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Advancing Sustainable Digital Industrial Security: Cross-Border Data Flow Regulation and Resilience of Digital Economy Core Industrial Chains in China

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Abstract

Against the backdrop of deepening global digital economic integration and intensifying geopolitical competition, cross-border data flow regulation has become a core institutional arrangement for coordinating development and security. Based on panel data from 31 Chinese provinces from 2015 to 2025, this study proposes an adapted provincial DFRI and a comprehensive resilience index, which together provide an operational foundation for examining the relationship between data regulation and industrial chain resilience across Chinese regions. It empirically examines the effects, transmission mechanisms, and configurational pathways through which regulation influences industrial chain resilience. The results show that cross-border data flow regulation significantly enhances the resilience of the core industrial chains of the digital economy. The balance between efficiency and security plays a key mediating role in the process through which regulation affects industrial chain resilience. Moreover, the regulatory effect exhibits significant heterogeneity in the level of digital economic development. The coefficient of REG is higher in provinces whose digital economy development index exceeds the sample mean than in provinces at or below the sample mean. Further, fuzzy-set qualitative comparative analysis (fsQCA) identifies four equivalent pathways through which regulatory improvement, infrastructure development, innovation investment, digital trade, and industrial compatibility jointly drive high resilience. The findings provide empirical evidence and policy implications for constructing regionally differentiated data governance systems and enhancing the resilience of China's core digital economy industrial chains.

Keywords: cross-border data flow regulation; core industrial chains of the digital economy; industrial chain resilience; mediating effect; fuzzy-set qualitative comparative analysis



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1. Introduction

Digital technologies—including cloud computing, big data, artificial intelligence, blockchain, and fifth-generation mobile communication technology (5G)—have become deeply embedded in manufacturing, services, finance, and governance, reshaping economic structures and industrial organization. In this process, data have evolved from an information carrier into a core factor of production and an institutional resource. The global digital economy now accounts for more than 30% of global GDP, while developed economies retain a dominant position; in 2020, their digital economy reached USD 24.4 trillion, or

74.7% of the global total, and exceeded 60% of GDP in countries such as the United States, Germany, and the United Kingdom [1].

Under digital globalization, the cross-border circulation and allocation of data have become essential to digital trade, multinational operations, collaborative innovation, and industrial-chain stability. China's cross-border e-commerce imports and exports reached RMB 2.38 trillion in 2023, up 15.6% year on year, supported by the real-time circulation of order, logistics, and user data [2]. In artificial intelligence, access to cross-border medical data or multilingual corpora can improve algorithmic accuracy by 5–10 percentage points [3]. However, such flows also create channels for data leakage, misuse, regulatory failure, and risk diffusion through technological vulnerabilities and fragmented governance, thereby threatening transaction trust, financial order, and national, economic, and cybersecurity.

Reconciling data-flow efficiency with security protection has therefore become a central issue in digital-economy governance. In 2023, China's digital economy reached RMB 56.1 trillion, accounting for 42.8% of GDP and contributing more than 60% of economic growth; digital industrialization and industrial digitalization amounted to RMB 10.5 trillion and RMB 45.6 trillion, respectively [4]. Yet the core industrial chains of the digital economy vary markedly across provinces. Guangdong has developed a complete electronic-information manufacturing chain, with output exceeding RMB 6 trillion in 2023 and substantial demand for consumer-electronics and supply-chain coordination data [5]. Zhejiang's platform economy generated a core digital-industry added-value share of 11.5% of provincial GDP, with cross-border data concentrated in user behavior and transaction settlement [6]. Beijing remains strong in artificial intelligence and cloud computing, with core industries exceeding RMB 250 billion and high demand for global algorithm-training data [7].

Central and western provinces have improved digital infrastructure but generally retain weaker core industrial layouts. Sichuan has developed 36 key provincial industrial-Internet platforms serving more than 340,000 enterprises [8]; Henan has expanded cross-border e-commerce, with Nanyang recording RMB 17.97 billion in transactions [9]; and Guizhou and Inner Mongolia have used cross-regional computing-power projects to support annual digital-economy growth of more than 25% [10]. These structural differences produce unequal dependence on data and exposure to risk. Eastern provinces face large, complex data flows and conflicts among multiple compliance regimes, whereas central and western provinces are more constrained by weaker regulatory technologies, incomplete downstream industrial chains, and delayed responses to changes in global rules [11].

These provincial differences preclude a uniform regulatory model. Industrial-chain resilience—the capacity to resist, recover from, transform under, and upgrade after external shocks—depends on both efficient data circulation and effective security protection. Excessively stringent regulation may raise institutional transaction costs, weaken innovation incentives and resource allocation, and hinder the integration of eastern provinces into global value chains. Insufficient enforcement, by contrast, may intensify data-leakage risks and damage the more fragile industrial foundations of central and western provinces. Accordingly, three questions remain: how does cross-border data-flow regulation affect the resilience of core digital-economy industrial chains; does this effect vary across provinces; and what differentiated regulatory pathways are appropriate for regions at different stages of digital-economy development?

To address these questions, this study examines how precise regulatory provision can balance data-flow efficiency and security while enhancing the six-dimensional resilience of China's core digital-economy industrial chains. It reconstructs a provincial Cross-Border Data Flow Regulation Index and an industrial-chain resilience index, and applies a two-way fixed-effects model and fuzzy-set qualitative comparative analysis to estimate direct

and mediating effects and identify configurational pathways. The study aims to provide theoretical and empirical support for regionally differentiated data-governance systems.

2. Literature Review and Theoretical Framework

Current academic research on cross-border data flow regulation and the resilience of core digital economy industrial chains has mainly focused on the following aspects:

2.1. The Connotation, Evolution, and International Strategic Competition of Cross-Border Data Flow Regulation

Given the high mobility and cross-domain allocation characteristics of data elements, cross-border data flow regulation has become a core issue in global digital governance. Scholars generally argue that the connotation of cross-border data flow regulation is rooted in the context of digital globalization, and that its core lies in constructing a balanced framework encompassing national security, economic and social development, and international cooperation [12]. Specifically, the regulatory system covers three core issues: personal information protection, cross-border data flows, and data localization storage [13]. With the evolution of the digital economy, regulatory instruments have gradually shifted from reliance on a single rigid legal approach toward coordination between flexible norms and binding legal rules, with increasing emphasis on mutual recognition of standards and the construction of trust mechanisms [14].

In this context, the regulation of cross-border data flows is not merely a matter of domestic data governance within a single country, but has gradually evolved into a key arena for the restructuring of global digital economy rules and institutional competition among nations. In response to the efficiency demands and security risks generated by data flows, the global rule system for the digital economy is undergoing profound restructuring. Countries are engaging in strategic competition over core issues such as cross-border data flows, localization of computing facilities, and protection of source code and algorithms, thereby forming differentiated regulatory models. Different countries have developed differentiated governance paths based on their economic interests, social values, and international strategic positions. The U.S. model tends to prioritize free markets and trade interests, advocating the free flow of data to promote the expansion of digital capital [15]. The European Union model, centered on the General Data Protection Regulation, gives priority to personal privacy rights and requires that data-receiving countries provide an adequate level of protection [16,17]. The Chinese model adheres to the principle of data sovereignty and constructs a classified and hierarchical regulatory system with national security as its baseline, and emphasizes the value concept of building a community with a shared future in cyberspace [18,19]. In addition, provisions on cross-border data flows in bilateral and multilateral free trade agreements, such as the Regional Comprehensive Economic Partnership and the Comprehensive and Progressive Agreement for Trans-Pacific Partnership, reflect the dual demands of global trade for both flexibility and security. However, significant institutional contestation and legal conflicts remain regarding the applicable standards and interpretive authority of security exception clauses [20–22]. From the perspective of economic effects, the fundamental objective of regulation is to accurately identify the balance point between data flows and secure development. Excessive restrictions may raise corporate compliance costs and suppress the development of digital services trade, whereas insufficient regulation may generate systemic risks [23,24].

Overall, existing studies have clarified the connotation, evolution, and international strategic competition of cross-border data flow regulation. However, two limitations remain. First, most studies focus on legal comparison or policy interpretation, while quantitative measurement at the provincial level remains insufficient. Second, existing research rarely

integrates regulatory intensity, compliance cost, and international coordination into a unified analytical framework, thus failing to fully capture the comprehensive impact of cross-border data flow regulation on industrial systems. Therefore, it is necessary to construct a provincial cross-border data flow regulation index and examine its economic consequences. This provides the basis for further analyzing whether cross-border data flow regulation can affect the resilience of core digital economy industrial chains.

2.2. Theoretical Framework, Multidimensional Measurement System and Determinants of Industrial Chain Resilience

The concept of industrial chain resilience originates from supply chain risk management and has been extended in multiple dimensions in the context of the digital economy. At the micro level, an industrial chain is regarded as an end-to-end process chain extending from natural resources to final consumption, and resilience is reflected in its capacity to absorb disturbances, adapt to changes, and recover rapidly when local links are disrupted. At the meso level, an industrial chain is manifested as a networked organization formed by enterprises based on competitive advantages and collaborative strategies; its resilience depends on the guiding capacity and risk-dispersal capability enhanced through alliance governance [25]. At the macro level, industrial chain resilience is defined as the overall stability of an industrial system under major external shocks, as well as its capacity for structural transition, upgrading, and renewal [26]. It is worth noting that the impact of financial agglomeration on industrial chain resilience follows an inverted U-shaped relationship: moderate agglomeration can optimize capital allocation, whereas excessive agglomeration may trigger risk contagion and become a “bottleneck” rather than a “catalyst.” Similarly, the effect of government subsidies on the resilience of resource-based industries follows a U-shaped pattern, with the current stage located in the positive range [27].

In terms of measurement methods, existing studies can be broadly divided into two categories. The first category constructs comprehensive indicator systems to conduct quantitative assessments from multiple dimensions, including the industrial chain foundation, resistance, recovery capacity, sustainability, and leadership capacity, thereby dynamically monitoring the modernization level and regional evolution of industrial chains [28–31]. The second category adopts quantitative tools based on input–output tables or proxy variables. For example, export complexity indicators are used to measure product technological content and value added, thereby indirectly revealing the position and resilience level of industrial chains in global value chains [32–34]. Other studies construct double machine learning models to quantify resilience performance by comparing actual changes with counterfactual scenarios [35]. These measurement tools provide quantitative support for macro-level industrial analysis and policy regulation.

In summary, existing studies have established a relatively rich theoretical and measurement foundation for industrial chain resilience. However, most studies focus on general manufacturing chains or traditional industrial chains, while paying insufficient attention to core digital economy industrial chains. Moreover, existing measurement frameworks rarely incorporate the specific characteristics of digital economy industries, such as data dependence, cross-border connectivity, platform-based coordination, and exposure to data security risks. Therefore, it is necessary to construct a resilience index specifically for core digital economy industrial chains and further examine how regulatory factors shape such resilience.

2.3. Transmission Mechanisms and Spatial Heterogeneity Through Which the Digital Economy Empowers Industrial Chain Resilience

With its efficiency and transparency in information flows, the digital economy has significantly changed the operational logic of industrial chains. Studies show that the digital

economy enhances industrial chain resilience mainly through three pathways: reducing information costs, optimizing resource allocation, and promoting R&D innovation [36]. It can also empower industrial chain resilience by reducing the risk of innovation outcome loss. The widespread application of digital technologies, such as artificial intelligence and the industrial Internet, not only improves the collaborative response efficiency of industrial chains, but also exerts mediating effects by improving firms' environmental performance and promoting knowledge spillovers [37,38].

Meanwhile, the empowering effect of the digital economy on industrial chain resilience exhibits significant regional heterogeneity and nonlinear characteristics. From the perspective of provincial distribution, eastern provinces rely on knowledge spillover effects generated by talent agglomeration to promote the upgrading of industrial chains toward higher-end segments. By contrast, due to constraints in factor endowments, the enabling role of the digital economy in central and western provinces is more reflected in improving the efficiency of basic industrial-chain links [39]. In addition, the digital economy has a double-threshold effect on industrial chain modernization, constrained by the proportion of scientific and technological innovation investment and the level of human capital [40]. In terms of green transformation, the penetration of digital finance has significant spatial spillover effects on green total factor productivity and industrial chain resilience. This effect is particularly prominent in urban agglomerations in eastern China, where it can effectively alleviate financing constraints faced by small and medium-sized enterprises and promote the diffusion of green technologies along industrial chains [41–43]. In response to different regional industrial foundations, scholars have suggested that eastern provinces should leverage digital technologies to overcome bottlenecks in core links and enhance the autonomy and controllability of industrial chains, whereas central and western provinces should prioritize the improvement of supporting industrial-chain facilities and reduce dependence on external links [44,45].

More recent scholarship has begun to move beyond the linear “digital–technology–outcome” specification by treating digital and AI-related governance outcomes as the joint product of multiple, interdependent conditions. Drawing on the Technology–Organization–Environment (TOE) framework and configurational reasoning, Zhou (2026) shows, using fsQCA, that AI adoption in environmental governance is shaped by configurations of cognitive, institutional, technological, and social-structural conditions [46]. In a closely related study, Cao et al. (2025) apply the TOE framework, random forest, and dynamic QCA to manufacturing enterprises and find that AI-driven green supply chain management depends on multiple equifinal configurations of technological, organizational, and environmental factors [47]. Similarly, Yan, Li, and Cao (2026) demonstrate that green-patent persistence in textile firms follows configurational pathways involving organisational, technological, and environmental factors [48]. These studies underscore two points directly relevant to the present research. First, the empowering role of digital and AI technologies in shaping governance-related outcomes cannot be adequately captured by average-effect estimation alone; it is contingent on the co-presence of complementary institutional and organizational conditions. Second, configurational tools such as fsQCA are increasingly recognized as complements—rather than substitutes—to regression-based inference in policy and governance research. This literature provides both a substantive and a methodological warrant for the mixed regression–fsQCA design adopted in Section 4.

While these studies convincingly confirm the enabling role of the digital economy, they implicitly assume that the institutional environment is either given or uniformly benign. In reality, when cross-border data flows are subject to stringent regulatory oversight, the “low-cost” enabling mechanisms of the digital economy may be significantly offset by rising compliance costs and administrative frictions. However, the existing literature rarely

incorporates regulatory policy as an exogenous institutional constraint into the analytical framework of the digital economy–resilience nexus. Consequently, whether and how the regulatory stringency of data flows moderates or mediates the empowering effects of digitalization remains an open empirical question, which we address explicitly in our theoretical mechanisms below.

2.4. Limitations of Existing Research and Future Research Trends

A synthesis of the existing literature shows that substantial progress has been made in research on cross-border data flow regulatory models, digital economy empowerment mechanisms, and the measurement of industrial chain resilience. Nevertheless, several areas remain to be further expanded.

First, integrating fragmented research perspectives into a unified analytical framework. Most studies focus on single fields such as legal regulation [49,50], data security [51], or international trade rules [52], while relatively few place cross-border data flow regulation and the resilience of core digital economy industrial chains within the same analytical framework for systematic investigation. Relatively few studies have simultaneously incorporated cross-border data flow regulation and the resilience of core digital economy industrial chains into a single analytical framework. This study supplements the literature by embedding regulatory intensity, data governance mechanisms, and industrial chain resilience into an integrated theoretical framework, thereby extending the analytical boundary of digital economy governance research.

Second, extending empirical evidence at the provincial level with a multidimensional quantitative indicator system. Empirical analysis remains insufficient, particularly in terms of quantifiable provincial-level measurement. Existing studies are largely limited to cross-country comparisons [53,54] or case analyses [55] and lack empirical verification based on large samples and multidimensional indicator systems. For a country like China with a complex internal structure, quantitative measurements at the local level remain limited. This study provides new empirical evidence by reconstructing a provincial-level Cross-Border Data Flow Regulation Index covering regulatory intensity, compliance costs, and international coordination, and by pairing it with a six-dimensional industrial chain resilience index. This contributes to the ongoing effort to move regulatory research from macro-level narratives toward finer-grained, verifiable empirical measurement.

Third, enriching dynamic and mechanism-oriented analysis of the efficiency–security balance. Existing studies have largely treated data flow efficiency and data security as parallel or competing objectives [56,57], with limited attention to how their dynamic balance mediates the transmission from regulation to industrial chain outcomes. This study extends this line of inquiry by explicitly modeling the efficiency–security balance as a mediating mechanism, thereby offering new insights into the transmission channels through which regulation shapes industrial chain resilience, and complementing prior research that has mostly examined direct effects.

Fourth, contributing heterogeneity evidence for differentiated data governance. Prior studies mostly use average-effect estimation. They also record regional gaps in digital empowerment [58]. However, few of them examine how regulatory effects on industrial chain resilience vary across regions. Fuzzy-set qualitative comparative analysis (fsQCA) has drawn growing attention in digital economy governance research [59]. Yet in the regulatory context, it is seldom paired with econometric evidence. Current policy-oriented studies often recommend a uniform regulatory approach [60]. They pay less attention to how regulatory design should fit provinces at different stages of digital economy development. This study provides complementary evidence by pairing two-way fixed-effects estimation with fsQCA, and by grouping provinces according to their level of digital economy devel-

opment, this study uncovers the underlying logic behind the regional heterogeneity in the effects of cross-border data flow regulation on the resilience of core digital industrial chains. Building on these findings, this study further proposes differentiated regulatory adaptation pathways, thereby offering practical references for constructing regionally differentiated data governance systems.

In view of these gaps, this study reconstructs a provincial Cross-Border Data Flow Regulation Index and a resilience index for the core industrial chains of the digital economy. Rather than treating regulation as a peripheral factor, we embed regulatory stringency, compliance costs, and international coordination into a unified analytical framework to examine their direct, mediating, and heterogenous effects on industrial chain resilience. The following section develops the theoretical mechanisms that connect these elements, culminating in three testable hypotheses.

2.5. Theoretical Mechanisms and Research Hypotheses

2.5.1. Direct Effects of Cross-Border Data Flow Regulation on Industrial Chain Resilience

Although cross-border data flow regulation and industrial chain resilience have often been discussed in separate research streams, they are closely connected in the digital economy. Data flows have become a key factor supporting industrial coordination, innovation, and participation in global value chains. Therefore, regulatory arrangements governing cross-border data flows may directly affect the resilience of core digital economy industrial chains.

As digital governance rules continue to evolve, the impact of regulatory policies on macroeconomic and industrial development has gradually become a research focus. On the one hand, an appropriate degree of data flow facilitation helps manufacturing enterprises achieve servitization transformation and enhances their forward participation in global value chains through value-added services such as remote diagnosis and predictive maintenance [16]. On the other hand, strict data localization requirements may increase firms' operating costs, suppress innovation investment, and weaken a country's competitiveness in the global digital division of labor.

The technological vulnerabilities and fragmentation of data governance associated with cross-border data flow regulation may generate a multiplier effect of risk diffusion by undermining transaction trust and disrupting financial order [61,62]. The core industries of the digital economy are characterized by dual functional attributes. On the one hand, as independent economic sectors, they directly create added value, employment, and exports. On the other hand, through technological spillovers and industrial linkages, they deeply empower traditional industries and promote "industrial digitalization," thereby becoming a key support for the formation of new quality productive forces [63]. Their development is not only related to a country's position in global digital competition, but also directly affects the realization of multiple objectives, including high-quality development, common prosperity, and national security [64].

Cross-border data flow regulation is not a single administrative directive. Rather, it exerts a systematic impact on the resilience of core digital economy industrial chains through the coordinated operation of several key mechanisms, including transaction costs, the network environment, innovation incentives, resource allocation, risk prevention and control, and the institutional environment. Specifically, by establishing standards for data classification and grading, procedures for outbound data security assessment, and compliance certification systems, regulation provides enterprises with standardized operational guidance. This effectively reduces trial-and-error costs and repeated assessment expenses arising from ambiguous rules, thereby improving the circulation efficiency of data elements and the collaborative capacity of industrial chains. Meanwhile, regulatory policies guide

the investment direction of provincial digital infrastructure and standardize the construction of dedicated channels for cross-border data transmission. Through a low-latency and high-bandwidth network environment, they strengthen real-time interaction and resource sharing among upstream and downstream enterprises in industrial chains.

On this basis, regulation provides institutional inclusiveness by establishing innovation-tolerant testing spaces and compliance exemption periods. This reduces enterprises' expectations of innovation risks and encourages them to increase R&D investment to accelerate breakthroughs in core technologies, thereby enhancing the transformative capacity of industrial chains in response to technological change. Moreover, regulation can guide the direction of cross-border data flows and maintain the order of data transactions. Relying on cross-border data trading platforms and mutual recognition mechanisms, it promotes the agglomeration of data elements toward high-productivity industries and core leading enterprises, enabling precise matching between supply and demand in global industrial chains and improving resource allocation efficiency. In addition, mandatory security assessments, the application of encryption technologies, and emergency response plans jointly establish a rigorous system for risk identification and response. This system can effectively prevent the leakage of core technological data and the misuse of sensitive data, weaken the impact of external geopolitical risks and cyberattacks on industrial chains, and substantially enhance industrial chain resistance. Cross-regional regulatory coordination further eliminates institutional fragmentation, provides a transparent, unified, and predictable institutional environment for industrial chain operations, reduces uncertainty, and comprehensively improves enterprises' adaptability amid global market fluctuations.

Given that previous studies (as noted in Sections 2.1–2.4) have neither systematically quantified these mechanisms at the provincial level nor integrated them into a resilience framework, we posit that the combined effect of these pathways yields a net positive impact. Based on the combined effects of these mechanisms, this study proposes the following hypothesis:

H1. *Cross-border data flow regulation has a significant positive effect on enhancing the resilience of core digital economy industrial chains.*

2.5.2. Mediating Role of the Balance Between Efficiency and Security

The impact of cross-border data flow regulation on industrial chain resilience is not transmitted merely through the six mechanisms discussed above in a linear manner. Instead, the balance between efficiency and security serves as a core mediating variable. Dynamic capabilities theory further explains the mediating role of the balance between efficiency and security. Firms' competitive advantage stems from their dynamic capabilities to sense, integrate, and reconfigure internal and external resources [65]. When the regulatory system can achieve a dynamic equilibrium between efficiency and security, data elements can circulate efficiently under controllable risk conditions. In this situation, the transaction cost mechanism and the innovation incentive mechanism can release efficiency dividends to the greatest extent, encouraging enterprises to optimize resource allocation and stimulate innovation vitality. At the same time, the risk prevention and control mechanism can accurately intercept substantive threats and safeguard the core confidential information and operational stability of industrial chains.

Under such a balanced state, the overall effect of regulation in enhancing industrial chain resilience is maximized. Conversely, if regulatory design becomes unbalanced, industrial chain resilience will be severely constrained. If regulation excessively prioritizes absolute security and adopts stringent blocking measures, data flow efficiency will decline sharply, corporate compliance costs will surge, and the resource allocation and innovation incentive mechanisms will fail. As a result, industrial chains may become rigid due to the

loss of data-driven support. If regulation excessively favors flow efficiency while neglecting the security baseline, security risks will continue to accumulate, the risk prevention and control mechanism will become ineffective, and industrial chains will be highly vulnerable to systemic collapse when facing external cyberattacks or data theft. Therefore, the balance between efficiency and security constitutes a key bridge through which regulatory policies are transformed into improved industrial chain resilience.

While the prior literature has acknowledged the trade-off between efficiency and security in general terms, it has rarely treated this balance as a formal mediating channel that transmits regulatory effects into resilience outcomes (see the gap identified in Section 2.1). We argue that this balance is the critical transmission belt linking regulation to resilience. Based on this reasoning, this study proposes the following hypothesis:

H2. *The balance between efficiency and security plays a key mediating role in the process through which cross-border data flow regulation affects industrial chain resilience.*

2.5.3. Regional Heterogeneity in the Effects of Cross-Border Data Flow Regulation

In terms of provincial policy adaptation, studies have pointed out that provinces with higher digital economy development levels, due to their deeper integration into global value chains, face more prominent compliance challenges and should explore compliance exemption licensing catalogues and innovation-tolerant testing mechanisms. Provinces with lower digital economy development levels, by contrast, should rely on cross-regional computing power dispatch projects to strengthen digital infrastructure construction and compliance capability training [66–68]. China has a vast territory, and its provinces differ significantly in terms of their stages of digital economy development, industrial structure, demand for data elements, and degree of risk exposure. Although these differences are often observed along east–central–west–northeast geographic lines, geographic grouping is largely a surface manifestation; the fundamental factor shaping regulatory transmission is the level of digital economy development. The level of digital economy development determines whether cross-border data flow regulation can be effectively absorbed and translated into industrial chain resilience, thereby giving rise to systematic spatial heterogeneity.

Provinces in the high-digital-economy group, such as Guangdong, Zhejiang, Shanghai, Jiangsu, and Beijing, possess a solid digital economy foundation, with core industrial chains deeply embedded in global value chains. These provinces exhibit extremely high requirements for the frequency, scale, and timeliness of cross-border data flows. They also possess relatively strong capabilities in international rule coordination and local legislative pilot authority, enabling them to take the lead in implementing compliance exemption licensing catalogues and classified-and-hierarchical regulatory innovations. Because digital infrastructure is dense, innovation investment is sustained, and enterprises have sufficient absorptive capacity to internalize compliance costs, regulatory policies can be rapidly translated into practical effects such as reduced transaction costs and released innovation vitality. Consequently, the positive effect of cross-border data flow regulation on industrial chain resilience in this group is the strongest.

Provinces in the low-digital-economy group, such as Guizhou, Sichuan, Hubei, Heilongjiang, Jilin, Liaoning, Gansu, and Guangxi, are still in a stage of accelerated cultivation or delayed transformation of the digital economy. Their digital infrastructure density is comparatively low, enterprise R&D investment and digital transformation remain insufficient, and international-rule coordination capacity is limited. Under these conditions, the marginal compliance cost of strict cross-border data flow regulation is high, and small, medium-sized, and microenterprises in particular find it difficult to absorb institutional transaction costs. Regulatory policies in this group therefore mainly play the role of strengthening the security baseline and standardizing resource allocation, producing ef-

fects primarily in enhancing industrial chain resistance and penetration capacity, while their overall contribution to industrial chain resilience is significantly weaker than in the high-digital-economy group.

This grouping analysis directly responds to the spatial heterogeneity gap noted in Section 2.3, where existing studies have largely examined regional differences in digital empowerment along coarse geographic lines but have left the underlying mechanism. By extending the heterogeneity logic from empowerment to regulation, and by shifting the grouping criterion from geographic zone to the digital economy development index, we argue that the regulatory–resilience nexus is fundamentally digital-capability-dependent rather than location-dependent. Based on the above analysis, this study proposes the following hypothesis:

H3. *The impact of cross-border data flow regulation on industrial chain resilience exhibits significant heterogeneity across digital economy development levels: the positive effect is significantly stronger in provinces whose digital economy development index exceeds the sample mean than in provinces at or below the sample mean.*

3. Methodology

3.1. Construction of the Measurement System and Data Processing

To systematically evaluate the impact of cross-border data flow regulation on the resilience of China's core digital economy industrial chains, this study moves beyond the limitations of previous single-dimensional measurement approaches and constructs a comprehensive measurement system comprising a provincial Cross-Border Data Flow Regulation Index, a provincially adapted version of internationally recognized digital trade indices, and a six-dimensional resilience index for the core industrial chains of the digital economy. This section elaborates on the design logic of the indicator system, the data processing methods, and the evolutionary characteristics of the measurement results.

3.1.1. Reconstruction and Measurement of the Provincial Cross-Border Data Flow Regulation Index

(1) Measurement logic and construction of the indicator system

Traditional digital trade restriction indices mainly focus on the number of prohibitive or restrictive provisions concerning outbound data transfers. They emphasize the static measurement of regulatory intensity and tend to overlook the positive functions of regulatory systems in promoting compliance efficiency, advancing international mutual recognition, and adapting to industrial development.

This study constructs an evaluation system for the provincial Cross-Border Data Flow Regulation Index (DFRI). The system consists of four primary dimensions: openness, institutional constraints, regulatory safeguards, and practical resistance. It further includes eight secondary indicators, aiming to comprehensively capture the evolutionary characteristics of China's regulatory system as it shifts from extensive control toward refined balancing. The DFRI adopts the core methodological logic of the ECIPE index but is recalibrated to accommodate the institutional features of data governance at the Chinese provincial level. Three considerations motivate this adaptation. First, the ECIPE index is designed primarily to measure digital-trade barriers, whereas the DFRI is intended to gauge the institutional maturity of provincial data-governance frameworks. Second, ECIPE's Intermediary Liability and Content Access dimensions are grounded in the content-moderation regimes typical of developed economies, and thus map only imperfectly onto the priorities of China's cross-border data-security assessment system. Third, the Cross-Border Data Facilitation Measures dimension introduced in this study captures China's distinctive "development-and-control"

regulatory approach, which is not represented in the original ECIPE framework. Table 1 reports a side-by-side comparison of the DFRI and ECIPE dimensions.

Table 1. Correspondence between the ECIPE and DFRI Dimensions.

ECIPE Dimension	ECIPE Sub-Indicators	Corresponding DFRI Dimension	Explanation of Correspondence
Data Policies	Cross-border data transfer restrictions; data localization requirements	Dimension 1: Regulatory Improvement (indicators omitted)	Partial correspondence. ECIPE emphasizes the degree of cross-border restriction, whereas the DFRI emphasizes the institutional completeness of the regulatory system.
Intermediary Liability	Platform liability regime; content-moderation obligations	Dimension 2: Infrastructure; Dimension 3: Innovation Investment	Indirect correspondence. The DFRI substitutes infrastructure and innovation-investment measures for platform-liability indicators.
Content Access	Online content control; access restrictions	Dimension 4: Security Governance (security_control)	Partial correspondence. The DFRI focuses on data-security incidents rather than on content control.

Note: Detailed sub-indicators of the DFRI are omitted from this table for brevity. The DFRI departs from the ECIPE index in analytical purpose: the former measures the institutional completeness of provincial data-governance systems, whereas the latter measures cross-border digital-trade barriers. Accordingly, re-weighting and indicator substitution were undertaken to align the index with the Chinese provincial context.

The selection of indicators follows three principles. First, data availability is emphasized, with priority given to provincial statistical yearbooks, government public reports, and survey data from authoritative institutions. Second, policy relevance is highlighted, with a focus on core policy instruments that affect cross-border data flows. Third, regional differentiation is considered, incorporating indicators that reflect the specific characteristics of both developed eastern provinces and less-developed central and western provinces (see Table 2).

Table 2. Measurement Framework of China’s Provincial Cross-Border Data Flow Regulation Index.

Primary Indicator	Secondary Indicator	Indicator Definition	Data Source	Indicator Attribute
Degree of openness	Freedom of cross-border data flows (X1)	The intensity of administrative intervention imposed by a province on cross-border data transmission, including whether a “negative list” management approach is adopted and the extent to which filing procedures for cross-border data transfer are simplified.	Policy documents issued by provincial cyberspace administrations, e.g., Measures for the Management of Cross-Border Data Flows in Guangdong Province; China Academy of Information and Communications Technology, Research Report on China’s Digital Economy Development 2024, p. 82.	Positive; a higher value indicates weaker restrictions.
Degree of openness	Number of cross-border data-sharing agreements (X2)	The number of data-sharing cooperation agreements signed between a province and overseas regions or enterprises, including bilateral and multilateral agreements.	Provincial departments of commerce, Reports on the Development of Cross-Border Digital Trade; China Academy of Information and Communications Technology, White Paper on the Global Digital Economy 2023, p. 64.	Positive.
Institutional constraints	Compliance requirements for cross-border data transfer (X3)	The degree of completeness of provincial laws and regulations related to cross-border data transfer, such as whether local rules for data export and implementation guidelines for data classification and grading have been issued.	Legislative documents issued by provincial people’s congresses, e.g., Shanghai Data Regulations; China Center for Information Industry Development, White Paper on New Forms and Models of the Digital Economy 2020, p. 99.	Positive; more reasonable compliance requirements indicate weaker restrictions.

Table 2. Cont.

Primary Indicator	Secondary Indicator	Indicator Definition	Data Source	Indicator Attribute
Institutional constraints	Implementation rate of data classification and grading (X4)	The proportion of enterprises above designated size in a province that have completed data classification and grading in accordance with the Information Security Technology—Guidelines for Data Classification and Grading.	Provincial digital economy reports issued by the Ministry of Industry and Information Technology; TRS Digital Economy Research Institute, White Paper on Data Elements 2023, p. 86.	Positive; a higher implementation rate indicates more standardized compliance and stronger regulatory rationality.
Regulatory safeguards	Intensity of cross-border data regulation (X5)	The coverage of regulatory measures for cross-border data security assessment and dynamic monitoring within a province, such as the number of security assessment institutions and the coverage rate of monitoring platforms.	Annual reports issued by provincial cyberspace administrations; China Mobile, Digital Trust White Paper 2025: Building a New Foundation of Mutual Trust for the Digital Economy, p. 51.	Positive; more science-based regulation indicates more moderate restrictions.
Regulatory safeguards	Efficiency of data security incident handling (X6)	The average time required for handling cross-border data security incidents in a province, measured in hours, covering the full process of incident response, traceability, and remediation.	Provincial public security departments, Cybersecurity Work Reports; Baidu, White Paper on Industrial Internet Finance Empowering Regional Digital New Economy 2023, p. 39.	Positive; higher handling efficiency indicates stronger regulatory effectiveness.
Practical impediments	Compliance cost of cross-border data transfer (X7)	The average expenditure incurred by enterprises in a province for cross-border data compliance, measured in RMB 10,000 per enterprise, including costs related to technological upgrading, third-party auditing, and personnel training.	Enterprise survey data, with reference to Deloitte's white paper methodology; Deloitte, Navigating the New World of Digital Economy Compliance: Recommendations for Chinese Enterprises Going Global 2023, p. 119.	Negative; a higher cost indicates stronger restrictions.
Practical impediments	Degree of digital trade barriers (X8)	The delay rate of digital trade processes caused by restrictions on data flows within a province, including delays in order processing and payment settlement.	Provincial departments of commerce, reports on cross-border digital trade; China Center for Information Industry Development, White Paper on the Map of the Consumer-Oriented Digital Economy, p. 55.	Negative; a higher delay rate indicates stronger restrictions.

(2) Data processing and index aggregation method

This study uses panel data from 31 Chinese provinces from 2015 to 2025 for measurement. For missing data in some provinces during the period from 2015 to 2018, such as compliance costs and the implementation rate of data classification and grading, a combination of linear interpolation and trend analysis is adopted for imputation. For indicators exhibiting linear trends, the linear interpolation method is used; for indicators showing nonlinear changes, the least squares method is employed to fit trend equations for prediction.

At the stage of data standardization, because the indicators differ in units of measurement and directional attributes, they are uniformly mapped onto the interval [0, 1].

For positive indicators, where a higher value indicates weaker restrictions and a more complete regulatory system, the standardization formula is as follows:

$$X'_{ijt} = \frac{X_{ijt} - \min(X_{jt})}{\max(X_{jt}) - \min(X_{jt})} \quad (1)$$

For negative indicators, where a higher value indicates stronger restrictions and greater practical resistance, the reverse standardization formula is as follows:

$$X'_{ijt} = \frac{\max(X_{jt}) - X_{ijt}}{\max(X_{jt}) - \min(X_{jt})} \quad (2)$$

where X'_{ijt} denotes the original value of indicator j for province i in year t ; $\max(X_{jt})$ and $\min(X_{jt})$ denote the maximum and minimum values, respectively, of indicator j across all provinces in year t ; and X'_{ijt} denotes the standardized value.

In terms of weight assignment, the entropy weight method is adopted as an objective weighting approach to avoid subjective bias. First, the proportion of each indicator is calculated as follows:

$$P_{ijt} = \frac{X'_{ijt}}{\sum_{i=1}^{31} X'_{ijt}} \quad (3)$$

If $X'_{ijt} = 0$, then P_{ijt} is set to 0, so as to avoid meaningless logarithmic operations. When calculating information entropy, the information entropy of indicator j in year t reflects the degree of variation in the indicator and is expressed as follows:

$$e_{jt} = -\frac{1}{\ln 31} \sum_{i=1}^{31} P_{ijt} \ln(P_{ijt}) \quad (4)$$

Here, 31 represents the number of Chinese provinces, and e_{jt} ranges from 0 to 1. The smaller the value of e_{jt} , the greater the variation in the corresponding indicator and the higher its information content.

Finally, the weights are calculated according to Formula (5):

$$W_{jt} = \frac{1 - e_{jt}}{\sum_{j=1}^8 (1 - e_{jt})} \quad (5)$$

When summing from $j = 1$ to $j = 8$, the total value of W_{jt} equals 1, thereby ensuring the rationality of weight allocation. The provincial DFRI is synthesized according to Formula (6):

$$DFRI_{it} = \sum_j W_{jt} \times X'_{ijt} \quad (6)$$

The index value is set within the interval [0, 1]. A higher value indicates stricter restrictions on cross-border data flows. Since neither the academic community nor policy bodies have proposed an officially recognized cut-off for classifying units by composite restrictiveness indices of this type. The ECIPE DTRI report only mentions 0.05 as a heuristic benchmark for “extremely low restriction [69],” while the OECD DSTRI reports scores in percentile rankings without prescribed thresholds [70]. This study adopts a sample-distribution-based classification approach combining the tercile method and the Jenks Natural Breaks Method [71].

Specifically, (1) sorting the 341 provincial-year DFRI observations from 2015 to 2025 in ascending order yields 33.3% and 66.7% quantiles of 0.447 and 0.652, respectively; (2) applying Jenks Natural Breaks to the same sample produces two clustering break points at 0.451 and 0.648, which closely align with the tercile results and confirm the existence of naturally occurring discontinuities in the sample distribution; and (3) for expositional convenience and policy interpretability, the two values are rounded to 0.45 and 0.65, classifying provinces into low-restriction ($DFRI_{it} \leq 0.45$), medium-restriction ($0.45 < DFRI_{it} < 0.65$), and high-restriction ($DFRI_{it} \geq 0.65$) groups. When $DFRI_{it} \geq 0.65$, the province is classified as a high-restriction province; when $0.45 < DFRI_{it} < 0.65$, it is

classified as a medium-restriction province; and when $DFRI_{it} \leq 0.45$, it is classified as a low-restriction province.

(3) Measurement results and robustness test

As shown in Figure 1, the national provincial DFRI exhibited an overall upward trend from 2015 to 2025, increasing from 0.48 in 2015 to 0.52 in 2024, with an average annual growth rate of 0.9%. This indicates that China's cross-border data flow regulation is shifting from extensive control toward refined governance. In terms of regional differences, the DFRI values of eastern provinces are significantly higher than those of central and western regions. In 2024, Beijing (0.78), Shanghai (0.75), and Guangdong (0.69) ranked among the top three nationwide and belonged to provinces with a high level of regulatory development. Zhejiang (0.65) and Jiangsu (0.62) belonged to provinces with a medium level of regulatory development, whereas Guizhou (0.28) and Guangxi (0.35) belonged to provinces with a relatively low level of regulatory development.

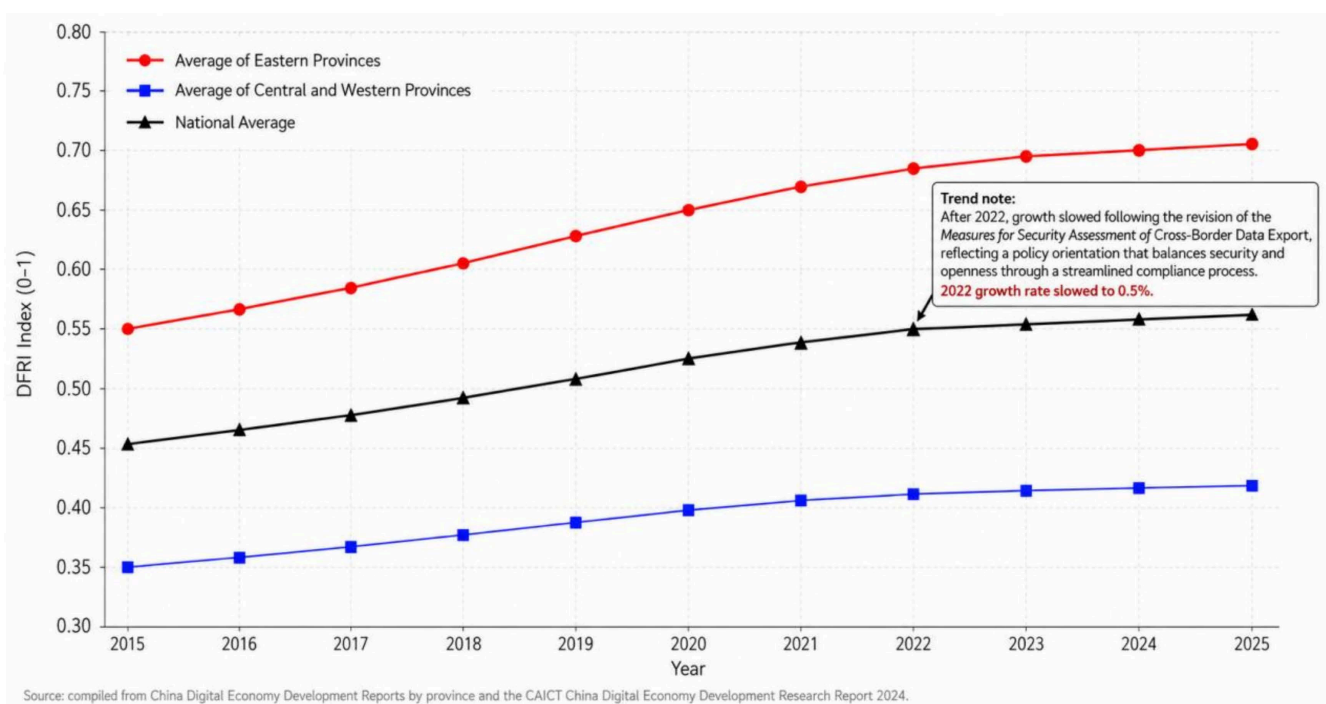


Figure 1. Trend comparison of China's provincial Cross-Border Data Flow Restriction Index (DFRI), 2015–2025.

To verify the reliability of the DFRI measurement results, this study conducts a robustness test using the indicator substitution method. Specifically, the negative indicator of cross-border data compliance costs is replaced by the approval duration for cross-border data flows, and the degree of digital trade barriers is replaced by the growth rate of digital service exports. The entropy weight method is then reapplied to calculate the provincial DFRI for 2024. As shown in Table 3, the Pearson correlation coefficient between the new index and the original index is 0.89, significant at the 1% level ($p < 0.01$). Moreover, the classification results for all 31 provinces are fully consistent, indicating that the measurement method is highly robust.

Table 3. Robustness test comparison of the provincial DFRI in 2024.

Province	Original DFRI	Alternative DFRI	Original Classification	Alternative Classification	Classification Consistency
Beijing	0.78	0.76	High Restriction	High Restriction	✓ Yes
Shanghai	0.75	0.73	High Restriction	High Restriction	✓ Yes
Guangdong	0.69	0.67	High Restriction	High Restriction	✓ Yes
Zhejiang	0.65	0.63	Medium Restriction	Medium Restriction	✓ Yes
Jiangsu	0.62	0.60	Medium Restriction	Medium Restriction	✓ Yes
Shandong	0.58	0.56	Medium Restriction	Medium Restriction	✓ Yes
Sichuan	0.55	0.53	Medium Restriction	Medium Restriction	✓ Yes
Hubei	0.52	0.50	Medium Restriction	Medium Restriction	✓ Yes
Fujian	0.49	0.47	Low Restriction	Low Restriction	✓ Yes
Hunan	0.47	0.45	Low Restriction	Low Restriction	✓ Yes
Guizhou	0.28	0.26	Low Restriction	Low Restriction	✓ Yes
Guangxi	0.35	0.33	Low Restriction	Low Restriction	✓ Yes

Note: “✓ Yes” indicates that all provinces show consistent classification results between the original and alternative DFRI measures. Source: Author’s calculations based on panel data from 31 Chinese provinces from 2015 to 2025.

3.1.2. Provincial Adaptation and Application of Internationally Recognized Digital Trade Indices

To provide a further benchmark framework for international comparison, this study localizes and adapts two internationally recognized indices—the Digital Services Trade Restrictiveness Index (DSTRI) and the Global Digital Trade Facilitation Index (GDTFI)—to the Chinese provincial context.

(1) Provincial adaptation of the Digital Services Trade Restrictiveness Index (DSTRI)

Based on the core logic of the DSTRI developed by the Organisation for Economic Co-operation and Development (OECD), and in combination with the characteristics of China’s provincial-level data, this study constructs a provincial adaptation framework comprising four dimensions: infrastructure and connectivity, electronic transactions and the legal-policy environment, payment systems, and market access and regulatory enforcement. The specific indicators are presented in Table 4. A weighted scoring aggregation method is used for calculation, and the index ranges from 1 to 5. A higher value indicates a stronger degree of restriction on digital service trade.

Table 4. Provincial adaptation indicator framework of China’s DSTRI.

Original DSTRI Primary Dimension	Province-Level Adapted Secondary Indicator	Indicator Description	Data Source	Original DSTRI Primary Dimension	Province-Level Adapted Secondary Indicator
Infrastructure and connectivity	Coverage of provincial ICT infrastructure	The density of 5G base stations in a province, measured as the number of stations per 10,000 persons, and the number of data-center racks, measured in ten thousand racks. This indicator reflects the supporting capacity of digital infrastructure.	Provincial communications administrations, Digital Infrastructure Development Reports; China Academy of Information and Communications Technology, Research Report on China’s Digital Economy Development 2024, p. 82.	Infrastructure and connectivity	Coverage of provincial ICT infrastructure
Infrastructure and connectivity	Level of interconnectivity assurance	Provincial backbone network bandwidth, measured in Tbps, and cross-regional data transmission latency, measured in milliseconds. This indicator evaluates the coordination efficiency of digital infrastructure.	China Mobile, White Paper on 5G-Enabled New Smart Cities 2021: Digital Economy Planning Volume, p. 31; provincial reports issued by the Ministry of Industry and Information Technology.	Infrastructure and connectivity	Level of interconnectivity assurance

Table 4. Cont.

Original DSTRI Primary Dimension	Province-Level Adapted Secondary Indicator	Indicator Description	Data Source	Original DSTRI Primary Dimension	Province-Level Adapted Secondary Indicator
Electronic transactions and legal/policy environment	Completeness of data security regulations	Whether a province has issued local data security regulations and detailed rules on personal information protection. This indicator reflects the maturity of the legal environment.	Legislative documents issued by provincial people's congresses, e.g., Zhejiang Data Security Regulations; China Center for Information Industry Development, White Paper on New Forms and Models of the Digital Economy 2020, p. 99.	Electronic transactions and legal/policy environment	Completeness of data security regulations
Electronic transactions	Legal adaptability of electronic transactions	The coverage rate of the legal validity of electronic signatures and the online filing rate of cross-border contracts in a province. This indicator captures the degree of standardization of electronic transactions.	Provincial market regulation administrations, E-commerce Development Reports; iResearch, White Paper on the Construction of Enterprise-Level Low-Code Platforms 2023, p. 56.	Electronic transactions	Legal adaptability of electronic transactions
Payment systems	Coverage of payment infrastructure	The mobile payment penetration rate and the settlement efficiency of cross-border payments, measured as transactions per second. This indicator evaluates the convenience of payment services.	Reports issued by provincial financial regulatory authorities; Baidu, White Paper on Industrial Internet Finance Empowering the Regional Digital New Economy 2023, p. 39.	Payment systems	Coverage of payment infrastructure
Market access	Openness of foreign investment access in digital services	The registered capital threshold for foreign-invested digital enterprises and the number of sectors subject to market access restrictions in a province. This indicator reflects the degree of market openness.	Provincial departments of commerce, Negative Lists for Foreign Investment Access; Cushman & Wakefield, White Paper on the Development of Digital Economy Industrial Clusters 2023, p. 72.	Market access	Openness of foreign investment access in digital services
Market access	Requirement for local commercial presence	Whether a province requires cross-border digital service providers to establish local branches, coded as 1 for “yes” and 0 for “no”. This indicator reflects the degree of market entry barriers.	Policy documents issued by provincial market regulation administrations; Deloitte, Navigating the New World of Digital Economy Compliance: Recommendations for Chinese Enterprises Going Global 2023, p. 119.	Market access	Requirement for local commercial presence
Intellectual property rights and regulatory enforcement	Intensity of digital service regulation	The frequency of random inspections of digital service enterprises and the amount of penalties imposed for violations in a province. This indicator reflects the strength of regulatory enforcement.	Annual reports issued by provincial cyberspace administrations; China Mobile, Digital Trust White Paper 2025: Building a New Foundation of Mutual Trust for the Digital Economy, p. 51.	Intellectual property rights and regulatory enforcement	Intensity of digital service regulation
Infrastructure and connectivity	Coverage of provincial ICT infrastructure	The density of 5G base stations in a province, measured as the number of stations per 10,000 persons, and the number of data-center racks, measured in ten thousand racks. This indicator reflects the supporting capacity of digital infrastructure.	Provincial communications administrations, Digital Infrastructure Development Reports; China Academy of Information and Communications Technology, Research Report on China's Digital Economy Development 2024, p. 82.	Infrastructure and connectivity	Coverage of provincial ICT infrastructure

Table 4. Cont.

Original DSTRI Primary Dimension	Province-Level Adapted Secondary Indicator	Indicator Description	Data Source	Original DSTRI Primary Dimension	Province-Level Adapted Secondary Indicator
Infrastructure and connectivity	Level of interconnectivity assurance	Provincial backbone network bandwidth, measured in Tbps, and cross-regional data transmission latency, measured in milliseconds. This indicator evaluates the coordination efficiency of digital infrastructure.	China Mobile, White Paper on 5G-Enabled New Smart Cities 2021: Digital Economy Planning Volume, p. 31; provincial reports issued by the Ministry of Industry and Information Technology.	Infrastructure and connectivity	Level of interconnectivity assurance
Electronic transactions and legal/policy environment	Completeness of data security regulations	Whether a province has issued local data security regulations and detailed rules on personal information protection. This indicator reflects the maturity of the legal environment.	Legislative documents issued by provincial people's congresses, e.g., Zhejiang Data Security Regulations; China Center for Information Industry Development, White Paper on New Forms and Models of the Digital Economy 2020, p. 99.	Electronic transactions and legal/policy environment	Completeness of data security regulations

(2) Provincial reference of the Global Digital Trade Facilitation Index (GDTFI)

Drawing on the core logic of the GDTFI, this study constructs a reference indicator system comprising four dimensions: market access, infrastructure, legal-policy environment, and business environment. The specific indicators are presented in Table 5.

According to the GDTFI scoring criteria, this study measures the 2024 data of 31 Chinese provinces. The final top 10 results are presented in Table 6.

Table 5. Reference indicator framework of China's provincial GDTFI.

GDTFI Primary Dimension	Province-Level Reference Indicator	Indicator Description	Data Source
Market access	Openness of digital trade sectors	The length of the negative list for foreign investment access in digital trade-related sectors, such as cross-border e-commerce and cloud computing, measured by the number of restricted items in each province.	Provincial departments of commerce, Digital Trade Development Reports; Cushman & Wakefield, White Paper on the Development of Digital Economy Industrial Clusters 2023, p. 72.
Market access	Convenience of cross-border data filing	The average time required for cross-border data filing in each province, measured in working days.	Data from provincial cyberspace administrations; TRS, White Paper on Data Elements 2023, p. 86.
Infrastructure	Quality of ICT infrastructure	The average broadband download speed in each province, measured in Mbps, and the power usage effectiveness (PUE) of data centers, where a lower PUE indicates higher efficiency.	Reports issued by provincial communications administrations; China Mobile, White Paper on New Smart Cities 2023: Digital Economy Volume, p. 52.
Infrastructure	Coverage of payment infrastructure	The mobile payment penetration rate and cross-border payment settlement efficiency in each province, measured as transactions per second.	Reports issued by provincial financial regulatory authorities; Baidu, White Paper on Industrial Internet Finance Empowering the Regional Digital New Economy 2023, p. 39.
Legal and policy environment	Completeness of digital policies	The number of policy documents related to the digital economy issued by each province and the evaluated effectiveness of policy implementation, scored on a scale from 1 to 5.	Provincial development and reform commissions, Digital Economy Policy Evaluation Reports; Digital Economy Laboratory, China Digital Economy White Paper 2023, June 1, 2024.
Legal and policy environment	Level of security environment assurance	The incidence rate of data security incidents in each province, measured as the number of incidents per 10,000 enterprises.	Data from provincial public security departments; China Mobile, Digital Trust White Paper 2025: Building a New Foundation of Mutual Trust for the Digital Economy, p. 51.

Table 5. Cont.

GDTFI Primary Dimension	Province-Level Reference Indicator	Indicator Description	Data Source
Business environment	Level of digital technology adoption	The digital transformation rate of enterprises above designated size in each province.	Provincial reports issued by the Ministry of Industry and Information Technology; iResearch, White Paper on the Construction of Enterprise-Level Low-Code Platforms 2023, p. 56.
Business environment	Digital technological capability	The share of R&D expenditure in the core industries of the digital economy in each province.	Reports issued by provincial departments of science and technology; MIT Technology Review, White Paper on the Artificial Intelligence Ecosystem in China's Digital Economy Era 2021, p. 40.

Table 6. Top 10 reference scores of the GDTFI for China's 31 provinces in 2024.

Rank	Province	GDTFI Reference Score	Core Strengths	Supporting Data Sources
1	Guangdong	0.82	Openness of digital trade sectors reached 0.85, with only eight items on the negative list; cross-border payment settlement efficiency reached 1200 transactions per second; the policy implementation effectiveness score was 4.8.	White Paper on the Development of Guangdong's Digital Economy 2024; China Academy of Information and Communications Technology, Research Report on China's Digital Economy Development 2024, p. 82.
2	Zhejiang	0.80	Mobile payment penetration reached 98%; the digital transformation rate of enterprises was 75%; the average time required for cross-border data filing was three working days.	Regulations of Zhejiang Province on Promoting the Digital Economy; iResearch, White Paper on the Construction of Enterprise-Level Low-Code Platforms 2023, p. 56.
3	Shanghai	0.78	The incidence rate of data security incidents was 0.2 per 10,000 enterprises; 120 policy documents were issued, the highest number nationwide; the share of R&D expenditure reached 8.2%.	Shanghai Digital Economy Development Plan 2024; Deloitte, Navigating the New World of Digital Economy Compliance: Recommendations for Chinese Enterprises Going Global 2023, p. 119.
4	Beijing	0.76	The share of R&D expenditure in digital technology reached 8.5%; the broadband speed was 500 Mbps, the highest nationwide; the level of security environment assurance was 0.78.	Regulations of Beijing Municipality on Promoting the Digital Economy; MIT Technology Review, White Paper on the Artificial Intelligence Ecosystem in China's Digital Economy Era 2021, p. 40.
5	Jiangsu	0.75	The digital transformation rate of enterprises reached 72%; the power usage effectiveness of data centers was 1.2, indicating an internationally advanced level; the completeness score of digital policies was 0.75.	White Paper on Jiangsu's Digital Economy 2024; CCID Think Tank, White Paper on the Evaluation of Digital Economy Development Levels in Yangtze River Delta Cities 2022, p. 73.
6	Fujian	0.72	The convenience score of cross-border data filing was 0.80, with an average filing time of three working days; the openness score of digital trade was 0.78; the coverage score of payment infrastructure was 0.75.	Fujian Digital Economy Development Report 2024; China Academy of Information and Communications Technology, White Paper on JD.com's Integration of the Digital and Real Economies for Industrial Empowerment 2022, p. 76.
7	Sichuan	0.68	Mobile payment penetration reached 92%; the policy implementation effectiveness score was 0.70; the level of digital technology adoption was 0.68.	White Paper on Sichuan's Digital Economy 2022, p. 35; EDA Future, White Paper on New Trends in Urban Development under the Digital Economy, p. 42.
8	Shandong	0.65	The level of digital technology adoption was 0.68; cross-border payment settlement efficiency reached 800 transactions per second; the openness score of digital trade sectors was 0.65.	Shandong Digital Economy Development Plan 2024; Cushman & Wakefield, White Paper on the Development of Digital Economy Industrial Clusters 2023, p. 72.
9	Hubei	0.62	The data security assurance score was 0.65; the share of R&D expenditure reached 5.8%; the quality score of ICT infrastructure was 0.62.	White Paper on Hubei's Digital Economy 2024; TRS, White Paper on Data Elements 2023, p. 86.
10	Hunan	0.60	The digital transformation rate of enterprises reached 65%; the quality score of ICT infrastructure was 0.62; the convenience score of cross-border data filing was 0.58.	Hunan Digital Economy Development Report 2024; China Mobile, White Paper on New Smart Cities 2023: Digital Economy Volume, p. 52.

In addition, Pearson correlation analysis shows that the correlation coefficient between the provincial GDTFI and DFRI is -0.81 , significant at the 1% level ($p < 0.01$). This indicates

a significant negative correlation and confirms the logical expectation that a higher level of facilitation corresponds to a lower degree of restriction.

3.1.3. Construction of the Evaluation System for the Development Level of Cross-Border Data Flow Regulation

The key objective of cross-border data flow regulation is to achieve a dynamic equilibrium between data security and flow efficiency. Referring to the three-dimensional “institution–practice–effect” framework presented in CAICT’s White Paper on New Business Forms and Models in the Digital Economy 2020, and considering the specific characteristics of provincial digital economy industries, this study constructs an evaluation system based on four primary dimensions: regulatory intensity, compliance costs, international coordination, and industrial adaptation. Twelve secondary indicators are selected for this system.

Among them, the regulatory intensity dimension reflects the actual level of institutional constraints; the compliance cost dimension captures the practical resistance faced by enterprises; the international coordination dimension measures cross-border cooperation capacity; and the industrial adaptation dimension highlights the degree of matching between regulation and provincial core industries. This design helps avoid the suppressive effect of a “one-size-fits-all” regulatory approach on industrial chain resilience (see Table 7).

Table 7. Specific indicator system and connotations.

Primary Dimension	Secondary Indicator	Indicator Code	Unit	Indicator Attribute	Core Connotation, Incorporating Provincial Practices	Data Source
Regulatory intensity	Coverage rate of security assessment for outbound data transfer	R1	%	Positive	The proportion of cross-border outbound data transfer activities within a province that are subject to security assessment. This indicator reflects the breadth of regulatory coverage; for example, Guangdong reached a coverage rate of 82% in 2023.	Reports issued by provincial big data administrations, e.g., White Paper on Digital Economy Talent Development in Guizhou Province 2022.
Regulatory intensity	Stringency of data localization requirements	R2	Score, 0–10	Positive	A score assigned according to the mandatory degree of local storage requirements. For example, under Guizhou’s “Eastern Data and Western Computing” hub strategy, core computing-power data are required to be stored locally, resulting in a score of 9.	China Academy of Information and Communications Technology, Report on JD.com’s Integration of the Digital and Real Economies for Industrial Empowerment 2022.
Regulatory intensity	Number of cross-border data classification and grading categories	R3	Item	Positive	The number of cross-border data classification and grading catalogues explicitly defined at the provincial level. For example, Zhejiang adopts a three-tier classification system consisting of “core, important, and general” data; thus, R3 = 3.	Provincial digital economy white papers, e.g., White Paper on Guangxi’s Digital Economy 2024.
Compliance cost	Average enterprise compliance expenditure	C1	RMB 10,000/year	Negative	The average annual investment made by digital economy enterprises in a province to comply with cross-border data regulations. For example, the average expenditure in Jiangsu was RMB 1.26 million in 2023.	CCID Think Tank, White Paper on the Evaluation of the Digital Economy in the Yangtze River Delta 2022.
Compliance cost	Compliance approval cycle	C2	Working days	Negative	The average processing time required for outbound data filing or security assessment. For example, Shanghai shortened the approval cycle to five working days in 2023.	China Association for Public Companies, White Paper on China’s Listed Companies in the Digital Economy 2022.
Compliance cost	Penetration rate of third-party compliance services	C3	%	Positive	The proportion of enterprises using third-party institutions, such as law firms and technology companies, to provide compliance services. For example, the penetration rate in Beijing reached 65% in 2023.	TRS, White Paper on Data Elements 2023.
International coordination	Number of cross-border data-sharing agreements	I1	Number	Positive	The number of data-sharing agreements signed between a province and other countries or regions. For example, Guangdong signed data-flow cooperation agreements with Singapore under the DEPA framework, with I1 = 5.	China Academy of Information and Communications Technology, White Paper on the Global Digital Economy 2023.

Table 7. Cont.

Primary Dimension	Secondary Indicator	Indicator Code	Unit	Indicator Attribute	Core Connotation, Incorporating Provincial Practices	Data Source
International coordination	Number of enterprises with internationally recognized compliance qualifications	I2	Enterprise	Positive	The number of enterprises that have obtained international compliance certifications, such as those aligned with the EU GDPR or the ASEAN data protection framework. For example, Zhejiang had 187 such enterprises in 2023.	Deloitte, White Paper on the New World of Digital Economy Compliance 2023.
International coordination	Number of cross-border data dispute resolution cases	I3	Case	Positive	The number of cross-border data compliance disputes successfully handled at the provincial level. For example, Jiangsu handled 32 such cases in 2023.	Beijing Yanqi Lake Institute of Applied Mathematics, China Digital Economy White Paper 2022.
Industrial adaptation	Regulatory adaptability to digital industries	A1	Score, 0–10	Positive	A score reflecting the degree of alignment between regulatory arrangements and a province's core digital industries, such as computing power in Guizhou or the industrial Internet in Jiangsu. For example, Guizhou scored 8.5 in 2023.	iResearch, White Paper on Enterprise-Level Low-Code Platforms 2023.
Industrial adaptation	Regulatory exemption rate for small, medium-sized, and micro enterprises	A2	%	Positive	The proportion of small, medium-sized, and micro enterprises benefiting from regulatory exemptions, such as simplified filing procedures. For example, Zhejiang reached 45% in 2023.	Jiangxi Provincial Development and Reform Commission, White Paper on the Development of Jiangxi's Digital Economy 2023.
Industrial adaptation	Regulatory flexibility in emergency scenarios	A3	Score, 0–10	Positive	The flexibility of regulatory adjustment under emergency scenarios, such as pandemics or natural disasters. For example, Shanghai received a flexibility score of 9 during the COVID-19 outbreak in 2022.	China Mobile, White Paper on New Smart Cities 2023: Digital Economy Volume.

3.1.4. Construction of the Six-Dimensional Resilience Measurement System for Core Digital Economy Industrial Chains

(1) Design principles and theoretical framework of the measurement system

Industrial chain resilience refers to the comprehensive capacity of an industrial chain to maintain structural stability and restore functions when facing external shocks or internal disturbances. Based on the definition of core digital economy industrial chains in the China Digital Economy Development Research Report, this study retains a six-dimensional theoretical framework comprising resistance, recovery capacity, transformation capacity, penetration capacity, value-added capacity, and upgrading capacity. These dimensions are further operationalized into quantitative indicators that are highly compatible with the core industries of the digital economy.

The selection of indicators follows three principles: industrial relevance, data availability, and dynamic adaptability. This ensures that the measurement system can accurately capture the characteristics of rapid iteration and renewal in digital technologies.

(2) Specific measurement indicators and data sources for the six dimensions

This study selects a total of 30 secondary indicators to construct the resilience measurement system for the core industrial chains of the digital economy. The specific indicators, calculation methods, and data sources are presented in Table 8.

Table 8. Measurement indicator system for the resilience of core digital economy industrial chains.

Primary Dimension	Secondary Indicator	Indicator Code	Unit	Indicator Attribute	Calculation Method	Data Source
Resistance capacity	Share of digital industry output	Re1	%	Positive	Value added of provincial digital industries/regional GDP $\times$ 100%. Digital industries include electronic information manufacturing, software services, and related sectors.	China Academy of Information and Communications Technology, White Paper on the Global Digital Economy 2023.
Resistance capacity	Coverage rate of cross-border data backup	Re2	%	Positive	The proportion of enterprises that have implemented off-site backup of cross-border data, such as backup arrangements between the Guizhou and Guangdong computing-power hubs.	White Paper on Digital Economy Talent Development in Guizhou Province 2022.

Table 8. Cont.

Primary Dimension	Secondary Indicator	Indicator Code	Unit	Indicator Attribute	Calculation Method	Data Source
Resistance capacity	Self-controllability rate of core data	Re3	%	Positive	The proportion of enterprises whose core business data, such as algorithmic models and user data, do not rely on overseas storage.	China Association for Public Companies, White Paper on China's Listed Companies in the Digital Economy 2022.
Resistance capacity	Incidence rate of data security incidents	Re4	Cases per 10,000 enterprises	Negative	The number of data leakage and illegal data transmission incidents occurring per 10,000 digital economy enterprises in a province.	China Mobile, Digital Trust White Paper 2025.
Resistance capacity	Emergency data scheduling capability	Re5	Minutes	Positive	The average time required to switch data to backup nodes under emergency scenarios, such as network outages. The indicator is reverse-standardized so that higher values indicate stronger capability.	Huawei, White Paper on Digital Twin Cities 2021.
Recovery capacity	Labor productivity of the digital economy	Reo1	RMB 10,000 per person	Positive	Value added of provincial digital industries/number of employees in digital industries, with the effect of price indices excluded.	White Paper on Guangxi's Digital Economy 2024.
Recovery capacity	Recovery period of cross-border data flows	Reo2	Days	Negative	The average time required for cross-border data flows to return to normal levels after a shock, such as the tightening of regulations.	Deloitte, White Paper on the New World of Digital Economy Compliance 2023.
Recovery capacity	Substitution rate of data elements	Reo3	%	Positive	The proportion of enterprises that substitute local data for overseas data, such as using domestic user data instead of overseas samples.	TRS, White Paper on Data Elements 2023.
Recovery capacity	Reduction in compliance costs during the recovery stage	Reo4	%	Positive	The percentage decrease in compliance costs during the post-shock recovery stage relative to the pre-shock level.	CCID Think Tank, White Paper on the Evaluation of the Digital Economy in the Yangtze River Delta 2022.
Recovery capacity	Collaborative recovery rate of the industrial chain	Reo5	%	Positive	The proportion of enterprises whose upstream and downstream data collaboration along the industrial chain has recovered to normal levels after a shock.	iResearch, White Paper on Enterprise-Level Low-Code Platforms 2023.
Transformative capacity	R&D intensity of digital industries	Tra1	%	Positive	R&D expenditure of digital industries/operating revenue of digital industries $\times 100\%$.	China Academy of Information and Communications Technology, Research Report on China's Digital Economy Development 2024.
Transformative capacity	Penetration rate of artificial intelligence technologies	Tra2	%	Positive	The proportion of digital enterprises applying AI technologies, such as large language models and computer vision.	MIT Technology Review, White Paper on the AI Ecosystem in China's Digital Economy Era 2021.
Transformative capacity	Utilization rate of low-code platforms	Tra3	%	Positive	The proportion of digital enterprises using low-code platforms, such as MyBricks, for application development.	iResearch, White Paper on Enterprise-Level Low-Code Platforms 2023.
Transformative capacity	Number of digital ecosystem partners	Tra4	Number	Positive	The number of cross-industry ecosystem partnerships in which provincial digital enterprises participate, such as the Huawei HarmonyOS ecosystem and Alibaba's digital agriculture ecosystem.	EDA Future, White Paper on Urban Development Perspectives in the Digital Economy, Part II.
Transformative capacity	Growth rate of emerging digital business forms	Tra5	%	Positive	The year-on-year growth rate of revenue from emerging digital business forms in a province, such as the low-altitude economy and digital twins.	IDEA Research Institute, White Paper on the Development of the Low-Altitude Economy 2.0, 2023.
Penetration capacity	Coverage rate of the industrial Internet	Pen1	%	Positive	The proportion of manufacturing enterprises connected to industrial Internet platforms; for example, Shandong reached 68% in 2023.	Baidu, White Paper on Industrial Internet Finance Empowering the Regional Digital New Economy 2023.
Penetration capacity	Number of "5G + Industrial Internet" projects	Pen2	Number	Positive	The number of 5G-enabled industrial application projects implemented in a province, such as remote operation and quality inspection scenarios.	China Mobile, White Paper on New Smart Cities 2023: Digital Economy Volume.
Penetration capacity	Digital transformation rate of enterprises	Pen3	%	Positive	The proportion of digital enterprises that have completed digital transformation in production, management, marketing, and other operational processes.	Jiangxi Provincial Big Data Center, White Paper on the Development of Jiangxi's Digital Economy 2022.

Table 8. Cont.

Primary Dimension	Secondary Indicator	Indicator Code	Unit	Indicator Attribute	Calculation Method	Data Source
Penetration capacity	Cross-enterprise data circulation volume	Pen4	100 million GB/year	Positive	The annual volume of data shared among digital enterprises within a province, including production data and supply-chain data.	China Academy of Information and Communications Technology, Report on JD.com's Integration of the Digital and Real Economies for Industrial Empowerment 2022.
Penetration capacity	Coverage rate of digital twin applications	Pen5	%	Positive	The proportion of enterprises in key industries, such as intelligent manufacturing and smart cities, that apply digital twin technologies.	Huawei, White Paper on Digital Twin Cities 2021.
Value-added capacity	Value-added rate of digital industries	Val1	%	Positive	Value added of digital industries / gross output value of digital industries $\times 100\%$, reflecting the efficiency of value creation.	China Academy of Information and Communications Technology, White Paper on the Global Digital Economy 2023.
Value-added capacity	Contribution of data elements	Val2	%	Positive	The contribution rate of data elements to the growth of digital industry output, calculated using the Solow residual method.	TRS, White Paper on Data Elements 2023.
Value-added capacity	Share of service-oriented digital revenue	Val3	%	Positive	The proportion of service revenue, such as data consulting and algorithmic services, in the total revenue of digital enterprises.	China Center for Information Industry Development, White Paper on the Map of the Consumer-Oriented Digital Economy.
Value-added capacity	Digital brand value density	Val4	RMB 100 million per brand	Positive	Total value of provincial digital brands, such as Huawei and Alibaba / number of digital brands.	Data from the China Council for Brand Development, cited in White Paper on Guangxi's Digital Economy 2025.
Value-added capacity	Transaction scale of data products	Val5	RMB 100 million	Positive	The annual transaction value of data products listed on provincial data exchanges; for example, the Shanghai Data Exchange reached RMB 12 billion in 2023.	Beijing Yanqi Lake Institute of Applied Mathematics, China Digital Economy White Paper 2022.
Upgrading capacity	Share of digital core technology patents	Cla1	%	Positive	Number of patents related to digital core technologies / total number of patents in digital industries $\times 100\%$. Digital core technologies include chips and AI algorithms.	National Intellectual Property Administration database, cited in White Paper on the Development of Jiangsu's Digital Economy 2023.
Upgrading capacity	Number of digital industry standards formulated	Cla2	Item	Positive	The number of national or industry standards led by or jointly developed by digital enterprises in a province; for example, Zhejiang led the formulation of 32 5G industry standards.	Standardization Administration of China, cited in White Paper on Zhejiang's Digital Economy 2023.
Upgrading capacity	Upstreamness in the global digital value chain	Cla3	Dimensionless	Positive	Calculated based on input–output tables: $U_i = 1 + \sum_j \frac{Z_{ij}}{x_i} U_j$. A larger (U_i) indicates a position closer to the upstream segment of the value chain.	OECD input–output database, cited in China Academy of Information and Communications Technology, White Paper on the Global Digital Economy 2023.
Upgrading capacity	Export sophistication of digital products	Cla4	Dimensionless	Positive	Calculated based on Hausmann's method: $PRODY_p = \sum_i \frac{z_{ip}}{\sum_p z_{ip}} GDP_p$.	UN Comtrade database, cited in Deloitte, White Paper on Digital Economy Compliance 2023.
Upgrading capacity	Share of cross-border digital service revenue	Cla5	%	Positive	The proportion of revenue from cross-border digital services, such as cloud computing and digital content, in total service trade revenue within a province.	China Center for Information Industry Development, White Paper on New Forms and Models of the Digital Economy 2020.

(3) Calculation of the composite industrial chain resilience score and evolutionary trends

The entropy weight method is used to objectively assign weights to the 24 indicators under the six dimensions described above. The comprehensive resilience score of the provincial core digital economy industrial chains ($TRes_{it}$) is then obtained through weighted aggregation. The calculation formula is shown in Formula (7):

$$TRes_{it} = W_{res}Res_{it} + W_{rec}Rec_{it} + W_{tra}Tra_{it} + W_{pen}Pen_{it} + W_{val}Val_{it} + W_{cla}Cla_{it} \quad (7)$$

where W_{res} denotes the weight of each dimension, and Res_{it} , Rec_{it} , Tra_{it} , Pen_{it} , Val_{it} , and Cla_{it} represent the dimensional scores of resistance, recovery capacity, transformation capacity, penetration capacity, value-added capacity, and upgrading capacity, respectively.

The measurement results show that in 2023, the resilience scores of the core digital economy industrial chains across China's 31 provinces exhibited a clear tiered distribution. Guangdong (0.81), Shanghai (0.79), Beijing (0.77), and Zhejiang (0.75) ranked in the first tier, with their core driving forces mainly derived from strong transformation capacity and upgrading capacity. Jiangsu (0.73), Guizhou (0.69), Shandong (0.67), and Sichuan (0.65) ranked in the second tier. Their advantages were mainly reflected in resistance and penetration capacity, while their upgrading capacity remained relatively weak. Other central and western provinces, together with northeastern provinces, were located in the third tier, with scores generally below 0.60. Their main weaknesses lay in insufficient transformation capacity and limited value-added capacity.

From the perspective of dynamic evolution, the national comprehensive resilience score of core digital economy industrial chains showed a steady upward trend from 2015 to 2025, increasing from 0.35 in 2015 to a predicted value of 0.58 in 2025, with an average annual growth rate of 6.8%. In particular, during the period from 2021 to 2023, driven by the implementation of national data security laws and regulations and digital economy development plans, the growth rate of the resilience score reached a peak of 11.2%. This indicates that, with the continuous improvement of digital infrastructure and the gradual strengthening of the data governance system, China's core digital economy industrial chains are significantly improving their capacity to withstand external shocks and achieve structural upgrading.

3.2. Empirical Research Design

3.2.1. Model Specification

When examining the interaction between macro-level policies and industrial economic development, panel data models can effectively control for unobservable individual heterogeneity and time-trend effects. To test the overall effect of cross-border data flow regulation on the resilience of core digital economy industrial chains, this study constructs a baseline two-way fixed effects regression model based on panel data from 31 Chinese provinces from 2015 to 2025. This model can not only capture the direct impact of dynamic changes in regulatory intensity on industrial chain resilience, but also effectively eliminate the interference of province-specific endowments and macroeconomic cycles. The baseline regression model is specified in Formula (8):

$$TRes_{it} = \alpha_0 + \alpha_1 REG_{it} + \alpha_2 DSTRI_{it} + \alpha_3 GDTFI_{it} + \alpha_4 Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (8)$$

where subscript i denotes the 31 Chinese provinces, and subscript t denotes the years from 2015 to 2025. $TRes_{it}$ is the dependent variable, representing the comprehensive resilience score of the core digital economy industrial chains in province i in year t . REG_{it} is the core explanatory variable, representing the comprehensive index of cross-border data flow regulation in province i in year t . $DSTRI_{it}$, namely the Digital Services Trade Restrictiveness Index, and $GDTFI_{it}$, namely the Global Digital Trade Facilitation Index, are introduced into the model as international reference control variables to isolate the external impacts of fluctuations in the international trade environment on domestic industrial chains. $Control_{it}$ denotes a matrix of other macro-level control variables, covering dimensions such as the level of digital economy development, infrastructure construction, and innovation investment. μ_i represents province fixed effects, which are used to control for time-invariant provincial characteristics, such as geographical location and historical industrial foundation. λ_t represents time fixed effects, which are used to absorb macro shocks that vary

over time but affect all provinces simultaneously, such as global economic crises and the introduction of major national policies. ε_{it} is the random error term, which is assumed to be independently and identically distributed. The coefficient α_1 measures the net effect of cross-border data flow regulation on industrial chain resilience. If α_1 is significantly positive, it indicates that the improvement of the regulatory system can effectively enhance industrial chain resilience.

The theoretical analysis suggests that the impact of cross-border data flow regulation on industrial chain resilience is not transmitted entirely through a direct linear pathway. Instead, it may operate by adjusting the relationship between data flow efficiency and security risk prevention and control. To further uncover this internal transmission mechanism and test the mediating effect of the balance between efficiency and security, this study builds on the baseline regression model and draws on the stepwise mediation-effect testing method proposed by Wen et al. (2004) [72], to construct the following mediation-effect testing model:

$$Balance_{it} = \beta_0 + \beta_1 REG_{it} + \beta_2 Control_{it} + \mu_i + \varepsilon_{it} \quad (9)$$

Second, the core explanatory variable and the mediating variable are simultaneously incorporated into the regression equation to test their joint effects on the dependent variable, as shown in Formula (10):

$$TRes_{it} = \gamma_0 + \gamma_1 REG_{it} + \gamma_2 Balance_{it} + \gamma_3 Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (10)$$

where $Balance_{it}$ is the mediating variable, representing the efficiency–security balance index of province i in year t . This index is designed to quantify a province's comprehensive capacity to simultaneously improve efficiency and prevent risks when promoting cross-border data flows. In this study, the index is calculated using a coordination-degree model, as shown in Formula (11):

$$Balance_{it} = \frac{DFEI_{it} \times SRCI_{it}}{DFEI_{it} + SRCI_{it} + 1} \quad (11)$$

where $DFEI_{it}$ denotes the data flow efficiency index of province i in year t ; $SRCI_{it}$ denotes the security risk control index of province i in year t .

Within this testing framework, if the coefficients α_1 , β_1 , and γ_2 are all significant, and the absolute value of the coefficient γ_1 of the core explanatory variable after adding the mediating variable is smaller than α_1 or its significance decreases, then it can be concluded that the balance between efficiency and security plays a partial mediating role in the process through which cross-border data flow regulation affects industrial chain resilience. It is worth noting that Balance Index is derived from a coordination model constructed based on two sub-indicators, and conceptually it may be related to the regulatory policies that constitute our independent variables.

3.2.2. Variable Description and Data Sources

To ensure the scientific validity and rigor of the empirical model, this study strictly follows the principles of theoretical relevance, data availability, and statistical continuity in variable selection. The definitions of the variables and the reasons for their selection are described as follows.

(1) Dependent variable: composite score of industrial chain resilience (TRes)

The core industrial chains of the digital economy are highly complex and dynamic. A single-dimensional indicator, such as output value or profit, cannot comprehensively reflect their systemic performance when facing external shocks. Therefore, based on the six-dimensional measurement system constructed above, this study adopts the entropy

weight method for objective weighting and synthesizes a composite score of industrial chain resilience. This variable can comprehensively capture the capacity of provincial core digital economy industrial chains to maintain structural stability, rapidly restore functions, and achieve value-chain upgrading when confronted with geopolitical competition, technological blockades, or supply chain disruptions.

(2) Core explanatory variable: composite index of cross-border data flow regulation (REG)

Traditional measurements of regulation mostly rely on simple counts of policy texts, making it difficult to reflect the actual enforcement intensity and overall quality of regulation. The composite regulatory index reconstructed in this study covers four dimensions: openness, institutional constraints, regulatory safeguards, and practical resistance. It not only quantifies the strictness of laws and regulations, but also incorporates practice-oriented indicators such as compliance costs, approval efficiency, and international coordination capacity. This variable can accurately capture the real trajectory of China's provincial data governance as it evolves from extensive control toward refined governance.

(3) Control variables

To effectively control for omitted variables that may simultaneously affect regulatory implementation and industrial chain resilience, this study selects the following control variables.

First, the level of digital economy development (Digital) is measured by the share of the output value of provincial core digital economy industries in gross domestic product (GDP). This variable is selected because provinces with a larger digital economy usually have stronger endogenous risk-resistance capacity in their industrial chains and are more sensitive to regulatory policies.

Second, the level of digital infrastructure (Infra) is measured by the standardized composite value of the number of 5G base stations per 10,000 people and the number of data center racks. This variable is selected because digital infrastructure serves as the physical carrier for the circulation of data elements. Well-developed computing power and network infrastructure can significantly reduce the physical latency of data transmission and provide fundamental support for efficient industrial chain coordination.

Third, innovation input intensity (RD) is measured by the ratio of R&D expenditure to operating revenue among provincial digital economy enterprises. This variable is selected because sustained R&D investment is the fundamental driver for overcoming bottlenecks in key core technologies and promoting industrial chains toward the high end of the value chain. It directly determines the transformation capacity and upgrading capacity of industrial chains.

Fourth, the supply level of digital talents (ln_Digital_Talent) is measured by the number of employees in the information transmission, software and information technology service industries in each province. Given that digital talents serve as the crucial human capital foundation for driving the application of digital technologies, ensuring data compliance management, facilitating enterprise digital transformation, and promoting collaborative innovation within the industrial chain. Including the level of digital talent supply as a control variable helps to alleviate the interference of inter-provincial differences in human capital on the estimation results, and improves the accuracy and robustness of model identification.

Fifth, international reference control variables are included through the provincially adapted scores of the Digital Services Trade Restrictiveness Index (DSTRI) and the Global Digital Trade Facilitation Index (GDTFI). These variables are selected because industrial chain resilience is inevitably affected by external shocks from global trade barriers and facilitation policies. Introducing these two variables helps effectively isolate the interference of the international macroeconomic environment.

(4) Data sources

The sample period of this study is set from 2015 to 2025, and the research objects cover 31 provinces in mainland China, excluding Hong Kong, Macao, and Taiwan. The panel data are mainly derived from the Statistical Yearbooks released by the National Bureau of Statistics and provincial statistical bureaus, Digital Infrastructure Development Reports issued by provincial communications administrations, the China Digital Economy Development Research Report published by the China Academy of Information and Communications Technology, regional digital economy evaluation white papers released by CCID Think Tank, and industry survey data published by relevant authoritative institutions. For a small number of missing values in certain years, this study uses linear interpolation and trend extrapolation for scientific imputation, so as to ensure the balance and continuity of the panel data. Considering that the error terms for different years in the same province may have autocorrelation, this paper has conducted provincial-level clustering adjustments for the standard errors in all panel regressions.

4. Results and Discussion

4.1. Descriptive Statistical Analysis

Table 9 reports the descriptive statistical results of the main variables.

Table 9. Descriptive statistics of variables.

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum	Median
TRes	341	0.47	0.16	0.21	0.81	0.46
REG	341	0.48	0.18	0.20	0.82	0.47
Balance	341	0.45	0.16	0.18	0.76	0.44
DSTRI	341	0.52	0.15	0.25	0.84	0.51
GDTFI	341	0.46	0.17	0.22	0.83	0.44
Digital	341	0.31	0.12	0.14	0.65	0.29
Infra	341	0.49	0.18	0.20	0.88	0.47
RD	341	0.08	0.03	0.03	0.15	0.08
ln_Digital_Talent	341	2.05	1.2	−0.56	4.60	2.00

Note: All variables have 341 observations; values are reported to two decimal places. Source: Author's calculations based on panel data from 31 Chinese provinces from 2015 to 2025, using Stata/MP 18.0.

The statistical results in Table 9 show that the dependent variable, the industrial chain resilience index (TRes), has a mean value of 0.47, a standard deviation of 0.16, a minimum value of 0.21, and a maximum value of 0.81. The relatively large range and standard deviation indicate significant imbalance in the resilience of core digital economy industrial chains across China's 31 provinces, with a pronounced resilience gap between leading provinces, such as Guangdong and Beijing, and lagging provinces. The core explanatory variable, cross-border data flow regulatory intensity (REG), has a mean value of 0.48, a standard deviation of 0.18, a minimum value of 0.20, and a maximum value of 0.82. This not only indicates that the regulatory systems of various provinces have been continuously improved over time, but also reflects that local governments have adopted differentiated regulatory paths according to their local industrial endowments when implementing the national unified data security strategy.

The mediating variable, the efficiency–security balance index (Balance), has a mean value of 0.45, suggesting that there remains considerable room for improvement nationwide in coordinating data flow efficiency and security risks. In addition, the standard deviations of control variables such as the level of digital economy development (Digital) and innovation input intensity (RD) also reflect objective interprovincial differences in

industrial scale and R&D momentum. This further confirms the necessity of introducing these control variables into the regression model to eliminate omitted-variable bias.

4.2. Baseline Regression Analysis

To rigorously verify the direct impact of cross-border data flow regulation on industrial chain resilience, this study adopts a hierarchical regression strategy by gradually adding control variables and fixed effects. Table 4 presents the detailed results of the full-sample baseline regression. Model 1 examines only the univariate effect of the core explanatory variable. Model 2 adds international reference control variables. Model 3 further incorporates domestic macro-level control variables. Model 4 is the final full model that simultaneously controls for province fixed effects and time fixed effects.

As shown in Table 10, after gradually adding various control variables and strictly controlling for two-way fixed effects, the model goodness of fit (R^2) increases steadily from 0.45 to 0.97, indicating that the explanatory power of the model is continuously enhanced. In the final specification, Model 4, the regression coefficient of the core explanatory variable, cross-border data flow regulation (REG), is 0.34 and is highly significant at the 1% statistical level. This result has a clear economic implication: holding other macro-level factors and spatiotemporal fixed effects constant, a 0.1-unit increase in the provincial cross-border data flow regulation index leads to a significant increase of 0.034 units in the comprehensive resilience score of the province's core digital economy industrial chains. This fully demonstrates that scientifically designed, rational, and refined cross-border data flow regulation can effectively reduce institutional transaction costs, standardize the order of factor allocation, and thereby significantly enhance the capacity of industrial chains to withstand external shocks and achieve structural upgrading. Therefore, Hypothesis 1 is strongly supported.

Table 10. Baseline regression results for the full sample.

Variable	Model 1	Model 2	Model 3	Model 4
REG	0.57 *** (17.82)	0.53 *** (17.83)	0.56 *** (25.07)	0.34 *** (24.92)
DSTRI	-	−0.15 *** (−4.15)	−0.13 *** (−15.31)	−0.11 *** (−13.73)
GDTFI	-	0.28 *** (7.28)	0.16 *** (15.39)	0.15 *** (14.60)
Digital	-	-	0.35 *** (20.99)	0.33 *** (19.70)
Infra	-	-	0.26 *** (26.46)	0.24 *** (25.65)
R&D	-	-	2.41 *** (40.52)	2.39 *** (43.98)
ln_Digital_Talent			−0.00 (−0.45)	0.00 (0.31)
Constant	0.20 *** (11.15)	0.17 *** (8.69)	−0.14 *** (−13.78)	−0.13 *** (−6.86)
N	341	341	341	341
Province Fixed Effects	No	No	No	Yes
Time Fixed Effects	No	No	No	Yes
R^2	0.45	0.57	0.96	0.97
χ^2 statistic	317.52	738.12	7701.00	-
F-statistic	-	-	-	797.72 ***

Note: t-values are reported in parentheses; *** $p < 0.01$. Source: Author's calculations based on panel data from 31 Chinese provinces from 2015 to 2025, using Stata.

4.3. Mediation Effect Analysis

The baseline regression confirms the overall effect of regulation on industrial chain resilience. To further reveal the internal transmission mechanism through which this macro-level policy is transformed into industrial performance, this study adopts the stepwise regression method to test the mediating role of the “balance between efficiency and security.” The significance of the mediating effect was further validated using both the Sobel test and the bootstrap resampling method. Table 11 reports the mediation effect test results in detail.

Table 11. Regression results of the mediation effect.

Variable	Model 1: Resilience	Model 2: Balance	Model 3: Resilience
REG	0.34 *** (24.92)	0.43 *** (51.68)	0.29 *** (8.54)
Balance	-	-	0.13 * (1.94)
DSTRI	−0.11 *** (−13.73)	−0.10 *** (08.06)	−0.10 *** (−10.11)
GDTFI	0.15 *** (14.60)	0.02 ** (2.22)	0.15 *** (14.61)
Digital	0.33 *** (19.70)	0.30 *** (15.22)	0.29 *** (9.21)
R&D	2.39 *** (43.98)	2.51 *** (38.79)	2.05 *** (11.11)
Infra	0.24 *** (25.65)	0.27 *** (26.72)	0.21 *** (10.34)
ln_Digital_Talent	0.00 (0.31)	0.00 (0.41)	0.00 (0.25)
Constant	−0.13 *** (−6.86)	−0.151 *** (−7.34)	−0.11 (−4.71)
N	341	341	341
Province fixed effects	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes
R ²	0.97	0.96	0.97
The results of the mediation effect test			
Sobel test(Z)		5.34 ***	
Bootstrap test (ACME)		0.06	
Bootstrap 95% CI		[0.01, 0.10]	
Proportion of mediation effect		16.39%	

Note: t-values are reported in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The Sobel test was calculated using the sgmediation command, while the bootstrap test was conducted using the medeff command with 1000 resamples. The latter additionally controlled for province and year fixed effects, and the confidence intervals were constructed using the bias-corrected method. Source: Author's calculations based on panel data from 31 Chinese provinces from 2015 to 2025, using Stata.

Model 1 in Table 11 is the total-effect model verified above, in which the coefficient of REG on Resilience is 0.34 ($p < 0.01$). Model 2 examines the effect of regulation on the mediating variable, Balance. The results show that the coefficient of REG is 0.43 and is highly significant at the 1% level. This indicates that a well-developed cross-border data flow regulatory system can effectively optimize provincial data governance systems and promote a high-level dynamic balance between data flow efficiency and security risk control.

Model 3 simultaneously incorporates the core explanatory variable, REG, and the mediating variable, Balance, into the regression equation. The results show that the coefficient of the mediating variable Balance on industrial chain resilience is 0.13 and is highly significant at the 10% level. Meanwhile, the coefficient of the core explanatory variable REG decreases from 0.34 in Model 1 to 0.29. According to the calculation logic of the mediation effect, the absolute size of the mediation effect is $\beta_1 \times \gamma_2$, namely $0.43 \times 0.13 = 0.1333$. This mediation effect accounts for as much as 39.21% of the total effect.

Furthermore, this study employs the Sobel test to precisely assess the significance of the indirect effect. The results show that the indirect effect is 0.12, with a Sobel Z-statistic of 5.34, and is highly significant at the 1% level. Considering that the Sobel test relies on the normality assumption and may be biased in small samples, this study further employs the bootstrap method to conduct robust inference on the mediating effect while controlling for two-way fixed effects of province and year. The bootstrap test results show that the estimated average causal mediation effect is 0.06, with a bias-corrected 95% confidence interval of [0.01, 0.10]. Since this confidence interval does not include zero, the indirect effect remains significant at the 5% level. At this stage, the direct effect is 0.29, the total effect is 0.34, and the mediating effect accounts for 16.39% of the total effect. Taken together, the results of both the Sobel test and the bootstrap test show that the indirect effect reaches

statistical significance, confirming that Balance plays a significant partial mediating role in the relationship between REG and TRes.

This empirical result reveals the transmission mechanism underlying regulatory policy: nearly third of the positive effect of cross-border data flow regulation on industrial chain resilience is achieved by promoting the balance between efficiency and security. Neither excessive defensive control nor disorderly laissez-faire can maximize policy effectiveness. Only through refined institutional design that safeguards the national data security baseline while maximizing the circulation vitality of data elements can regulatory policy be truly transformed into strong resilience for industrial chains to withstand shocks and achieve transformation and upgrading. Hypothesis 2 is therefore fully supported.

4.4. Regional Heterogeneity Analysis

Considering the substantial spatial imbalance among Chinese provinces in terms of resource endowments, industrial foundations, and degrees of openness, full-sample regression may mask the heterogeneity of regulatory effects. Therefore, this study partitions the 30 provincial samples into two groups based on whether each province's digital economy development index exceeds the full-sample mean: the high-digital-economy group and the low-digital-economy group. The level of digital economy development is closely related to the regional distribution in China. To further verify whether the heterogeneity results based on the division of digital economy development levels are robust, this study divides the 31 provinces into three subsamples—eastern China, central and western China, and conduct supplementary heterogeneity tests. Tables 12 and 13 report the results of the heterogeneity tests based on digital-economy-level and regional classification, respectively.

Table 12. Regression results of regional heterogeneity.

Variable	High Digital Economy	Low Digital Economy
REG	0.38 *** (16.22)	0.32 *** (25.96)
DSTRI	−0.12 *** (−6.23)	−0.11 *** (−10.23)
GDTFI	−0.15 *** (10.56)	−0.15 *** (11.61)
Digital	0.35 *** (8.83)	0.25 *** (6.14)
Infra	0.23 *** (11.69)	0.25 *** (16.80)
R&D	2.43 *** (29.42)	2.34 *** (28.16)
ln_Digital_Talent	−0.00 (−0.00)	0.00 (0.18)
R ²	0.96	0.97
N	150	191

Note: t-values are reported in parentheses; *** $p < 0.01$. Source: Author's calculations based on panel data from 31 Chinese provinces from 2015 to 2025, using Stata.

Table 13. Regression results of digital economy development index.

Variable	Eastern Provinces	Central and Western Provinces	Northeastern Provinces
REG	0.41 *** (21.66)	0.33 *** (23.60)	0.25 ** (18.78)
DSTRI	−0.12 *** (−11.45)	−0.11 *** (−9.10)	−0.13 *** (−13.41)
GDTFI	0.16 *** (8.78)	0.15 *** (9.82)	0.14 *** (4.99)
Digital	0.33 *** (9.22)	0.34 *** (23.25)	0.29 *** (6.68)
Infra	0.23 *** (13.83)	0.26 *** (21.17)	0.20 *** (10.24)
R&D	2.22 *** (32.30)	2.49 *** (37.04)	2.41 ** (19.00)
ln_Digital_Talent	−0.00 (−0.11)	0.00 (0.09)	−0.02 (−1.12)
R ²	0.97	0.98	0.97
N	121	165	55

Note: t-values are reported in parentheses; *** $p < 0.01$, ** $p < 0.05$. Source: Author's calculations based on panel data from 31 Chinese provinces from 2015 to 2025, using Stata.

The results in Table 12 clearly demonstrate the heterogeneity of regulatory effects across different levels of digital economy development. The coefficient of REG is higher in provinces whose digital economy development index exceeds the sample mean than in provinces at or below the sample mean.

Specifically, Provinces with stronger digital economic foundations exhibit greater capabilities in data element allocation, local legislative capacity, and international rule coordination, which enables them to more effectively leverage regulatory policies to reduce transaction costs, regulate data flows, and promote collaborative innovation. They can be rapidly transformed into practical effects, such as reducing transaction costs and stimulating innovation vitality. As a result, their positive effect on industrial chain resilience is the strongest. In contrast, provinces at a lower stage of digital economy development tend to have a weaker positive impact on industrial chain resilience, primarily because their relatively inadequate digital infrastructure and enterprise digital capabilities impede the effective transmission of regulatory policies.

The results in Table 11 clearly outline the regional gradient pattern of regulatory effects. The coefficient of REG is the highest for eastern provinces, followed by central and western provinces, and is the lowest for northeastern provinces. This gradient pattern is highly consistent with the spatial distribution of digital economy development levels across regions, preliminarily indicating that digital infrastructure conditions play a key moderating role in the transmission of regulatory policy effects.

Specifically, eastern provinces, such as Guangdong, Shanghai, and Zhejiang, have a highly developed digital economy foundation, and their core industrial chains are deeply embedded in global value chains. These regions have substantial demand for the timeliness and scale of cross-border data flows. They also possess relatively strong local legislative authority and international rule-coordination capacity, enabling them to take the lead in institutional innovation. Therefore, regulatory policies in eastern China can be rapidly transformed into practical effects, such as reducing transaction costs and stimulating innovation vitality. As a result, their positive effect on industrial chain resilience is the strongest.

Central and western provinces, such as Guizhou and Sichuan, are in a stage of accelerated digital economy development. Their core industrial chains are mostly supported by cross-regional computing power dispatch projects or specific industrial Internet scenarios. In these regions, regulatory policies mainly function to strengthen the security baseline and standardize the allocation of computing power resources, producing a significant effect in improving industrial chain resistance. However, due to relatively weak international coordination capacity and limited industrial-chain extension, their overall enabling effect remains moderate.

Northeastern provinces have experienced relatively delayed digital economy transformation, with lower digital infrastructure density and insufficient enterprise digital transformation and R&D investment. In the absence of adequate industrial foundations and technological support, strict cross-border data flow regulation often turns into a heavy compliance cost burden, thereby obstructing policy transmission.

Consequently, the results of the heterogeneity analysis fully support Hypothesis 3. Its positive effect on industrial chain resilience is the weakest in these provinces. The results of the regional heterogeneity analysis fully support Hypothesis 3. Only with a sound digital economy foundation can the enabling effect of regulatory policies on industrial chain resilience be fully realized. This finding provides important empirical evidence for tailoring regulatory policies to local conditions and implementing digital governance in a differentiated manner.

4.5. Robustness Tests

To ensure the reliability of the empirical results, this study conducts robustness tests using the following methods, as shown in Table 14.

Table 14. Robustness test results.

Robustness Test Method	Proportion of Mediating Effect (%)	Coefficient of the Mediating Variable	Significance
Baseline regression (original indicators)	39.21	0.13	*
Transformed regression model (OLS)	34.28	0.28	***
Replacement of the mediating variable indicator	39.52	0.30	***
Exclusion of outliers	34.08	0.29	***
One-period lag of the explanatory variable	32.36	0.69	***

Source: *** $p < 0.01$, * $p < 0.1$. Author's calculations based on panel data from 31 Chinese provinces from 2015 to 2025, using Stata.

Change the estimation method: To avoid bias caused by a single estimation method, this study re-estimated the regression model using the OLS method. The results showed that the coefficient of the mediating variable was significantly positive at the 1% level, and the mediating effect accounted for 34.28%, which was consistent with the baseline results.

Replacement of the mediating variable indicator: To prevent bias arising from a single measurement method, this study replaces the original coordination-degree balance index with the “ratio between the growth rate of data flow efficiency and the growth rate of security incidents” and re-estimates the regression. The results show that the coefficient of the mediating variable remains significantly positive at the 1% level, and the proportion of the mediating effect is 39.52%, which is highly consistent with the baseline results.

Exclusion of outliers: To eliminate the distortion effect of extreme observations on the fitted regression curve, this study conducts winsorization on the top and bottom 1% of the samples for the industrial chain resilience index and regulatory intensity. After excluding outliers, the core conclusion remains substantially unchanged, with the proportion of the mediating effect remaining stable at 34.08%.

One-period lag of the explanatory variable: Considering that there may be a time lag between the implementation of macro-level regulatory policies and their transmission to micro-level industrial chains, this study includes the one-period lag of the core explanatory variable (REG) in the model. The results show that lagged regulatory intensity still has a significant positive effect on current industrial chain resilience, with the proportion of the mediating effect reaching 32.36%. This effectively alleviates endogeneity concerns arising from reverse causality.

Instrumental variable method: To further address potential endogeneity problems caused by omitted variables and bidirectional causality, this study selects the “number of provincial data security enforcement personnel” and the “number of national data security pilot cities” as instrumental variables for regulatory intensity and conducts a two-stage least squares regression. The rationale is that these two variables directly reflect national and local regulatory inputs and policy support for data security, and are therefore highly correlated with regulatory intensity. At the same time, the staffing of enforcement personnel and the allocation of national pilot-city quotas are exogenous administrative arrangements, which do not directly affect specific industrial chain resilience through channels other than regulation. The regression results show that, after the first-stage F-test rules out the problem of weak instruments, the coefficient of REG in the second stage is 0.34, which is very close to the baseline regression result and remains highly significant.

Taken together, the above four rigorous robustness tests demonstrate that the core empirical conclusion of this study—that cross-border data flow regulation significantly

enhances industrial chain resilience by optimizing the balance between efficiency and security—is highly robust and reliable.

4.6. fsQCA Pathways Through Which Cross-Border Data Flow Regulation Enhances Industrial Chain Resilience

Traditional regression analysis focuses on the net effect of a single variable and is therefore limited in revealing the complex interactions among multiple antecedent conditions. The choice of fuzzy-set qualitative comparative analysis (fsQCA) is grounded in a rapidly expanding body of governance research that employs configurational methods to unpack complex causal architectures. This study takes “high-resilience provinces” as the outcome variable, and selects five conditional variables: regulatory improvement (C1), infrastructure (C2), innovation investment (C3), digital trade (C4), and industrial adaptation (C5). It then explores the configurational pathways that drive high resilience.

4.6.1. Necessity Analysis

First, each single condition is tested to determine whether it constitutes a necessary condition for “high resilience.” The threshold adopted here is consistency ≥ 0.9 (see Table 15).

Table 15. Necessity analysis result.

Conditional Variable	Consistency	Coverage	Conclusion
C1 (regulatory improvement)	0.87	0.78	Not a necessary condition
C2 (infrastructure)	0.85	0.75	Not a necessary condition
C3 (innovation investment)	0.89	0.81	Not a necessary condition
C4 (digital trade)	0.82	0.72	Not a necessary condition
C5 (industrial adaptation)	0.84	0.74	Not a necessary condition

Source: Author’s calculations based on panel data from 31 Chinese provinces from 2015 to 2025, using Stata.

The results clearly show that no single condition satisfies the necessity criterion (see Table 15). This indicates that the achievement of high resilience depends on the synergistic interaction of multiple conditions, which is consistent with the logic of multiple conjunctural causation.

4.6.2. Sufficiency Analysis and Configurational Pathways

The fsQCA 3.0 software is used to identify four core configurational pathways that drive high-resilience provinces, as shown in Table 16.

Table 16. Sufficiency analysis.

Path No.	Conditional Configuration (Core Condition ●/Peripheral Condition ○)	Consistency	Number of Cases	Typical Cases
Path 1	C1● + C3● + C4● + C5○	0.92	8	Guangdong, Shanghai, Beijing
Path 2	C1● + C2● + C5● + C3○	0.89	6	Guizhou, Jiangsu, Chongqing
Path 3	C2● + C3● + C4● + C1○	0.87	5	Zhejiang, Fujian, Anhui
Path 4	C1● + C2● + C3● + C4○	0.85	4	Shandong, Sichuan, Hubei

Source: Author’s calculations based on panel data from 31 Chinese provinces from 2015 to 2025, using Stata.

Path 1: The core *conditions* include regulatory improvement, high innovation investment, and digital trade facilitation, while industrial adaptation serves as a peripheral condition. Typical cases include Guangdong and Shanghai. Provinces following this pathway achieve high resilience by relying on well-developed cross-border data regulation, high R&D investment, and facilitated digital trade. This pathway is consistent with the

“compliance + innovation + trade synergy” model proposed in Deloitte’s Digital Economy Compliance White Paper 2023.

Path 2: The core conditions include regulatory improvement, sound infrastructure, and industrial adaptation, while innovation investment serves as a peripheral condition. Typical cases include Guizhou and Jiangsu. Guizhou relies on computing power hub infrastructure and regulation adapted to the computing power industry, whereas Jiangsu relies on industrial Internet infrastructure and regulation adapted to industrial data. This confirms the significance of the “infrastructure + industrial adaptation” model discussed in the IDEA Research Institute’s Low-Altitude Economy White Paper.

Path 3: The core conditions include sound infrastructure, high innovation investment, and digital trade facilitation, while regulation serves as a peripheral condition. Typical cases include Zhejiang and Fujian. Zhejiang relies on digital trade infrastructure and high innovation investment, while Fujian benefits from maritime digital trade channels. In this pathway, regulation functions only as a peripheral condition, indicating that infrastructure and innovation can, to some extent, compensate for deficiencies in regulation.

Path 4: The core conditions include regulatory improvement, sound infrastructure, and high innovation investment, while digital trade serves as a peripheral condition. Typical cases include Shandong and Sichuan. Shandong relies on industrial Internet infrastructure and high R&D investment, whereas Sichuan relies on data security infrastructure. Digital trade functions only as a peripheral condition in this pathway, making it suitable for inland provinces with distinctive digital industry characteristics.

The robustness of these pathways is verified using the following approaches. First, the crossover point is adjusted from the 50th percentile to the 45th percentile, and the core pathways remain unchanged. Second, pathways with only one case are removed, and the remaining four core pathways are retained. Third, the outcome variable is replaced with “high-transformation-capacity provinces,” and the core pathways remain robust. These results demonstrate the robustness of the conclusions.

4.7. Integrating Regression and fsQCA Findings

This subsection therefore integrates the two sets of results along three dimensions: (1) the correspondence between the four configurational pathways identified in the fsQCA and the differences in the level of digital economic development captured in the heterogeneity regression; (2) the mechanism-level triangulation between the mediation channel and the core–peripheral condition structure; (3) the methodological complementarity that allows the two approaches to jointly generate a more complete causal account of industrial-chain resilience under cross-border data flow regulation.

First, the configurational pathways identified through fsQCA map with striking regularity onto the regional heterogeneity documented in Table 13. However, such regional differences are not determined merely by geographic location; rather, they are driven by differences in the level of digital economy development across regions. The REG coefficient is largest in the eastern provinces ($\beta = 0.41, p < 0.01$). These provinces cluster mainly on Path 1 ($C1 \cdot C3 \cdot C4 \cdot c5$) and Path 3 ($C2 \cdot C3 \cdot C4 \cdot c1$). The typical cases for Path 1 are Guangdong, Shanghai, and Beijing. The typical cases for Path 3 are Zhejiang, Fujian, and Anhui. What these two pathways share is that innovation investment (C3) and digital-trade facilitation (C4) both enter as core conditions, while infrastructure or regulation play only a supporting role. This configurational signature is fully consistent with the interpretation offered by the eastern-region regression. The fsQCA results further validate the conclusions of Tables 12 and 13 from a set-theoretic perspective.

By contrast, the central and western provinces, whose REG coefficient is more moderate ($\beta = 0.33, p < 0.01$), correspond most closely to Path 2 ($C1 \cdot C2 \cdot C5 \cdot c3$) and Path 4

(C1 · C2 · C3 · c4), whose typical cases are Guizhou, Jiangsu, and Chongqing on the one hand, and Shandong, Sichuan, and Hubei on the other. In both pathways, infrastructure (C2) rises to a core condition, while digital trade or innovation investment recedes to a peripheral role. This indicates that, for regions with relatively low levels of digital economy development or those still in the catch-up stage, the positive effect of regulatory policies depends more on infrastructure development and industrial adaptability, rather than being directly released through innovation investment and cross-border digital trade capabilities. Therefore, fsQCA has confirmed the existence of an "infrastructure-driven" resilience mechanism in the mainland.

The northeastern provinces, in turn, exhibit the weakest regression coefficient ($\beta = 0.25$, $p < 0.05$) and are conspicuously absent from the typical cases listed under any of the four sufficient configurations. This absence is itself analytically informative: it indicates that no combination of the five conditions is currently assembled at levels sufficient to place northeastern provinces in the outcome set of high-resilience cases. The regression results and the fsQCA results therefore lead to the same substantive conclusion. Regression analysis detects only a modest average marginal effect. In contrast, fsQCA reveals that infrastructure, innovation, digital trade and regulatory capacity are the key elements that a feasible configuration relies on. This cross-method convergence reinforces the credibility of Hypothesis 3.

Second, the two methods jointly clarify the transmission mechanism. The mediation analysis (Table 10) established that approximately 53.12% of the total effect of regulation on resilience runs through the efficiency–security balance. The fsQCA adds set-theoretic content to this finding by showing that regulatory improvement (C1) never appears as a solitary sufficient condition; in every observed pathway it is embedded in a conjunction with either innovation and trade conditions (Paths 1 and 4) or infrastructure and industrial-adaptation conditions (Path 2). This configurational fact operationalizes, at the case level, the mediation logic already estimated at the population level: regulation exerts its resilience-enhancing effect not autonomously but by conditioning, and being conditioned by, other elements of the provincial data-governance ecosystem. Path 3, in which regulation is only a peripheral condition, further specifies a substitution boundary that the mediation model cannot detect—namely, that a sufficiently strong combination of infrastructure, innovation, and digital trade can partially compensate for a weaker regulatory regime, the finding that is invisible to a linear-additive estimator.

Third, the two methods are complementary in a deeper epistemological sense. Two-way fixed-effects regression analysis is variable-oriented; it estimates the net effect of cross-border data flow regulation on industrial chain resilience after controlling for other covariates, and quantifies the proportion of this effect transmitted through mediating channels. However, this approach implicitly assumes that relationships are linear, additive, and homogeneous across observations, with regional heterogeneity captured only through sample splitting or interaction terms. In contrast, fsQCA is case-oriented and follows a logic of multiple conjunctural causation. Rather than isolating the net effect of a single condition, it identifies multiple equifinal configurations of conditions that are jointly sufficient for producing the outcome. Read together, the regressions answer the question “how much, on average, does cross-border data flow regulation raise industrial-chain resilience?” while the fsQCA answers the question “through which combinations of conditions, and in which types of provinces, does that average effect actually materialize?” The value of jointly deploying them lies in the extent to which their findings converge, diverge, and mutually inform one another.

Taken together, the two methods yield a policy implication that neither could sustain in isolation. Because the average effect is positive and robust, a uniform strengthening of cross-

border data flow regulation is defensible as a baseline national strategy. However, because the pathways through which that effect is realized are region-specific, effective implementation requires differentiated policy design: an innovation- and trade-facilitation package for eastern provinces consistent with Paths 1 and 3; an infrastructure- and industrial-adaptation package for central and western provinces consistent with Paths 2 and 4; and, for the northeastern provinces, a foundational program that simultaneously builds the infrastructure, innovation, and trade capacities that are currently missing from any sufficient configuration. In this way, the joint use of regression and fsQCA moves the analysis from the identification of an average causal effect to the specification of the region-specific configurational conditions under which that effect can be reproduced.

4.8. Comparison with Previous Studies

The empirical findings of this study engage in a systematic dialogue with the existing literature, both corroborating and advancing prior research.

First, with respect to the overall positive effect of cross-border data flow regulation on industrial chain resilience, this study finds that, after controlling for other macro-level factors and spatiotemporal fixed effects, a 0.1-unit increase in the provincial cross-border data flow regulation index leads to a significant increase of 0.032 units in the comprehensive resilience score of the province's core digital economy industrial chains. This directional finding is consistent with Yu's (2024) conclusion, based on the OECD DSTRI, that moderate digital trade regulation can significantly enhance manufacturing firms' positions in global value chains [73], and also echoes Liu's (2026) assertion that cross-border data regulation constitutes the institutional infrastructure of digital trade [74]. Cheng et al. (2025) found that cross-border data flow restrictions significantly inhibit the upgrading of China's manufacturing GVC position [75], whereas our study identifies a significantly positive effect of REG on industrial chain resilience. This divergence essentially stems from the different operationalization of regulation across the two studies: the former measures restriction intensity, whereas the latter measures institutional completeness. Thus, the opposing directional findings do not constitute a substantive contradiction; rather, they collectively support the policy orientation that "rule-based regulation is superior to both indiscriminate tightening and disorderly deregulation." Meanwhile, based on provincial-level panel data from China, this study provides complementary evidence at the subnational level to the finding by Ding et al. (2026) that, drawing on a sample of 55 countries, digital services trade barriers weaken GVC resilience [76].

Second, with respect to the mediating role of the "balance between efficiency and security," this study estimates that the mediation effect accounts for 39.21% of the total effect. This result translates the normative proposition of "promoting safe and orderly cross-border data flows" first advanced by Hong and Zhang (2022) [77], as well as the theoretical argument concerning the "open-protection equilibrium under institutional fragmentation" put forward by Rong et al. (2026) [78], into empirically estimable and decomposable parameters. Moreover, our approach to constructing the mediating variable maintains methodological consistency with Ma (2025), who employs data factor endowment as a mediating channel [79].

With respect to regional heterogeneity, the "eastern–central–western–northeastern" declining gradient pattern identified in this study is consistent with the findings of Huang (2024) based on provincial panel data from 30 provinces over 2000–2022 [80], the evidence of geographic heterogeneity in regional digital economy development presented by Li (2023) [81], and the research on digital economy spillover effects across the eight major comprehensive economic zones by Xia et al. (2025) [82]. This study further treats Northeast China separately and interprets its distinct pattern through the mechanism of

“weak digital infrastructure–compliance cost crowding-out,” thereby supplementing the lower-end boundary condition for the existing gradient-decreasing model.

With respect to the fsQCA configurational path analysis, the four concurrent paths identified in this study are consistent with the methodological consensus of Kumar et al. (2022) that fsQCA is suitable for depicting multiple conjunctural causation in digital transformation [83], as well as with the equifinal conclusions derived from SEM + fsQCA by Jiang et al. (2025) [84].

Taken together, This study may make progress in the following aspects:

First, this study is the first to construct a REG index at the provincial level in China and to directly link it to the dependent variable of “resilience of core digital economy industrial chains,” thereby filling the gap in the existing literature, which predominantly relies on cross-country panel data and takes GVC position or export quality as the dependent variable.

Second, this study transforms the “efficiency–security balance” from a normative discussion into an estimable mediating variable, and quantitatively reveals the transmission pathway through which nearly one third of the policy effect is channeled.

Third, this study finds that regulatory effects are heterogeneous across regions with different levels of digital economic development, and this is supported by the regional gradient characteristics of the regulatory effects. This is of great significance for the design of differentiated policies in different regions.

Fourth, employing fsQCA, this study validates that the achievement of high resilience depends on the synergistic interaction of multiple conditions, and further reveals that regulation is not the sole necessary condition, as infrastructure and innovation investment can serve as substitutes under certain configurations, thereby shifting the analytical lens from a single net effect perspective to a multiple conjunctural causation perspective.

5. Conclusions and Policy Recommendations

5.1. Research Conclusions

1. Cross-border data flow regulation has a significant positive effect on enhancing the resilience of core digital economy industrial chains. This conclusion fully confirms that scientifically designed, rational, and refined cross-border data flow regulation is not merely an administrative constraint, but an institutional safeguard that can effectively reduce institutional transaction costs and standardize the allocation order of data elements. By providing standardized compliance guidance and clear legal expectations, the regulatory system can significantly strengthen the resistance, recovery capacity, transformation capacity, penetration capacity, value-added capacity, and upgrading capacity of industrial chains when facing external geopolitical competition and supply chain disruption risks.

2. The balance between efficiency and security plays a key mediating role in the process through which regulation affects industrial chain resilience. A purely defensive and restrictive approach would obstruct the circulation of data elements, sharply increase enterprises’ compliance costs, and thereby suppress the innovation vitality of industrial chains. Conversely, disorderly laissez-faire would trigger systemic risks of data leakage and undermine the stable operation of industrial chains. Only by safeguarding the national data security baseline while maximizing the circulation efficiency of data elements can macro-level regulatory policies be truly transformed into strong resilience at the micro-level industrial chain.

3. The regulatory effect exhibits significant regional heterogeneity, following a gradient pattern in which the effect is stronger in eastern China than in central and western China, and weakest in northeastern China. Eastern coastal provinces have a solid digital economy foundation and strong capacity for international rule coordination. Regulatory policies in these regions can be rapidly transformed into practical effects, such as reducing transaction

costs and stimulating innovation vitality, and therefore exert the strongest positive effect. Central and western provinces are in a period of accelerated digital economy cultivation. Regulatory policies have significant effects in strengthening the security baseline and standardizing resource allocation, but their overall enabling effect remains moderate due to limited international coordination capacity. Northeastern provinces are constrained by weak digital infrastructure and insufficient innovation investment. In these regions, strict regulation often becomes a heavy compliance cost burden, obstructing policy transmission and resulting in the weakest positive effect.

4. The realization of high industrial chain resilience does not depend on a single factor, but results from the synergistic interaction of multiple elements, including regulatory improvement, infrastructure, innovation investment, digital trade, and industrial adaptation. The fuzzy-set qualitative comparative analysis reveals four equivalent configurational pathways: the regulation–innovation–trade-driven pathway, the regulation–infrastructure–industry-driven pathway, the infrastructure–innovation–trade-driven pathway, and the regulation–infrastructure–innovation-driven pathway. This conclusion confirms that enhancing the resilience of core digital economy industrial chains is a complex systemic project. Policy stimulus from a single dimension is unlikely to achieve optimal results; instead, coordinated interaction among multiple antecedent conditions is required.

5.2. Policy Recommendations

1. The construction of the cross-border data flow regulatory system should be firmly advanced to consolidate the institutional foundation of industrial chain resilience. In light of the finding that regulation has a significant positive effect, both national and local governments should continue to improve the top-level design and supporting implementation rules for cross-border data flows. First, implementation guidelines for data classification and graded protection should be accelerated and refined, with clear boundaries among core data, important data, and general data. This would provide enterprises with clear and operable compliance guidance, thereby reducing trial-and-error costs and repeated assessment expenses arising from ambiguous rules. Second, a full-life-cycle compliance service system should be established. Local governments and industry associations should be encouraged to take the lead in building provincial public compliance service platforms, providing standardized outbound data filing templates and legal consulting services for digital economy enterprises, especially small, medium-sized, and micro enterprises. Finally, the transparency and predictability of regulatory policies should be strengthened. Institutional fragmentation across departments and regions should be eliminated, and stable institutional expectations should be used to reduce uncertainty in industrial chain operations and comprehensively improve enterprises' adaptability amid global market fluctuations.

2. A governance mechanism that dynamically balances efficiency and security should be established to smooth the transmission channel of regulatory policies. Given the key mediating role of the balance between efficiency and security, policymaking should firmly avoid extreme approaches and seek a dynamic optimum. On the one hand, to improve data flow efficiency, national cyberspace authorities and relevant regulatory agencies should expand the coverage of compliance exemption licensing catalogues for low-risk business data, such as general order data in cross-border e-commerce and non-sensitive enterprise operational data. A regulatory model combining filing-based administration with ex post random inspections should be fully implemented to substantially shorten enterprises' compliance approval cycles. On the other hand, to strengthen the security defense line, a nationally unified dynamic monitoring network for cross-border data security should be established. Advanced compliance technologies, such as privacy-preserving computing and federated learning, should be used to provide real-time warnings and full-process

traceability for abnormal transmission behavior while ensuring that data are usable but not visible. In addition, provincial efficiency–security balance indices should be released regularly to dynamically correct tendencies toward excessive regulation or regulatory absence in local implementation, thereby maximizing regulatory effectiveness.

3. Differentiated provincial regulatory optimization pathways should be implemented to address digital economy development imbalances. In response to the regional heterogeneity of regulatory effects, undifferentiated nationwide regulation should be firmly avoided, and precise classified guidance should be adopted. For the provinces with a high level of digital economic development, greater institutional exploration authority should be granted. These provinces should be encouraged to establish cross-border data innovation-tolerant testing mechanisms within pilot free trade zones, allowing enterprises to conduct frontier business testing in controlled environments. They should also be supported in benchmarking against high-standard international digital trade rules and concentrating resources on overcoming bottlenecks in key core technologies. For the provinces with a low level of digital economic development, the focus should be placed on deep industrial adaptation and cross-regional coordination. Relying on cross-regional computing power dispatch projects, these provinces should formulate classified and graded management measures for computing power data, promote cross-regional data-sharing mechanisms, break down data silos between governments and enterprises, and establish industrial data alliances. Special provincial fiscal funds should be established to reduce or subsidize expenses related to third-party security audits and compliance certification for digital economy enterprises, thereby easing transformation pressure and focusing policy efforts on basic compliance capacity building.

4. A multi-factor coordinated policy system should be developed to broaden the configurational pathways for enhancing industrial chain resilience. In response to the multiple conjunctural causation underlying the realization of high resilience, governments at all levels and enterprises should strengthen overall planning and implement coordinated policy packages. First, the evolution and upgrading of digital infrastructure should be accelerated. Greater investment should be directed toward fifth-generation mobile communication technology base stations, large-scale data centers, and dedicated channels for cross-border data transmission, so as to address weaknesses in the physical foundation and provide hardware support for the efficient circulation of data. Second, the role of enterprises as the main actors of innovation should be strengthened. Fiscal instruments such as tax incentives and R&D subsidies should be used to encourage digital economy enterprises to increase R&D investment in core technologies, particularly in compliance technologies such as encrypted transmission and data desensitization, thereby offsetting compliance costs through technological innovation. Third, digital trade facilitation reform should be deepened. Customs clearance and settlement processes in areas such as cross-border e-commerce and digital content services should be optimized, and new forms of digital business should be cultivated and expanded. Fourth, deep adaptation between regulation and industry should be strengthened. Policymakers should conduct in-depth investigations into the actual data needs and risk characteristics of local core industrial chains, tailor data governance solutions accordingly, and ensure that macro-level regulatory policies, meso-level industrial layouts, and micro-level enterprise innovation move in synergy, jointly driving the core industrial chains of the digital economy toward a higher level of resilience.

5.3. Limitations and Future Research

Although this study has yielded several findings, several limitations remain, which provide valuable directions for future research.

First, this study constructs a provincial-level Cross-Border DFRI. Although the selection of indicators is based on the ECIPE framework and adjusted to reflect the institutional characteristics of different provinces, the choice of indicators itself reflects the researchers' conceptual understanding of "regulatory completeness." Therefore, decisions regarding which dimensions should be included and how they should be weighted inevitably involve a degree of subjective judgment. The entropy weight method mitigates but does not eliminate this concern.

Second, the mediating variable 'efficiency and security balance' in this study has a certain conceptual connection with the core independent variable "cross-border data flow regulation." Since the regulatory policies themselves are designed to balance efficiency and safety goals, the mediating variable may, to a certain extent, be regarded as an endogenous factor within the regulatory framework rather than functioning as an independent transmission channel. Although the entropy method and the coordination degree model were used to enhance the independence of the two constructs, and the Sobel and bootstrap tests confirmed the statistical significance of the indirect effect, this potential overlap may to some extent affect the estimation of the mediating effect.

Third, although the panel data selected for the empirical analysis of this study comprehensively covered all provincial regions of China, there are still some limitations related to the scope of the research. On the one hand, the fsQCA pathways identified in this study are based on provincial-level averages and may therefore not fully capture configurational dynamics at the city or county level. On the other hand, countries differ substantially in their data governance systems, levels of digital economic development, and supply chain management models. These differences may affect the mechanisms and effects through which regulation influences industrial chain resilience, thereby limiting the generalizability of the findings to other institutional contexts.

In summary, future research should pursue three complementary avenues: First, it should further improve the measurement of the DFRI, refine the sample granularity, and incorporate granular data on regulatory implementation at the city or firm level. Second, future research should identify more independent mediating variables in order to further validate the conclusions of this study. Third, by conducting cross-national comparative studies using a unified regulatory index and resilience indicators, the external validity and generalizability of the findings can be improved.

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