention (Gov): local fiscal expenditure divided by GDP.

Openness (Open): imports plus exports divided by GDP.

Infrastructure (Infra): road length per 10,000 people, measured in kilometers.

3.2.4. Data sources

The study covers 30 provincial-level administrative regions in China from 2013 to 2022, excluding Tibet, Hong Kong, Macao, and Taiwan. The primary data sources are the China Statistical Yearbook, China Science and Technology Statistical Yearbook, China Financial Yearbook, and provincial statistical bulletins. Linear interpolation is used to fill in missing values in the source series. The descriptive dataset contains 300 province-year observations, whereas the dynamic regressions include 270 observations after accounting for the lagged outcome. Consistent geographic coverage and indicator definitions are important for comparability; interpolation and the aggregation of heterogeneous provinces are accounted for when interpreting the findings.

4. Empirical Results

4.1. Descriptive Statistics

Table 3 reports a mean resilience of 0.382 and a standard deviation of 0.156, indicating considerable variation among province-year observations. Mean coordination is 0.421, with a reported maximum of 0.783 in Beijing in 2022 and a minimum of 0.215 in Gansu in 2013. The meaning lies in the descriptive medium-coordination interval but masks uneven regional development. The index range is subject to the scale limitation in Section 5.5.

Table 3. Descriptive statistics

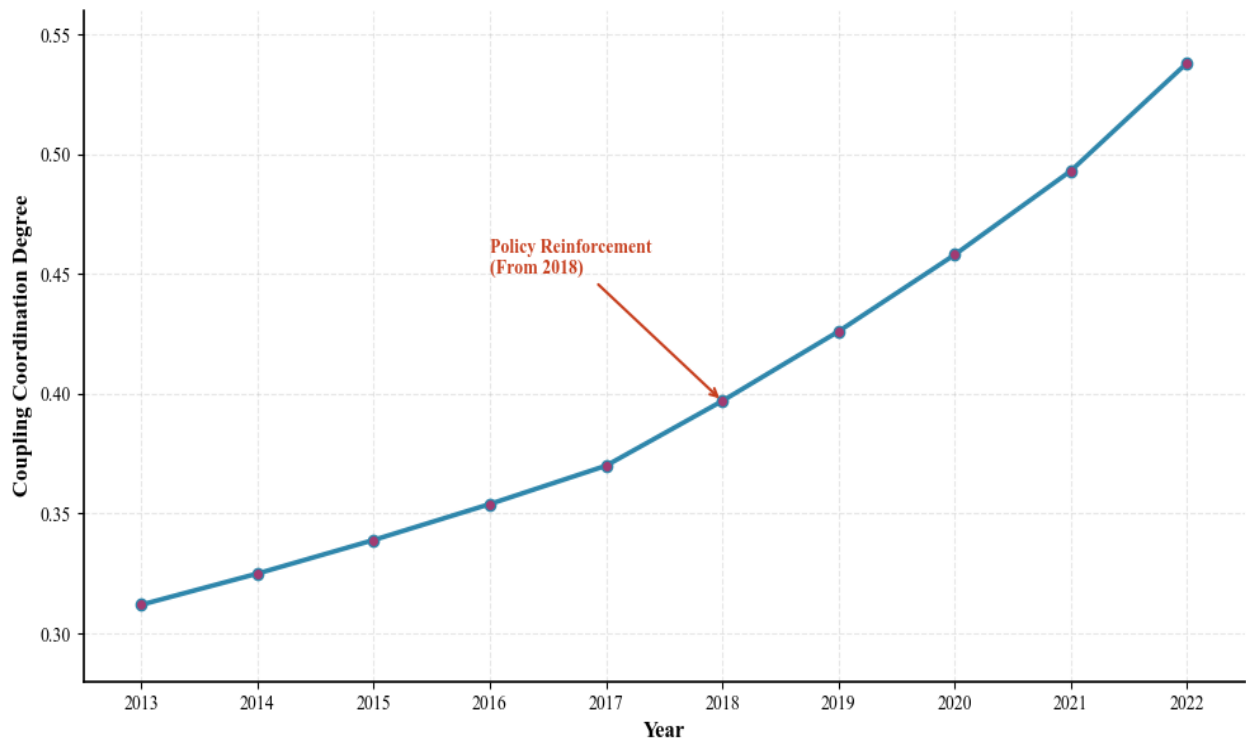
Variable	N	Mean	SD	Min.	Max.
Resilience	300	0.382	0.156	0.124	0.798
D	300	0.421	0.135	0.215	0.783
PGDP	300	6.824	2.915	2.135	14.321
Gov	300	0.256	0.087	0.121	0.568
Open	300	0.342	0.289	0.056	1.872
Infra	300	145.62	45.38	68.21	289.75

Note: N is the number of observations; SD is the standard deviation.

4.2. Patterns of Four-Chain Coordination

4.2.1. Temporal pattern

From 2013 to 2022, the mean four-chain coordination rose from 0.312 to 0.538, an increase of 0.226 and a compound annual growth of 6.24% across nine annual intervals. Fig. 1 retains the original annual trajectory, suggesting faster growth in later years. The visual pattern does not independently establish a policy effect. The timing of the 2018 annotation provides context; identifying its contribution would require policy-specific analysis and the underlying annual observations.

**Fig. 1.** Mean four-chain coordination, 2013–2022

Note: Original annual trajectory for the 30-province sample. Endpoint values are 0.312 and 0.538. The policy annotation indicates timing and does not establish causation.

4.2.2. Provincial pattern

Fig. 2 shows a broad spatial gradient, with higher coordination concentrated in several eastern provinces and lower coordination more common in the west. Beijing, Shanghai, Guangdong, Jiangsu, and Zhejiang fall in the high-coordination category. These regions combine substantial industrial activity with innovation, financial, and talent resources. The medium group includes Shandong, Tianjin, Fujian, Hubei, and Sichuan, among others, indicating that intermediate coordination is found in both coastal and inland areas. Gansu, Qinghai, Ningxia, and Guizhou belong to the low group. Differences in development foundations and access to complementary resources offer plausible explanations for these patterns, but the category chart does not independently test their causes. The figure displays the classifications available for 28 provinces; Xinjiang and Hainan are left unclassified. Its descriptive category boundaries are separate from the regression threshold estimated in Section 4.4.

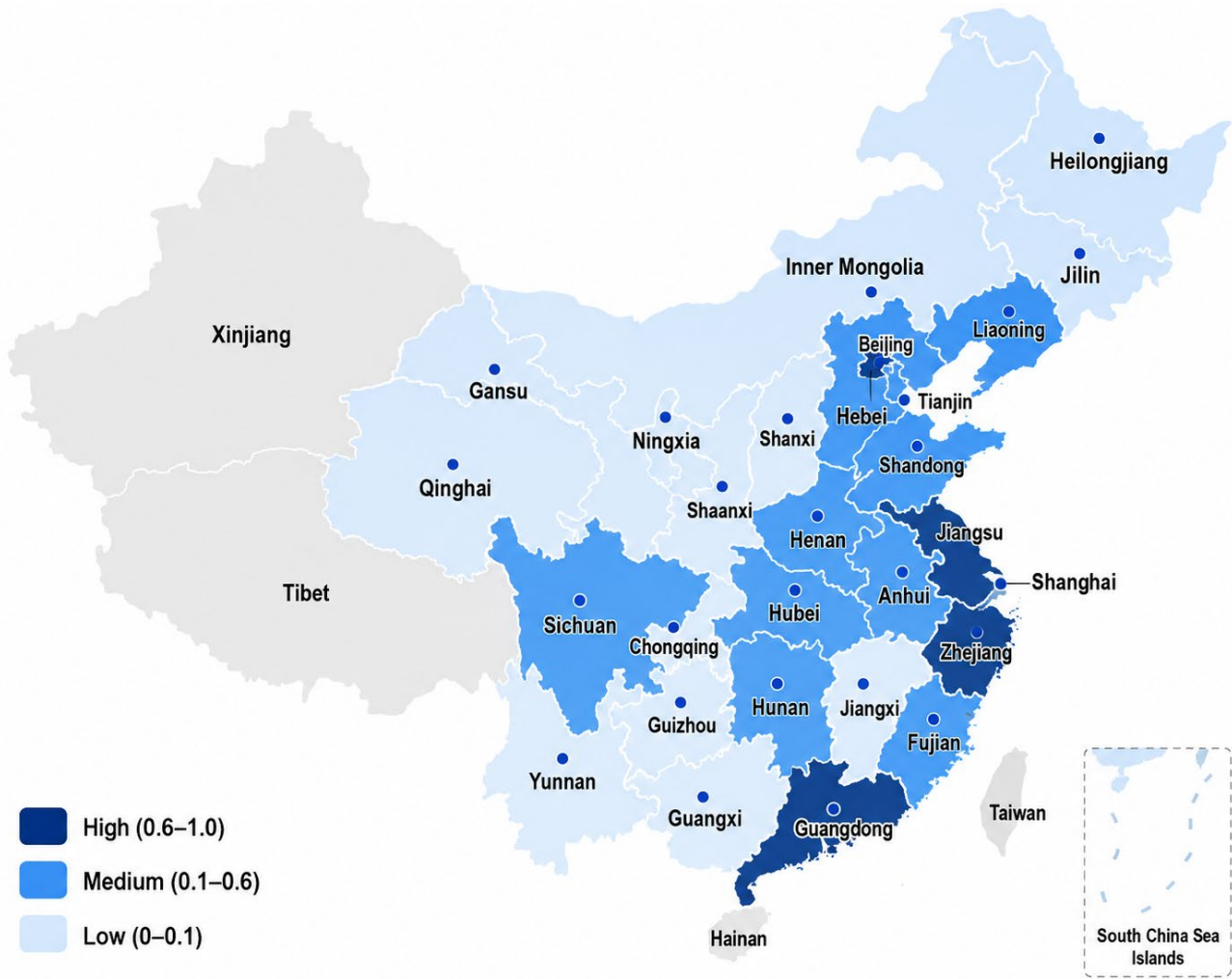


Fig. 2. Provincial coordination categories, 2022

Note: High: $D > 0.6$; medium: $0.4 < D \leq 0.6$; low: $D \leq 0.4$. These descriptive cutoffs differ from the estimated threshold of 0.523. Categories are available for 28 provinces; Xinjiang and Hainan remain unclassified.

4.3. Benchmark Regression

Table 4 reports system GMM estimates. Model 1 includes coordination and lagged resilience; Model 2 adds economic development, government intervention, openness, and infrastructure. The comparison assesses whether the association remains after controlling for observed regional characteristics. The coefficient coordination is positive in both specifications, at 0.256 in Model 1 and 0.214 in Model 2, supporting the direction proposed in H1. In the full model, a 0.10-unit increase in D corresponds to a 0.0214-unit increase in the resilience score, conditional on the included variables. The lagged resilience coefficient of 0.387 indicates persistence, consistent with the cumulative development of regional capabilities. Economic development, openness, and infrastructure have positive coefficients, suggesting that economic foundations, external connections, and transport provision are associated with resilience. Government intervention has a negative coefficient. Crowding out of market-based allocation is one possible interpretation, but fiscal spending may also respond to weak local conditions. The coefficient alone cannot distinguish these explanations, so the result does not justify a general recommendation to reduce government expenditure.

4.4. Threshold Results

4.4.1. Threshold estimate

The single-threshold test yields an F-statistic of 28.75 and $p = 0.012$. The null of no threshold is therefore rejected at the 5% level, rather than at the 1% level. The test for an additional threshold produces $F = 15.32$ and $p = 0.187$, providing no significant evidence for a second break. The reported results consequently favor a single-threshold specification. The estimated threshold is $\gamma = 0.523$, with a 95% confidence interval of 0.501 to 0.545. Economically, the estimated threshold separates two coordination regimes within the sample. Below 0.523, shortages in finance, skills, or commercialization capacity may limit the benefits of advances in another chain. Above it, more complete resource combinations may support stronger links between integration and resilience. This interpretation is consistent with the complementarity argument in Section 2.2.3. However, the estimate does not establish a universally required minimum or a fixed transition between

development stages. Its use in practice depends on the validity and comparability of the underlying index, including the scale issue discussed in Section 5.5.

Table 4. Dynamic panel system GMM estimates

Variable	Model 1	Model 2
Resilience (-1)	0.423*** (0.065)	0.387*** (0.058)
D	0.256*** (0.042)	0.214*** (0.039)
PGDP	-	0.156** (0.068)
Gov	-	-0.087* (0.045)
Open	-	0.098** (0.041)
Infra	-	0.123*** (0.036)
AR (1) p-value	0.021	0.025
AR (2) p-value	0.345	0.387
Sargan p-value	0.456	0.512
N	270	270

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$. Robust standard errors are in parentheses. AR(1), AR(2), and Sargan entries are diagnostic p-values. N denotes the number of observations.

4.4.2. Regime coefficients

Table 5 reports estimates for the lower-coordination regime, $D \leq 0.523$, and higher-coordination regime, $D > 0.523$.

Table 5. Single-threshold regression estimates

Variable	Coefficient	standard error	t	p-value
Resilience (-1)	0.356***	0.061	5.84	<0.001
D×I ($D \leq 0.523$)	0.124**	0.051	2.43	0.016
D×I ($D > 0.523$)	0.387***	0.068	5.69	<0.001
PGDP	0.142**	0.065	2.18	0.030
Gov	-0.079*	0.043	-1.84	0.066
Open	0.089**	0.039	2.28	0.023
Infra	0.115***	0.034	3.38	0.001
N	270			

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$. Values smaller than 0.001 are displayed as <0.001. N denotes the number of observations.

The lower-regime coefficient is 0.124 and is significant at the 5% level, while the upper-regime coefficient is 0.387 and is significant at the 1% level. The latter exceeds the former by 0.263, indicating a stronger estimated association at higher coordination levels. Together with the single-threshold test, this pattern is consistent with H3 and with the idea that complementary resources become more effective when key bottlenecks ease. The significance of the individual slopes should not be treated as an additional test of their difference, and the result remains specific to the sample and model.

4.5. Regional Heterogeneity

The sample is divided into 11 eastern and 19 central-western provinces, and the dynamic panel model is estimated separately for each. Table 6 compares the relationships across these development contexts, recognizing substantial diversity within each group. The estimated coordination coefficient is 0.302 in the eastern group and 0.158 in the central-western group, a ratio of approximately 1.9. The direction is consistent with H4, although a formal test of the difference in coefficients would be needed to establish statistical significance between groups. More developed innovation and industrial bases, deeper financing networks, and greater access to skilled workers may help eastern provinces convert coordination into the capacity for economic adjustment. Faster commercialization and more effective resource matching provide plausible mechanisms. In central and western regions, financing constraints and difficulties retaining skilled personnel may

limit these complementarities. These explanations motivate the differentiated recommendations in Section 5.3; they are not separately identified effects of regional location or institutional quality.

Table 6. Regional heterogeneity estimates

Variable	Eastern	Central-western
Resilience (-1)	0.321*** (0.059)	0.456*** (0.067)
D	0.302*** (0.048)	0.158** (0.062)
PGDP	0.123* (0.067)	0.187** (0.075)
Gov	-0.065 (0.042)	-0.102** (0.049)
Open	0.115*** (0.038)	0.068* (0.036)
Infra	0.098** (0.041)	0.145*** (0.042)
AR(2) p-value	0.412	0.356
Sargan p-value	0.523	0.487
N	99	171

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$. Robust standard errors are in parentheses. The sample contains 11 eastern and 19 central-western provinces. Diagnostic entries are p-values.

4.6. Mechanism Analysis

To examine the channels proposed in H2, the analysis follows a three-stage mechanism framework. First, the benchmark regression relates four-chain coordination to resilience. Second, separate regressions relate coordination to innovation investment, measured by R&D expenditure relative to GDP, and industrial upgrading, measured by the ratio of tertiary-sector to secondary-sector output. Third, coordination and both channel variables are included together in the resilience regression. A positive channel coefficient, combined with a reduction in the coordination coefficient, is consistent with an indirect pathway but does not, by itself, establish causal mediation. In particular, mediator endogeneity, differing dynamic specifications, and overlapping index components may affect the comparison. Table 7 reports the estimates, and the Appendix records the sequence of calculations.

Table 7. Mechanism regression estimates

Variable				
Innovation	Upgrade	Resilience		
D		0.321*** (0.052)	0.287*** (0.049)	0.156*** (0.041)
Innovation	-	-	-	0.187** (0.078)
Upgrade	-	-	-	0.145** (0.062)
Resilience (-1)	-	-	-	0.365*** (0.061)
Control variables		Control	Control	Control
AR(2) p-value		0.387	0.421	0.398
Sargan p-value		0.512	0.487	0.534
N		270	270	270

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$. Robust standard errors are in parentheses. The first two columns model the two-channel variables separately; the third includes them jointly in the resilience regression.

The coefficients on the innovation and upgrading variables in the innovation and upgrading regressions are 0.321 and 0.287, respectively. In the resilience regression that includes both channel variables, the coefficients on the channel variables remain positive at 0.187 and 0.145, while the coordination coefficient falls from 0.214 to 0.156. These patterns are consistent with the proposition that innovation investment and industrial change accompany the integration-resilience relationship, providing suggestive support for H2. However, the coefficient reduction is not a verified additive

decomposition of indirect effects. The innovation variable measures expenditure intensity rather than knowledge spillovers, and the upgrading variable measures sectoral composition rather than every aspect of structural improvement. The findings are therefore presented as potential channels rather than conclusive causal mediation.

4.7. Robustness Checks

Two alternative specifications assess the sensitivity of the findings to measurement choices. First, assigning equal weights of 0.25 to the four chains yields a coordination coefficient of 0.198. Second, reconstructing the resilience index using principal component analysis (PCA) yields a coefficient of 0.203. Both coefficients are positive and significant at the 1% level, consistent with the sign of the benchmark estimate. These results support directional stability under the two reported alternatives. They do not resolve all concerns about index scaling, common shocks, instrument selection, or the identification of the mechanism and threshold models.

5. Conclusions and Implications

5.1. Answers to the Research Questions

RQ1. Overall relationship and persistence: Four-chain integration is positively associated with resilience, with a full-model coefficient of 0.214 and a lag coefficient of 0.387. The association remains positive under the alternative index constructions. The findings connect complementary regional resources to adjustment capacity, conditional on measurement consistency and dynamic-model assumptions.

RQ2. Innovation and upgrading channels: Innovation investment and industrial upgrading are potential channels. Both are positively associated with coordination and resilience, and their inclusion reduces the coordination coefficient to 0.156. The results concern expenditure intensity and sectoral composition; they do not directly identify cross-regional spillovers or causal indirect effects.

RQ3. Nonlinear coordination regimes: The estimated relationship is stronger above 0.523, with slopes of 0.124 below the threshold and 0.387 above it. The single-threshold test is significant at the 5% level, while an additional break is not supported. The pattern is consistent with resource complementarity, but the threshold remains sample- and measurement-specific.

RQ4. Regional differences: The eastern coefficient (0.302) exceeds the central-western coefficient (0.158). This motivates strategies attentive to development foundations, financing, and talent capacity. It does not establish a causal regional effect or a statistically significant difference between the subgroup coefficients.

5.2. Theoretical and Practical Implications

Theoretically, the study connects regional economic resilience with the coordination of complementary resources rather than treating innovation, industry, finance, or talent in isolation. Dynamic and threshold perspectives allow persistence and development conditions to matter for the observed relationships. The analysis also distinguishes the four-chain concept from the technological infrastructure that might support it. IIoT may facilitate resource matching and operational information exchange, but its effects are not separately tested here. In practice, the findings provide a basis for joint consideration of resource needs across regional agencies, industrial parks, and project portfolios. They inform three specific decision processes, while requiring additional evidence before provincial findings are applied as project-level causal estimates.

Project appraisal and cross-chain coordination.

Managers can assess proposed projects jointly across technological readiness, industrial demand, financing continuity, and workforce capability. A project with strong technical potential but no credible commercialization partner or staffing plan should trigger a coordination review before funds are committed. Regional coordinating bodies can bring together science and technology, industry, finance, and human resources agencies to resolve interdepartmental information gaps. Shared information systems and suitable IIoT infrastructure may support this process. The decision change is to evaluate the completeness of the resource combination, alongside the merits of individual projects, rather than relying only on separate departmental approval criteria.

Budget allocation and implementation order.

Managers can use a chain-by-chain diagnosis to identify the constraint most likely to prevent implementation. In a region with research capability but limited commercialization finance, priority may be given to financing arrangements and industry partnerships. Where available capital cannot be used due to a lack of skills, training and recruitment may need to precede equipment expansion. The threshold findings motivate the examination of such complementarities, but do not automatically justify approving a project because an index exceeds 0.523. Budget decisions should be based on verified local indicators, project feasibility, and the expected contribution of the proposed intervention.

Operational monitoring and continuation decisions.

Project and program reviews can track how coordinated resources translate into implementation, including technology transfer, financing continuity, workforce readiness, and adaptation to changes in demand. If one chain repeatedly delays the others, managers can reallocate support, revise the implementation sequence, or reconsider continuation. Monitoring should include recovery and adaptation outcomes, so that a higher coordination score is not treated as sufficient evidence of resilience. This makes integration an input to an iterative decision process rather than an isolated performance target.

5.3. Differentiated Regional Recommendations

Across regions, a collaborative mechanism can align innovation assets, industrial needs, financing availability, and talent development. Coordination responsibilities should be explicit, with shared appraisal criteria and regular review of inter-chain constraints. Regional assessment can include integration indicators alongside economic outcomes, provided the measurement is validated and does not reward balance among uniformly weak chains. Support for information-sharing infrastructure should respond to actual coordination needs and implementation capacity.

For eastern provinces with comparatively strong development foundations, the priority is to improve coordination efficiency. Industrial innovation consortia and cooperation between research organizations and enterprises can strengthen the connection between scientific advances and production needs. Venture capital, seed funding, and other financing arrangements can support different stages of technology-oriented firms, while incentives and flexible research administration can help retain skilled personnel. IIoT applications may support information exchange across these activities when they meet clear operational needs. The emphasis is on converting existing advantages into more effective collaboration, rather than increasing each chain's scale independently.

For the central and western regions, strategies should address locally verified constraints on financing and talent. Fiscal support, cooperation with financial institutions, and inclusive or technology-oriented finance may improve access to capital where viable enterprises face funding gaps. Talent policy can combine external recruitment with local training, including university-enterprise partnerships and practical skills development. Housing or family-support measures may assist retention when they respond to demonstrated needs. Regional resources and established agricultural or specialized industries provide a basis for distinctive development paths. Digital tools can help these activities connect to markets and knowledge networks, but advanced infrastructure should be matched to skills and maintenance capacity. The subgroup estimates motivate differentiated diagnosis rather than a uniform policy package for all inland provinces.

5.4. Applicability across Countries and Regions

The four-chain framework can be applied outside China by mapping the functions of innovation, production, financing, and workforce to local institutions. Regions with bank-based finance, venture-capital networks, public research systems, or apprenticeship-based training may require different indicators for the same function. Comparable geographic units, price bases, sector definitions, and observation periods should be established before estimating local relationships. Managers and policymakers can then examine which chain is constraining adjustment and whether coordinated support improves observed recovery or adaptation. The Chinese coefficients and threshold should not be transferred directly because governance, industrial concentration, labor mobility, and financial access can alter the relationship. Comparative applications, therefore, require local longitudinal data and re-estimation. Firm-level and construction-project decisions also require evidence at the corresponding level rather than assuming that provincial estimates apply unchanged.

5.5. Limitations and Future Research

This study has several limitations. First, provincial data conceal city- and firm-level variation, and the resilience index does not directly measure responses to a particular external shock, such as a pandemic or trade disruption. Second, innovation investment and industrial upgrading are only two possible channels; institutional quality, digitalization, and direct IIoT indicators warrant further analysis. Third, the coordination formula and reported index range require reconciliation. With chain scores bounded by one, Eq. (5) implies $C \leq 0.5$ and Eq. (6) implies $D \leq$ approximately 0.707, whereas Table 3 reports a maximum of 0.783. This inconsistency limits the numerical interpretation of the index and threshold. Fourth, overlapping indicators, the small provincial sample, instrument assumptions, and common shocks limit causal inference. Future work should verify the index implementation, document instruments and estimation settings, separate overlapping measures, and examine alternative dynamic threshold specifications. City- and firm-level panels and industrial case studies would also help evaluate shock responses and the practical role of IIoT-enabled coordination.

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Declaration of Artificial Intelligence (AI) Tools

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Appendix. Supplementary Methodological Details

The following steps record the mechanism, threshold, and index-construction procedures used in the study.

Mechanism analysis. Step 1 estimates the conditional relationship between D and resilience using the dynamic specification in Eq. (8). Step 2 relates each channel variable, innovation investment and industrial upgrading, to D and the control variables. Step 3 includes D and both channel variables in the resilience regression. The comparison examines the signs of the channel coefficients and the change in the coefficient on D. A smaller coordination coefficient is suggestive of an indirect pathway, but is not a sufficient condition for partial or full causal mediation. Such an interpretation additionally requires compatible specifications, mediator identification, and appropriate uncertainty estimates for indirect effects.

Threshold inference. The reported bootstrap procedure uses 500 replications. The single-threshold test gives $F = 28.75$ and $p = 0.012$, supporting a break at the 5% level. The additional-threshold test gives $F = 15.32$ and $p = 0.187$ and does not support a second break. The estimated threshold and interval are reported in Section 4.4. These results are interpreted subject to the dynamic-model assumptions and the scaling of D.

Index calculation. Step 1 standardizes the original indicators using Eq. (1) or Eq. (2), according to their direction. Step 2 obtains entropy weights from Eq. (3). Step 3 calculates the four development scores using Eq. (4). Step 4 calculates coupling with Eq. (5). Step 5 calculates the comprehensive development score with Eq. (7). Step 6 obtains coordination from Eq. (6). The same definitions and normalization must be used consistently when comparing descriptive statistics, regression coefficients, and threshold estimates.