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SPECIAL ISSUE PAPER

Enhancing the resilience of regional digital innovation ecosystems: a pathway analysis from the lens of resource orchestration theory

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Abstract
Enhancing the resilience of regional digital innovation ecosystems represents an effective strategy for managing risky shocks and fostering sustainable regional development. This study investigates the regional digital innovation ecosystems in 30 provinces and cities across China. Grounded in resource orchestration theory, this research employs the fsQCA method to examine the configuration paths through which traditional and digital resources and capabilities contribute to the resilience of these ecosystems. By developing an evaluative framework for the resilience of regional digital innovation ecosystems, this study reveals a fluctuating upward trend in resilience across China's regions, albeit with slow improvement rates and uneven development. The fsQCA identifies six configurational paths that bolster ecosystem resilience, categorized into two types: Technology Innovation-Digital Platforms and Financial-Physical Dominant. Furthermore, the paper highlights insufficient technological innovation capacity and imperfect digital governance as critical barriers to strengthening the resilience of regional digital innovation ecosystems. This research improves the evaluative framework for resilience in regional digital innovation ecosystems and extends the application of resource orchestration theory to the domain of resilience. The findings offer significant theoretical and practical insights into how regions can utilize both traditional and digital resources and capabilities to reinforce the resilience of their digital innovation ecosystems.

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1 Introduction

The rapid development and widespread application of digital technologies profoundly transform the patterns and pathways of regional innovation. Regional innovation activities are increasingly characterized by digitalization, ecological integration, and networked features (Cooke 2017). Regional digital innovation ecosystems, formed through the co-evolution of various innovation actors, are emerging as new drivers of regional innovation and economic development. A regional digital innovation ecosystem refers to a complex dynamic system within a specific regional scope, where digital innovation actors engage in efficient, cross-spatial, and cross-boundary interactions on digital innovation platforms centered around digital infrastructure (Li and Rao 2023). Compared to traditional regional innovation ecosystems, regional digital innovation ecosystems demonstrate stronger heterogeneity in their actors and resources, significantly enhancing their impact on regional innovation development (Yang et al. 2022a, b). However, as the economic environment transitions into the VUCA (volatility, uncertainty, complexity, ambiguity) era, regional digital innovation ecosystems face significant challenges. These ecosystems are impacted not only by "black swan" events, like natural disasters such as earthquakes and tsunamis, but also by "gray rhinoceros" events, including trade frictions and geopolitical conflicts (Zhang et al. 2024). Under multiple pressures, the vulnerability and instability of regional digital innovation ecosystems are becoming increasingly prominent, urgently requiring policymakers to take effective measures to promote their sustainable development.

In the current context, resilience theory provides a novel perspective for the continued evolution and healthy development of regional digital innovation ecosystems. The concept of resilience originated in physics, referring to a material's ability to rebound, bounce back, and recover when subjected to deformation forces, expressed as resistance to breakage (Holling 1996). Subsequently, scholars have expanded the application of resilience to various fields, such as ecology (Brand 2009), economics (Martin et al. 2016), management (Khurana et al. 2022), and psychology (Troy et al. 2023), enriching and deepening the connotations of resilience theory. With the burgeoning interest in resilience theory within regional studies and the rapid growth of the digital economy, scholars have begun to focus on regional digital innovation ecosystem resilience (RDIER). Chen and Cai (2023) defined RDIER as the ecosystem's ability to withstand shocks through multidimensional capabilities such as self-adaptation, self-learning, and self-adjustment, thereby improving the ecosystem's functional level. Yang et al. (2022a, b) constructed a regional digital innovation ecosystem resilience evaluation framework based on four dimensions—diversity, flowability, evolution, and buffering—and identified diverse governance methods to enhance ecosystem resilience. In general, research on RDIER remains nascent, mainly focusing on its conceptualization and evaluation. There is insufficient attention given to the antecedent conditions of RDIER, and few studies have dealt with the paths to enhance it. Given the practical challenges and research limitations outlined above, this paper primarily focuses on the core issue of how to enhance the RDIER. It aims to provide theoretical support and practical guidance for improving the resilience of these ecosystems and fostering regional innovation development.

Enhancing RDIER critically depends on supporting resources and capabilities, particularly the effective combination of various resources and capabilities. In the context of digitalization, traditional and digital resources and capabilities in regional digital innovation ecosystems are intertwined, jointly shaping the innovation capacity and resilience level of the ecosystem. On the one hand, the key resources that traditional regional innovation relies on, such as human resources, capital, and technology, face new challenges in allocation and integration in the digital era (Hervas-Oliver et al. 2021). On the other hand, digital resources and capabilities, such as data, computing power, and platforms, are gradually becoming new driving forces for regional innovation and development (Yi et al. 2023). Effectively utilizing and coordinating diverse and complementary resources to establish synergistic relationships between resources is crucial for enhancing the overall resilience of an ecosystem. Resource orchestration theory provides a useful perspective to address this issue. Resource orchestration theory emphasizes that an organization's dynamic management of resources is the source of its sustainable competitive advantage. Organizations can achieve new development goals and maintain a competitive edge by strategically forming combinations of resources and capabilities that match the environment's needs (Liu et al. 2016). The advent of the digital economy has transformed data into a new production factor for enterprises. Compared to traditional resources, changes in the attributes and value creation mechanisms of digital resources have inevitably led to an increase in the objects and scenarios of resource orchestration (Amit and Han 2017), creating greater space for research on resource orchestration. To enhance the RDIER, it is necessary to orchestrate traditional and digital resources and capabilities. However, the integration of resource orchestration theory and RDIER remains underexplored in existing research. Further discussion is needed to understand how to effectively utilize and synergize "traditional + digital" resources and capabilities to strengthen the RDIER.

In summary, based on the understanding and evaluation of RDIER, this paper summarizes the digital and traditional resources and capabilities that affect the RDIER from the perspective of resource orchestration theory. It focuses on identifying differentiated configuration paths that drive the improvement of RDIER to answer the core question of how to promote the improvement of RDIER. The research is specifically carried out around the following two aspects. First, this paper constructs an evaluation index system of RDIER across five dimensions: diversity, evolution, fluidity, buffering, and collaboration, and evaluates the RDIER in 30 provinces and cities in China. Second, based on resource orchestration theory, this paper explores four traditional resources and capabilities (human resources, financial resources, physical resources, and technological innovation capabilities) and three digital resources and capabilities (data resources, digital platforms, and digital governance) that affect the RDIER. Fuzzy-set qualitative comparative analysis (fsQCA) is employed to identify new combinations of "traditional + digital" resource and capability orchestration in the digital context, clarifying the multiple concurrent causal relationships and diverse configurational paths that promote the

RDIER. This study conducts an empirical investigation into the RDIER using panel data from 30 provinces and cities in China (excluding Hong Kong, Macau, Taiwan, and Tibet) from 2017 to 2021. The results reveal six paths that promote the RDIER, which can be categorized into two types: Technology Innovation-Digital Platform Driven and Financial-Physical Driven.

This paper makes several contributions. First, when exploring multidimensional evaluation systems for RDIER, existing research often fails to fully consider the importance of collaboration (Yang et al. 2022a, b; Chen and Cai 2023). Drawing upon open innovation theory, this study is the first to introduce collaboration into the evaluation system for RDIER. It focuses on the synergistic effects among government, industry, academia, and research within the ecosystem and their interactions with external innovation cooperation. This approach enriches and improves the existing evaluation frameworks for assessing the RDIER. Second, drawing upon resource orchestration theory, this paper considers four traditional resources and capabilities and introduces three digital resources and capabilities in the context of digitalization. It explores how to effectively orchestrate traditional and digital resources and capabilities to enhance the RDIER. This expands the cross-integration between resource orchestration theory and the resilience domain. Third, compared to traditional research that analyzes the RDIER from a single perspective (Chen and Cai 2023), this paper employs configurational thinking to clarify the differences in conditional configurations that enhance the RDIER and the underlying logical mechanisms. This approach not only enables each region to choose the most suitable development path according to its specific conditions but also responds to the academic community's call for adopting a configurational perspective and qualitative comparative analysis methods to study complex management systems (Roundy et al. 2018).

The remainder of the paper is organized as follows. Section 2 provides the literature review and research framework. Section 3 describes the research design. Section 4 analyzes the results of the data processing. Section 5 presents the research conclusions and policy implications.

2 Literature review and theoretical analysis

2.1 Concept and evaluation of RDIER

2.1.1 The concept of RDIER

Ecosystems originated in biology to describe the interactions between organisms and their environment (Pimm 1984; Jacobides et al. 2018). In contrast to general systems that emphasize the relationships and mechanisms among elements, ecosystems focus more on the system's organic nature, adaptability, and dynamic equilibrium (Pickett and Cadenasso 2002). Subsequently, scholars have increasingly applied the concept of ecosystems to domains such as business and innovation. Adner (2006) was among the first to articulate the innovation ecosystem concept, viewing it as a coherent, customer-oriented solution formed through collaborative arrangements among firms. Russell and Smorodinskaya (2018) further elaborated that innovation ecosystems are holistic and dynamic and exhibit characteristics typical of complex adaptive systems, such as emergence, synergy, self-organization, autonomy, and adaptiveness to changing environments. In recent years, the rapid advancement of digital technology has been transforming the structure and function of innovation ecosystems, leading to the emergence of digital innovation ecosystems (Suseno et al. 2018). As a subset of the innovation ecosystem, the digital innovation ecosystem places more emphasis on the collaborative symbiotic relationship between digital innovation entities, which results from the reorganization of element associations and changes in the logic of system behavior due to the introduction of digital elements (Beltagui et al. 2020; Theodoraki and Catanzaro 2022). Suseno et al. (2018) view digital innovation ecosystems from a value co-creation perspective, considering them as complex economic structures established by interacting organizations and individuals who jointly participate in creating new products and services using digital technologies. Yi et al. (2023) argue that the digital innovation ecosystem exhibits two forms. The first is an innovation-oriented digital ecosystem, centered around digital entities aimed at enhancing the generation, application, and diffusion of digital innovations. The second is a digitally empowered innovation ecosystem, resulting from the deep integration of digital processes and value creation among innovation actors. This integration facilitates the digital transformation of entities, structures, policies, functions, and their evolution within the ecosystem. These two forms are interdependent and mutually reinforcing.

Although digital technology facilitates global connections and resource integration within innovation ecosystems, the development of digital innovation ecosystems remains deeply embedded in regional contexts (Zhang et al. 2024). First, digital innovation activities rely heavily on various entities, including enterprises, universities, and research institutions. While digital technologies facilitate remote collaboration, regional embeddedness and geographic proximity offer many advantages (Keeble et al. 1998; Stathaki et al. 2020), such as convenient face-to-face communication, rapid feedback loops, and a stronger sense of community, which foster innovation. Moreover, despite the ability of digital technologies to transcend geographical boundaries, their application and commercialization often require integration with the economic, social, and cultural context of a specific region. Second, the construction of high-quality regional digital infrastructure can reduce the digitalization costs for innovation entities within a region and promote the flow and sharing of data, information, and knowledge (Hao and Zhang 2021), providing fertile ground for digital innovation. There are obvious differences in the development level of digital infrastructure in different regions, which leads to an imbalance in the development of regional digital innovation ecosystems (Yi et al. 2023). Finally, regarding the institutional environment, regional governments play a crucial role in fostering digital innovation ecosystems by providing policy support (Pistorio et al. 2018), which tends to be bounded by regional boundaries. Therefore, this paper focuses on the digital innovation ecosystem at the regional level, which, on the one hand, helps to reveal the regional embeddedness mechanism of digital innovation and to understand the unique ways in which the regional environment shapes the digital innovation ecosystem; on the other hand, the analysis of the regional digital innovation ecosystem also provides important insights into the formulation of innovation policies tailored to the local context and the optimization of the regional innovation governance. Regional digital innovation ecosystems are defined as complex, dynamic systems formed within a specific spatiotemporal scope. These ecosystems are influenced by the digital ecological environment and involve efficient cross-spatial and cross-boundary interactions and collaborations among digital innovation actors on digital innovation platforms centered around digital infrastructure (Li and Rao 2023).

Resilience has emerged as a focal point in management research, particularly in the wake of the COVID-19 pandemic. The term "resilience" originates from the 17th-century Latin word "Resilire," meaning to rebound or recover. The understanding of resilience has evolved through three developmental stages: engineering resilience, ecological resilience, and evolutionary resilience (Chen et al. 2024). Initially, resilience in engineering described the ability of materials to resist external shocks within the field of physics. Ecological resilience, as characterized by Holling (1973), examines whether systems can maintain their state despite disturbances, underscoring the importance of stability in structure and function. The concept has since extended from ecological to social systems, where evolutionary resilience views the process as continually evolving. Evolutionary resilience recognizes the non-equilibrium evolutionary characteristics of the system (Simmie and Martin 2010) and puts more emphasis on the adaptive transformation of the system structure and function.

The RDIER has evolved from the concept of evolutionary resilience. Chen and Cai (2023) conceptualize the RDIER as a multi-phase process where the ecosystem employs various capacities, such as adaptability, self-learning, and self-regulation, to withstand and counter shocks, consequently enhancing its functional performance. This paper posits that a resilient regional digital innovation ecosystem exhibits adaptability to unexpected external shocks and ongoing internal disruptions, ensuring its stable functionality and sustained evolution under these unfavorable conditions. Thus, we define the RDIER as the capacity of various innovation actors within a specific spatial range to leverage digital technology, dynamically amalgamate internal and external innovation resources, and adjust ecosystem structures and operational states flexibly, thereby adapting to the intricate and volatile regional environmental impacts. This resilience bestows the regional digital innovation ecosystem with the capability to maintain crucial functionality and stability amidst perturbations, facilitating quick recovery and continual innovative development. Ultimately, regional digital innovation ecosystems enable a dynamic adaptation process that recovers from and upgrades within the context of regional adversity.

2.1.2 The evaluation system for the RDIER

Currently, the academic community primarily adopts the method of constructing indicator systems to measure the RDIER. Liang and Li (2023) developed a resilience monitoring and evaluation framework for regional innovation ecosystems, focusing on diversity, evolution, flowability, and buffering. Building on this work, scholars such as Yang et al. (2022a, b) and Chen and Cai (2023) concentrated on regional digital innovation ecosystems, establishing a resilience evaluation framework that also considers diversity, evolution, fluidity, and buffering. Moreover, scholars have underscored the indispensable role of collaboration in enabling ecosystems to mitigate risks and foster sustainable development (Li et al. 2022; Yi et al. 2023). Collaboration is viewed as an interactive process in which participants share information, resources, responsibilities, and risks to jointly plan, implement, and evaluate activity programs aimed at achieving common goals (Russell and Smorodinskaya 2018). Open innovation theory posits that a firm's competitive advantage no longer rests solely on internal resources but stems from its capacity to integrate both internal and external innovation resources (Chesbrough 2003). This means that collaboration is not merely an antithesis to competition but also a crucial strategy for building competitive advantage. Consequently, regions with high levels of collaboration digital innovation ecosystems demonstrate greater resilience against external shocks and uncertainties. From the perspective of ecosystem resilience, resilience underscores an ecosystem's capacity to withstand external shocks, rapidly recover, and continually evolve. This requires building extensive interconnections and establishing robust collaborative networks within the ecosystem. On the one hand, collaboration among actors facilitates the flow and dissemination of knowledge, thereby enhancing the 'collective intelligence' of the ecosystem and its ability to manage uncertainties (Yi et al. 2023). On the other hand, by collaboratively sharing data, facilities, and talent, innovators can reduce costs and improve resource efficiency. Efficient resource allocation and flow within an ecosystem are critical for its sustained robust development (Li et al. 2022).

Notably, from a resilience perspective, the role of collaboration becomes more pronounced, yet this does not imply that competition is unimportant. Within ecosystems, collaboration does not preclude competition among participants or with other regions worldwide. On the contrary, market competition intensifies in an open environment, augmenting the uncertainties and challenges organizations face. To address the fierce innovation competition and the VUCA environment, organizations must forge tighter and more flexible collaborative relationships with partners to swiftly detect and respond to market changes (Camarinha-Matos et al. 2009). Consequently, competition compels collaboration to evolve toward greater closeness and flexibility under open conditions. Particularly in ecosystems with common institutional features, actors engaged in long-term projects collaborate through relational contracts and coordinate activities based on a shared strategy to meet the challenges of intense global competition (Russell and Smorodinskaya 2018). This collaboration signifies the complex interrelations and specific dynamic equilibria within the ecosystem.

Considering the emphasis of open innovation theory on collaboration and the focus of ecosystem resilience theory on managing uncertainty, this paper adds collaborative to the existing evaluation index system on the RDIER (Yang et al. 2022a, b; Chen and Cai 2023). Specifically, a comprehensive set of resilience evaluation indicators for digital innovation ecosystems is proposed, encompassing diversity, evolutionary, flowability, buffering, and collaboration. Among these, diversity refers to various subjects within the digital innovation ecosystem. The entities encompass talents, enterprises, industries, universities, and more. This paper measures the diversity of regional digital innovation ecosystems by considering the dimensions of talents, enterprises, industries, and universities. Evolutionary capacity represents the ability to allocate resources. In this paper, evolutionary capacity is assessed based on two aspects: digital innovation inputs and outputs. Flowability represents the mobilization of internal elements within the regional digital innovation ecosystem. In this paper, flowability is primarily measured through the dimensions of financial flow, population flow, information flow, and technology flow. Buffering capacity represents the reserve of innovative elements. In this paper, buffering is assessed using economic resources, social environmental resources, and natural environmental resources as indicators. Collaboration represents the interactivity and symbiotic relationships among different entities within the regional digital innovation ecosystem, encompassing intra-ecosystem collaboration among internal entities and collaboration between the ecosystem and external stakeholders. This paper primarily measures the collaboration of regional digital innovation ecosystems through internal and external collaboration within the region. The specific indicators are shown in Table 1.

2.2 Resource orchestration theory and RDIER

Resource orchestration theory points out that an organization's dynamic management of resources is the source of its sustainable competitive advantage (Sirmon et al. 2007). The resource orchestration process includes three basic subprocesses: resource structuring, resource capability formation, and resource leveraging (Liu et al. 2016; Suseno et al. 2018), which sequentially address the issues of resource construction, resource transformation to form capabilities, and the use of capabilities to create value. In each resource orchestration process, resources and capabilities jointly determine the subject's sustainable competitive advantage (Zhu and Li 2023). Resource orchestration theory has been widely used in resource management (Sirmon et al. 2007), supply chain management (Gligor 2018), innovation (Bittencourt et al. 2021), and entrepreneurship (Baert et al. 2016), as well as other fields. With the advent of the digital economy, scholars have started to focus on resource orchestration in digital scenarios. Urbinati et al. (2022) explored how firms can effectively orchestrate, coordinate, and utilize different resources to achieve digital innovation. Zhu and Li (2023) explored the mediating role of resource orchestration between data-driven insights and bidirectional digital transformation.

The existing research on resource orchestration theory provides an analytical framework for exploring pathways to enhance the RDIER in this study. On the one hand, resource orchestration theory serves as a theoretical foundation for analyzing the enhancement of RDIER. The essence of resilience lies in the creative combination and utilization of resources when confronting risks, which aligns with the core principles of resource orchestration theory, thus reflecting a parallelism of ideas. On the other hand, the existing literature lacks substantial research on how to orchestrate traditional and digital resources and capabilities to enhance the RDIER. By drawing upon resource orchestration theory and conducting an analysis from the perspectives of traditional and digital resources and capabilities, this study offers valuable insights into the multifaceted antecedents of RDIER. This analysis provides practical guidance for advancing RDIER.

Table 1 Evaluation index system of RDIER

Primary indicators	Secondary indicators	Measurement mode (unit)
Diversity	Talent diversity	Distribution of employed persons with higher education
	Enterprise diversity	Number of information technology enterprises (number)
	Industry diversity	Industry distribution
	University diversity	The proportion of double first-class institutions in ordinary higher education institutions (%)
		Number of national university science and technology parks (number)
Evolutionary	Digital innovation inputs	The full-time equivalent of R&D personnel (person-years)
		Expenditure on internal funding for R&D (ten thousand yuan)
		Number of people in information transmission, software, and information technology services (ten thousand people)
		Intensity of investment in research and experimental development in high-tech industries (%)
	Digital innovation outputs	Software product revenue (100 million yuan)
		Embedded systems software revenue (100 million yuan)
		Information technology services revenue (ten thousand yuan)
		Total telecoms business as a percentage of GDP (%)
Flowability	Financial flow	E-commerce sales (100 million yuan)
		Digital inclusive finance index
	Population flow	Urban population density (person/square kilometer)
	Information flow	Internet broadband access ports (10,000)
		Length of fiber-optic lines (kilometers)
	Technology flow	Inflow of technology market contracts (ten thousand yuan)
		Outflow of technology market contracts (ten thousand yuan)

Table 1 (continued)

Primary indicators	Secondary indicators	Measurement mode (unit)
Buffering	Economic resources	Per capita end-of-year financial institution loan balance (ten thousand yuan)
		Year-end deposit balance of financial institutions per capita (ten thousand yuan)
	Socio-Environmental Resources	Number of books in public libraries per 10,000 people (volumes/10,000 people)
		Number of science and technology museums (number)
		Health technical personnel per 1,000 people (person)
	Natural environmental resources	Percentage of forest cover (%)
		Water resources per capita (m^3/ person)
Collaboration	Internal Collaborative	The proportion of corporate funds in internal R&D expenditures of universities and scientific research institutes (%)
		Proportion of government funds in R&D funds of industrial enterprises above designated size (%)
		The growth rate of scientific papers written by authors in the same province but in different units (%)
		Proportion of the number of invention patents jointly applied by industry, academia, and research parties or two of them to the total number of patents (%)
	External collaborative	The growth rate of scientific papers co-authored by authors from other provinces (%)
		The growth rate of scientific papers with authors from different countries (%)
		Proportion of foreign funds in internal expenditures of R&D funds of higher education institutions (%)
		Proportion of foreign funds in regional R&D internal expenditures (%)

Drawing on research on resources, capabilities, and ecosystem resilience in regional digital innovation ecosystems (Zhu and Li 2023; Zhang et al. 2024; Xie et al. 2024), this paper selects four traditional resources and capabilities, namely talent resources, financial resources, physical resources, and technological innovation capability, as well as three digital resources and capabilities, including big data resources, digital platforms, and digital governance. The discussion in this paper revolves around these seven resources and capabilities, exploring the configuration of resources and capabilities that contribute to enhancing RDIER. To elucidate how to enhance the RDIER through allocating resources and capabilities, we introduce a comprehensive theoretical framework as depicted in Fig. 1. This paper posits that the RDIER is not contingent upon a single antecedent condition but rather relies on the interplay between traditional resources and capabilities, as well as digital resources and capabilities. Therefore, to foster high RDIER, the configurational effects of "traditional + digital" resources and capabilities should be taken into consideration.

Talent resources. As an independent, dynamic, and highly valuable resource, talent resources have always been the core competitive advantage of regional innovation and development. As owners of knowledge and technology, the accumulation of knowledge and diffusion of technology brought about by talent resources are conducive to advancing the socialized collaboration of innovation activities, enhancing the economic benefits of agglomeration (Jian et al. 2024), and providing a driving force for RDIER.

Financial resources. Financial resources serve as a prerequisite for facilitating the activities within regional digital innovation ecosystems. On the one hand, abundant financial resources attract diverse actors, such as talent and businesses, thereby enhancing the diversity of entities within the ecosystem and promoting resource aggregation (Wen et al. 2023). On the other hand, sufficient financial resources endow the ecosystem with a higher degree of resilience by providing a buffer against external shocks, thus enabling the ecosystem to withstand risks and facilitating the recovery and adjustment of its functional capabilities (Zhang et al. 2024).

Physical resources. Physical resources mainly refer to the material elements that maintain ecosystem operation and carry out activities (Zheng et al. 2020), providing the underlying foundation for resource utilization in the regional digital

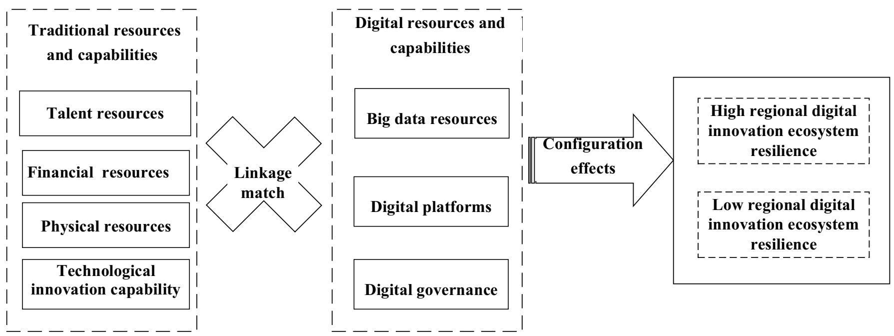

Fig. 1 Configuration effects model

innovation ecosystem (Wang et al. 2022a, b). Sufficient physical resources enable the ecosystem to have abundant resource reserves when it suffers external shocks and can maintain its structure and avoid fragility, leading to ecosystem collapse.

Technological innovation capability. Technological innovation capability refers to a region's ability to transform knowledge into new products, new processes, and new services (Wang and Luo 2020). Innovation, as a key adaptive factor, gives regional digital innovation ecosystems the potential to use existing knowledge to find new opportunities when the environment changes (Chen and Cai 2023). In areas with stronger technological innovation capability, the ecosystem has higher capabilities of self-learning and self-adjustment (Balland et al. 2015). The result is the optimization of ecosystem elements and structural reconstruction, reflected in the continuous improvement of resilience.

Big data resources. Big data resources are defined as combinations of IT resources that are necessary when using big data to enhance performance (Suoniemi et al. 2020). Big data resources use their reusability and value-added characteristics to achieve knowledge accumulation and resource augmentation in regional digital innovation ecosystems, which is conducive to enhancing the ecosystem's resource reserves and buffers. In the context of digitalization, big data resources have become essential resource for the digital transformation of enterprises and industries (Xie et al. 2024). With the help of big data resources, different subjects in the regional digital innovation ecosystems can improve the efficiency of resource allocation and then enhance the ecosystem's adaptive response to shocks.

Digital platforms. Digital platforms play a crucial role in enhancing the RDIER through two primary mechanisms. First, digital platforms facilitate the rapid flow of resources, thereby improving the speed of information dissemination. Consequently, this enhances the alertness and opportunity sensitivity of regional entities, enabling timely responses to environmental changes (Xu et al. 2013). Second, the openness of digital platforms facilitates the aggregation of diverse innovative actors in risk mitigation efforts. This fosters digital resource sharing, co-creation, and collaborative governance and enables digital information sharing and agile flexibility within the value chain (Constantinides et al. 2018). As a result, the RDIER is elevated.

Digital governance. Digital governance refers to governance capacity based on information technology, encompassing analysis, decision-making, and feedback supervision, with an emphasis on the widespread application of digital technologies (Zamora et al. 2016). In the context of governing regional digital innovation ecosystems, government entities often play a pivotal role (Hopkins et al. 2019). A high level of digital governance capacity within the government yields several benefits. First, it facilitates the shift of daily management toward online governance focused on service organization, process optimization, and digital service delivery. Second, it enables the rapid transmission of risk management-related information between innovative actors and government entities, significantly enhancing the efficiency of risk identification and response within the digital innovation ecosystem. As a result, the development of regional digital innovation ecosystems is empowered with greater resilience.

3 Research design

3.1 Research methods and data sources

3.1.1 Research methods

First, this paper adopts the entropy TOPSIS method to measure the RDIER. The entropy weight method can determine the weight of each indicator according to the degree of variation of each indicator, which can effectively avoid the bias brought by human factors. TOPSIS can achieve a more comprehensive and balanced evaluation of the RDIER by setting up an ideal solution. The entropy TOPSIS method can make the evaluation results more objective, accurate, and scientific. Therefore, this paper adopts the entropy TOPSIS method to measure the composite index of RDIER, as well as the secondary indicators of digital resources and capabilities.

Second, the fsQCA method is employed to examine the configurational paths that enhance the RDIER. Introduced by Ragin in 1987, qualitative comparative analysis (QCA) utilizes Boolean algebraic set theory and configurational analysis to examine complex social issues. It elucidates these issues by identifying sufficient and necessary relationships among various antecedent conditions and outcomes, providing a holistic perspective on multiple concurrent causations (Fiss 2011; Pappas and Woodside 2021). QCA is categorized into crisp-set QCA (csQCA), multi-value QCA (mvQCA), and fuzzy-set QCA (fsQCA) based on variable type. In contrast to csQCA and mvQCA, which are tailored for categorical issues, fsQCA excels in identifying continuous variations in conditions. FsQCA achieves this through the calibration of data, the transformation of fuzzy-set data into truth tables, and the evaluation of variables' necessity and sufficiency (Kraus et al. 2018). This paper employs fsQCA primarily for two reasons. First, the regional digital innovation ecosystem, characterized as a complex adaptive system, requires a holistic approach to understanding resilience improvements, which cannot be explained by a single factor. FsQCA's configuration-based, whole-system perspective facilitates the study of synergistic effects among various antecedent conditions. Second, fsQCA enables the identification of typical cases within each configuration (Pappas and Woodside 2021), revealing potential regional differences in ecosystem resilience strategies, thereby deepening our understanding of the complexities of regional digital innovation ecosystems. The analysis was conducted using fsQCA 4.0 software.

3.1.2 Data sources

This paper selects 30 provinces and cities in China as research samples based on several key considerations. First, China, as the world's largest developing country, exhibits significant regional variations in digital economy development, making it an ideal sample for analyzing how to enhance the RDIER (Wang et al.

2022a, b). Second, despite the rapid growth of its digital economy, China faces numerous challenges, including a significant digital divide and uneven distribution of innovation resources. These issues critically impact the stability and sustainability of regional digital innovation ecosystems, urgently calling for effective solutions. Finally, as a major global player in the digital economy, China's extensive experience in digital transformation provides valuable insights for other countries and regions aiming to develop resilient digital innovation ecosystems. Focusing on the Chinese case, this study offers important lessons for global digital economic governance.

The report of the 19th National Congress of the Communist Party of China in 2017 explicitly proposed building a digital China. China's digital development has been accelerating since the "digital economy" was first mentioned in the 2017 government work report. Therefore, the data for the study in this paper are selected from the panel data of 30 provinces and cities in China (excluding Hong Kong, Macao, Taiwan, and Tibet) from 2017 to 2021. Research data were primarily sourced from three main channels: (1) official statistics, including the China Statistical Yearbook, China Science and Technology Statistical Yearbook, City Statistical Yearbook, and China Environmental Statistical Yearbook, along with other provincial and city statistical publications. (2) Research reports, such as the China Regional Innovation Capability Evaluation Report, China Internet Development Statistical Report, Peking University Digital Financial Inclusion Index Report, and Government Weibo Influence Report. (3) Public database platforms, including the PatSnap global patent search and analysis database, China National Knowledge Infrastructure (CNKI), and the Web of Science. For some of the missing values, the linear interpolation method and linear prediction method are used for interpolation.

3.2 Description of variables

3.2.1 Outcome variable

Combined with the RDIER measurement index system in Table 1, this paper applies the entropy TOPSIS method to measure the RDIER level of 30 provinces and cities in China. The final results are shown in Table 2.

Based on Table 2, the following observations can be made. (1) Overall, the RDIER in China exhibits a fluctuating upward trend, but the overall level remains relatively low. From 2017 to 2021, the RDIER in China showed an overall increase, with the mean resilience value rising from 0.219 to 0.243, indicating a total growth of 10.959%. However, the growth rate is sluggish, with an average annual increase of only 2.192%. (2) When examining different provinces, significant variations in the RDIER can be observed. As of 2021, Guangdong, Beijing, Jiangsu, and Shanghai were leading in RDIER. Some central and western provinces, such as Anhui, Shandong, Ningxia, Guangxi, Henan, and Shanxi, demonstrated higher average annual growth rates, indicating rapid development momentum. In contrast, regions such as Xinjiang, Ningxia, and Jilin exhibited lower levels of resilience. Moreover, notable disparities exist among provinces, with Guangdong (0.479) being nearly

Table 2 Measures of RDIER

Region	Provinces	2017	2018	2019	2020	2021	Averages	Annual rate of growth
Eastern	Beijing	0.495	0.497	0.440	0.468	0.477	0.475	− 0.727
	Tianjin	0.260	0.202	0.200	0.207	0.211	0.216	− 3.769
	Hebei	0.172	0.174	0.190	0.199	0.206	0.188	3.953
	Shanghai	0.341	0.358	0.333	0.344	0.358	0.347	0.997
	Jiangsu	0.420	0.411	0.360	0.385	0.414	0.398	− 0.286
	Zhejiang	0.299	0.332	0.310	0.325	0.338	0.321	2.609
	Fujian	0.223	0.222	0.224	0.226	0.235	0.226	1.076
	Shandong	0.264	0.276	0.258	0.290	0.350	0.288	6.515
	Guangdong	0.442	0.472	0.418	0.456	0.479	0.453	1.674
	Hainan	0.166	0.155	0.174	0.197	0.178	0.174	1.446
	Averages	0.308	0.310	0.291	0.310	0.325	0.309	1.064
Central	Shanxi	0.143	0.143	0.170	0.184	0.176	0.163	4.615
	Anhui	0.161	0.155	0.187	0.205	0.216	0.185	6.832
	Jiangxi	0.226	0.182	0.202	0.208	0.207	0.205	− 1.681
	Henan	0.179	0.189	0.200	0.218	0.221	0.201	4.693
	Hubei	0.210	0.206	0.221	0.235	0.247	0.224	3.524
	Hunan	0.180	0.176	0.193	0.207	0.222	0.196	4.667
	Averages	0.183	0.175	0.196	0.210	0.215	0.196	3.458
Western	Inner Mongolia	0.150	0.123	0.167	0.176	0.181	0.159	4.133
	Guangxi	0.154	0.154	0.187	0.200	0.191	0.177	4.805
	Chongqing	0.161	0.156	0.199	0.184	0.197	0.179	4.472
	Sichuan	0.222	0.232	0.234	0.256	0.263	0.241	3.694
	Guizhou	0.166	0.148	0.193	0.211	0.180	0.180	1.687
	Yunnan	0.171	0.172	0.197	0.210	0.191	0.188	2.339
	Shaanxi	0.212	0.215	0.226	0.232	0.247	0.226	3.302
	Gansu	0.140	0.136	0.196	0.203	0.174	0.170	4.857
	Qinghai	0.194	0.196	0.216	0.238	0.216	0.212	2.268
	Ningxia	0.131	0.112	0.174	0.186	0.164	0.153	5.038
	Xinjiang	0.135	0.128	0.162	0.177	0.160	0.152	3.704
	Averages	0.167	0.161	0.196	0.207	0.197	0.185	3.573
Northeastern	Liaoning	0.183	0.175	0.195	0.204	0.209	0.193	2.842
	Jilin	0.145	0.129	0.210	0.179	0.164	0.165	2.621
	Heilongjiang	0.210	0.180	0.216	0.223	0.221	0.210	1.048
	Averages	0.179	0.161	0.207	0.202	0.198	0.190	2.082
Total	Averages	0.219	0.214	0.228	0.241	0.243	0.229	2.192

three times more resilient than Xinjiang (0.160) in 2021. (3) Examining the four major regions, the mean resilience values indicate that the eastern region performs the best (0.309), followed by the central region (0.196), while the northeastern and western regions show lower resilience levels, at 0.190 and 0.185, respectively.

However, in terms of growth rates, the western (3.573) and central (3.458) regions exhibit higher rates, while the northeastern (2.082) and eastern regions (1.064) demonstrate lower growth rates. The resilience level of the eastern regions significantly surpasses that of other areas, indicating a pronounced imbalance in the resilience of China's digital innovation ecosystems, both overall and regionally. Regions with low resilience, such as the western and northeastern regions, still have significant room for improvement.

In general, the RDIER in China shows a fluctuating upward trend. However, significant challenges persist, including low resilience levels, sluggish growth rates, and regional development disparities. Consequently, enhancing RDIER remains a pressing concern that warrants immediate attention.

3.2.2 Conditional variables

Traditional resources and capabilities. (1) Talent resources. Referring to Jian et al. (2024) using the entropy of talent location to measure regional talent agglomeration, this paper uses the proportion of regional and national employment personnel to measure talent resources, while this paper requires that these employment personnel have a bachelor's degree and above. (2) Financial resources. Referring to Xu et al. (2024), this paper adopts the ratio of local science and technology expenditure to general public budget expenditure to measure financial resources. (3) Physical resources. Referring to existing research, this paper uses the fixed asset investment of the region for measurement. (4) Technological innovation capacity. Drawing on the practice of Xu et al. (2023), this paper selects the logarithm of the number of regional invention patent applications to indicate technological innovation capacity.

Digital resources and capabilities. (1) Big data resources. Artificial intelligence, blockchain, cloud computing, and big data technologies (ABCD) are regarded as the digital pedestal of digital transformation, bringing about great changes in all aspects of economic development and social life (Akter et al. 2022). Therefore, this paper adopts the number of invention patent applications and the number of papers related to AI, blockchain, cloud computing, and big data as indicators of big data resources. Among them, the number of papers comes from the sum of China Knowledge Network and Web of Science papers; the number of patents comes from the PatSnap global patent search database. (2) Digital platforms. Referring to Yang et al. (2022a, b) study on platform economy, this paper measures digital platforms from three aspects: the proportion of Internet users, the ratio of domain names, and the proportion of web pages, based on data availability. (3) Digital governance. Referring to the study of Li and Rao (2023), the number of government websites, the interactive power of regional government microblogs, and the service power of regional government microblogs are used as the measurement indicators of digital governance.

3.3 Variable calibration

Calibration is a pivotal step in the QCA process. This paper employs the direct calibration method, assigning the upper and lower 25th percentiles and the median of the research data as points of full membership, full non-membership, and crossover, respectively (Fiss 2011; Xie and Wang 2020). This approach converts the original variable data into fuzzy membership scores ranging from 0 to 1, facilitating the fsQCA. To avoid the value of 0.5 being excluded by the software, the data calibrated as 0.5 were directly assigned to 0.5001. Descriptive statistics and calibration anchors for key variables can be found in Table 3.

4 Empirical findings and analyses

4.1 Necessity analysis of a single condition

Necessity analysis is employed to examine whether the occurrence of results relies on a single independent variable. When the consistency of a particular independent variable exceeds 0.9, it indicates that the variable is a necessary condition for the outcome. The results in Table 4 demonstrate that in the necessity analysis of single conditions, the consistency of the independent variables is less than 0.9, indicating the absence of necessary conditions for driving the enhancement of RDIER. This result suggests that a single condition cannot enhance the RDIER but requires linkage and matching between diverse resources and capabilities.

4.2 Analysis of the driving paths to enhance the RDIER

In this paper, the original consistency threshold and PRI consistency threshold are set to 0.8 and 0.7, respectively, and the frequency threshold is set to 1. Table 5 presents the two core pathways driving the enhancement of RDIER. These pathways further encompass six specific configurational paths. Based on the results, the solution consistency is 0.906, indicating that among all the cases of regional digital innovation ecosystem development that satisfy these six driving paths, 90.6% of the regional digital innovation ecosystems demonstrate high resilience. The solution coverage is 0.710, indicating that the six configurational paths can account for 71% of the typical cases of resilience enhancement in regional digital innovation ecosystems.

(1) Technology Innovation-Digital Platforms type. In configuration H1, technology innovation capability and digital platforms play a central role, while other variables have a supporting role. Therefore, we collectively refer to configuration H1 as the Technology Innovation-Digital Platforms type.

Among them, configuration H1a suggests that even if the talent resources are not in a high state, when a regional digital innovation ecosystem possesses high technological innovation capability, high digital governance capabilities, sufficient physical resources, big data resources, and digital platforms, resilience enhancement can still be achieved. We refer to configuration H1a as the "digital-led innovation driven type." Taking Sichuan Province as a typical case, despite lacking significant geographical advantages and having relatively fewer talent resources compared to some eastern provinces, Sichuan has opened up

Table 3 Descriptive statistics and calibration anchors

Conditions and results	Descriptive statistics				Calibration anchors		
	Mean	Standard	Min	Max	Full membership	Crossover	Full non-membership
Regional digital innovation ecosystem resilience	0.229	0.086	0.125	0.475	0.226	0.199	0.178
Talent resources	1.091	0.495	0.596	2.871	1.136	0.971	0.816
Financial resources	2.364	1.611	0.626	5.937	3.259	1.801	1.128
Physical resources	3.314	2.329	0.431	8.280	5.171	2.981	1.259
Technological innovation capability	9.964	1.313	7.151	12.261	10.807	10.004	9.165
Big data resources	0.089	0.119	0.003	0.543	0.071	0.045	0.029
Digital platforms	0.135	0.143	0.042	0.749	0.111	0.078	0.070
Digital governance	0.488	0.143	0.178	0.749	0.573	0.493	0.409

Table 4 Necessity analysis

Condition variables	High regional digital innovation ecosystem resilience		Non-high regional digital innovation ecosystem resilience	
	Consistency	Coverage	Consistency	Coverage
Talent resources	0.639	0.620	0.466	0.459
~Talent resources	0.442	0.449	0.614	0.634
Financial resources	0.751	0.770	0.308	0.321
~Financial resources	0.338	0.325	0.779	0.760
Physical resources	0.673	0.685	0.381	0.394
~Physical resources	0.405	0.391	0.696	0.684
Technological innovation capability	0.821	0.807	0.300	0.299
~Technological innovation capability	0.286	0.287	0.806	0.821
Big data resources	0.748	0.737	0.352	0.352
~Big data resources	0.343	0.342	0.737	0.748
Digital platforms	0.752	0.750	0.317	0.321
~Digital platforms	0.319	0.315	0.753	0.755
Digital governance	0.694	0.702	0.390	0.401
~Digital governance	0.408	0.397	0.710	0.702

~represents logical "not"

Table 5 Configurational pathways driving RDIER

Condition variables	H1				H2	
	H1a	H1b	H1c	H1d	H2a	H2b
Talent resources	⊗		•	•	⊗	•
Financial resources		•	•	⊗	●	●
Physical resources	•	•	⊗	•	●	●
Technological innovation capability	●	●	●	●	⊗	•
Big data resources	•	•	•	⊗	⨂	⨂
Digital platforms	●	●	●	●	⊗	•
Digital governance	•	•	⊗	•	•	⊗
Consistency	0.837	0.931	0.93	0.982	0.898	0.955
Raw coverage	0.276	0.426	0.17	0.074	0.083	0.072
Unique coverage	0.042	0.186	0.129	0.028	0.048	0.03
Solution coverage	0.710					
Solution consistency	0.906					

● indicates that the core condition exists; • indicates that the marginal condition exists; ⨂ indicates that the core condition is missing; ⊗ indicates that the marginal condition is missing; blank indicates that the condition is optional. Same as below

new pathways for development in the digital economy. It has vigorously built a national-level Tianfu Data Center cluster, strengthened the core industries of the digital economy, continuously promoted the integration of the real economy and the digital economy, enhanced innovative development momentum, and empowered the resilience evolution and upgrading of the regional digital innovation ecosystem.

Configuration H1b encompasses three traditional resources and capabilities (financial resources, physical resources, and technological innovation capability) and three digital resources and capabilities (big data resources, digital platforms, and digital governance). This path represents the most diverse configuration of resources and capabilities among the six driving paths, highlighting the synergistic interaction between traditional and digital resources and capabilities. Therefore, we label this path the "balanced resources and capability type." Moreover, the consistency of path H1b is 0.931, with the highest original coverage rate of 42.6%. It serves as the primary driving path for enhancing RDIER. In the typical cases of Jiangsu, Guangdong, Zhejiang, and other provinces, they not only possess abundant traditional resources such as talent, financial, and physical resources but also rank among the top in digital development. The dual combination of "traditional + digital" resources and capabilities has contributed to the high RDIER in these provinces.

Configuration H1c is characterized by the absence of physical resources and digital governance. Although it only encompasses high technological innovation capability as a traditional capability, it also possesses high talent resources, financial resources as traditional resources, big data resources, and digital platforms as digital resources. Therefore, we label this path the "technology innovation-led resource utilization type." The typical cases of this pathway include Shanghai and Beijing. According to the China Regional Science and Technology Innovation Evaluation Report 2022, Shanghai and Beijing continue to rank first and second in terms of the comprehensive science and technology innovation level index nationwide. The efficient integration and utilization of resources driven by high technological innovation capabilities are essential conditions to enhance the resilience of the ecosystem in these provinces.

Configuration H1d indicates that in the absence of financial resources and big data resources, a regional digital innovation ecosystem can still achieve resilience enhancement if it possesses high technological innovation capability, digital governance capabilities, and sufficient digital platforms, talent resources, and physical resources. We label this pathway the "digitally led talent-physical complementarity type." A typical case of this configuration pathway is Shaanxi province. In this configuration pathway, digital platforms mitigate the limitations imposed on the regional digital innovation ecosystem by financial resources and big data resources. Simultaneously, digital platforms facilitate the integration and coordination of complementary resources and competitive resources from both internal and external innovation actors, enabling advantages complementarity and risk sharing among different groups. Supported by high digital governance capabilities and technological innovation capability, along with the rapid rise of digital platforms, resource utilization efficiency is improved, leading to resilience enhancement.

(2) Financial-Physical Dominant type. In configuration H2, high financial resources, high physical resources, and non-high big data resources play a central role. Therefore, this paper names the whole configuration H2 as Financial-Physical Dominant Type.

In the configuration H2a, high digital governance plays a complementary role. Configuration H2a indicates that in the absence of high technological innovation capability, insufficient talent resources, big data resources, and digital platforms, a regional digital innovation ecosystem can enhance its resilience by efficiently allocating physical and financial resources facilitated by high digital governance capabilities. We label configuration H2a the “traditional resource dominant with digital governance type.” A typical case that this configuration can explain is Jiangxi Province. In recent years, Jiangxi has actively constructed the Jiangxi Social Governance Big Data Platform, a new data platform, and launched the Overall Plan for Digital Government Construction in Jiangxi Province. This initiative not only demonstrates the valuable application of big data technology in the field of social governance but also effectively promotes the optimization and improvement of public services, providing robust data support and assurance for the economic development and resilience enhancement of Jiangxi Province.

In the configuration H2b, the core conditions contain both high financial resources and high physical resources. High technological innovation capacity, high digital platforms, and high talent resources complement the core conditions as supplementary conditions, constituting a path to enhance the RDIER. We label configuration H2b as the "traditional resource dominant with digital platforms type.” A typical case of such configuration pathways is Fujian Province. As the origin and starting point of the Digital China initiative, Fujian has been at the forefront of digital development in recent years. The establishment of integrated digital platforms for digital government services and the implementation of digital monitoring platforms for business environments have provided a robust foundation for fostering an open and healthy digital ecosystem in Fujian Province. By strategically leveraging digital platforms and effectively mobilizing traditional resources and capabilities, Fujian Province has experienced flourishing development in the face of uncertainties, ultimately evolving into a resilient digital innovation ecosystem.

In this paper, two core paths for enhancing the RDIER are identified utilizing configurational analysis: the Technology Innovation-Digital Platforms type and the Financial-Physical Dominant type. These paths encompass six distinct driving paths, each characterized by unique configurations of resources and capabilities. Notably, each path involves both traditional and digital resources and capabilities. This means that enhancing RDIER necessitates effectively orchestrating "traditional + digital" resources and capabilities.

4.3 Analysis of constraint pathways

The results of the configurational path analysis, which identifies the pathways constraining the enhancement of RDIER, are presented in Table 6. The table reveals the presence of two core pathways constraining the enhancement of RDIER. In configuration L1, non-high physical resources and non-high technological innovation capability serve as core conditions. In configuration L2, non-high financial resources, non-high technological innovation capability, and non-high digital governance act as core conditions. It is worth noting that the inclusion of all four non-high resources

Table 6 Constraining paths for enhancing RDIER

Condition variables	L1			L2	
	L1a	L1b	L1c	L2a	L2b
Talent resources	•	•	⊗	⊗	
Financial resources		⊗	•	⨂	⨂
Physical resources	⨂	⨂	⨂		⊗
Technological innovation capability	⨂	⨂	⨂	⨂	⨂
Big data resources	⊗	⊗	⊗	⊗	
Digital platforms	⊗		•	⨂	⨂
Digital governance	⊗	⊗	⊗	⊗	⊗
Consistency	0.836	0.848	0.914	0.878	0.828
Raw coverage	0.294	0.295	0.070	0.338	0.454
Unique coverage	0.033	0.033	0.004	0.099	0.043
Solution coverage	0.628				
Solution consistency	0.846				

and capabilities inevitably hinders the improvement of RDIER, as demonstrated by configuration L2b. From the perspective of each pathway, the lack of various resources and capabilities in regional digital innovation ecosystems results in non-high resilience. Each constraining path involves both non-high technological innovation capabilities and non-high digital governance, indicating that when both technological innovation capabilities and digital governance are low, even with resources such as talent resources, financial resources, and digital platforms, effective resource allocation cannot be achieved, thereby impeding the enhancement of RDIER.

4.4 Robustness test

Following the relevant research by Xie and Wang (2020), this study conducts robustness tests using two approaches. First, the original consistency threshold is increased from 0.800 to 0.850, resulting in configurations that remain consistent with the original findings. Second, building upon the increase of the original consistency threshold to 0.850, the PRI consistency threshold is raised from 0.700 to 0.800. This generates configurations that are subsets of the original results, corresponding to H1b, H1c, H1d, and H2b in the original configurations. These findings are largely consistent with the original results, demonstrating the robustness of the research outcomes.

5 Conclusion and policy implications

5.1 Research conclusion

This paper first enriches the resilience evaluation system of regional digital innovation ecosystems based on existing research. Using panel data from 30 provinces and cities in China (excluding Hong Kong, Macao, Taiwan, and Tibet) from 2017 to 2021, the entropy TOPSIS method is employed to calculate the RDIER. Second, from a resource orchestration perspective, this study selects four types of traditional resources and capabilities, including talent resources, and three types of digital resources and capabilities. The fsQCA method is utilized to explore the configuration pathways for enhancing the RDIER, revealing the essential interplay of core conditions and antecedent conditions influencing resilience improvement. The main conclusions of this study are as follows.

(1) The RDIER demonstrates a fluctuating upward trend, indicating an overall improvement in its adaptive and risk mitigation capabilities. This result generally agrees with the findings of Chen and Cai (2023). Nevertheless, despite this observed trend, several crucial challenges persist. First, the rate of resilience enhancement in regional digital innovation ecosystems is insufficient, implying the need to further strengthen their adaptability and recovery capacity when confronted with rapid changes and uncertainties. In recent years, the inadequate driving force behind the resilience enhancement of China's regional digital innovation ecosystems, brought about by challenges such as the COVID-19 pandemic and escalating Sino-US trade tensions, has hindered the speed of resilience improvement. Second, significant disparities exist among different regions, possibly attributable to variations in the degree of digital development, innovation capabilities, and resource allocation. Consequently, to enhance the RDIER, it is imperative to intensify attention on the pace of enhancement while actively promoting balanced development of resources and capabilities to narrow the gaps between regions.

(2) Neither traditional nor digital resources and capabilities alone are sufficient to enhance the RDIER. This is because the RDIER is a complex and comprehensive characteristic that requires the integrated utilization and synergistic effect of different types of resources and capabilities. Traditional resources and capabilities can provide fundamental support, such as human resources, material assets, and industry experience (Xu et al. 2022; Zhang et al. 2024), while digital resources and capabilities emphasize technological innovation, digitalization capabilities, and data-driven abilities. By leveraging and integrating traditional and digital resources and capabilities, regional digital innovation ecosystems can better cope with uncertainties and risks, and possess stronger adaptability and innovation capabilities. This comprehensive configuration of resources and capabilities is crucial to ensure the continuous development and innovation of regional digital innovation ecosystems in an ever-changing environment.

(3) Traditional and digital resources and capabilities provide multiple pathways to enhance the RDIER. First, there are two core paths, namely H1 Technological Innovation-Digital Platforms type and H2 Financial-Physical Dominant type. Configuration H1 emphasizes technology innovation and the construction of digital platforms, aiming to promote the healthy development of the region through the enhancement of technological innovation and digital capabilities, as well as the establishment of digital platforms and ecosystems. Configuration H2 focuses on the dominant role of financial and physical resources, aiming to promote the RDIER through financial investments and the construction of physical infrastructure. Second, these two core paths can be further subdivided into six configurational paths, each representing a different way of allocating resources and requiring a combination of traditional and

digital resources and capabilities. Among them, the "balanced resources and capabilities type" is the most important driving path to enhance the RDIER. This also re-emphasizes that to enhance the RDIER, it is important to focus not only on the accumulation and development of traditional resources and capabilities but also on the cultivation and application of digital resources and capabilities.

(4) The absence of technological innovation capabilities and inadequate digital governance emerge as critical factors constraining the enhancement of RDIER. The absence of these two factors renders regional digital innovation ecosystems vulnerable when confronted with changes and challenges. First, the lack of technological innovation capabilities hampers the speed and quality of regional innovation, making it difficult to swiftly adapt to new technological advancements and market demands. Second, insufficient digital governance hinders effective data management and security protection, impeding collaboration and synergistic innovation in the digital environment. These issues collectively weaken the RDIER, rendering them less capable of responding to external shocks and internal changes.

5.2 Policy implications

Based on the above research results, this paper has the following policy implications.

First, it is essential to establish innovative spatial carriers that complement each other, fostering a conducive atmosphere for coordinated regional development. To rapidly enhance overall RDIER, each region should leverage its comparative advantages, creating synergistic efforts that promote a more balanced resilience across the entire ecosystem. For the eastern and central regions, it is essential to leverage the radiation effect of resources and capabilities while steadily developing the economy and enhancing ecosystem resilience. This approach aims to drive the improvement of resilience in less developed regions. In the western and northeastern regions, it is important to base efforts on practical development and effectively extend configurational thinking to resilience enhancement. By fully utilizing existing resources and capabilities, the goal is to financialize strengths and address weaknesses, narrowing the gap between regions and preventing the widening digital divide.

Second, it is important to uphold the parallel development of “traditional + digital” approaches to empower the iterative upgrading of ecosystem resilience. This study reveals that in each pathway that promotes the enhancement of RDIER, there exists a synergistic linkage effect between traditional and digital resources and capabilities. This not only highlights the complexity of improving RDIER but also signifies that focusing solely on one aspect of resources or capabilities cannot achieve comprehensive ecosystem effects. The enhancement of RDIER requires the collaborative contribution of multiple innovative elements. Therefore, it is crucial for each region to fully unleash the value of “traditional + digital” resources and capabilities. By strategically allocating traditional and digital resources and capabilities, the RDIER can be optimized to withstand external shocks and disturbances effectively. This approach ensures a more stable and sustainable development of the regional digital innovation ecosystem.

Third, enhancing technological innovation capabilities and strengthening digital governance are crucial. The research findings indicate that RDIER improvement is hindered by the generally low levels of technological innovation capabilities and digital governance capacity within regions. This limitation makes it challenging to enhance ecosystem resilience by effectively integrating traditional and digital resources. For these regions, while continuously enriching resource reserves, it is imperative to adopt a two-pronged approach. First, efforts should be intensified to address weaknesses in basic research and achieve breakthroughs in core technologies, leveraging the leadership role of leading enterprises and the connecting role of digital platforms. This will foster a comprehensive and multifactor-driven pattern of technological innovation. Second, the focus should be directed toward resolving the pain points and challenges in governance. This entails accelerating the construction of a digital governance institutional framework, harnessing the full potential of digital technologies to empower grassroots governance, and promoting a holistic governance chain for innovative data applications. By continuously enhancing digital governance capabilities, these regions can effectively respond to and adapt to external environmental shocks.

5.3 Limitations and future research

Although this paper has made certain research progress, it still has the following limitations. First, while panel data were used, we did not address the dynamic changes in the pathways for enhancing RDIER. Future research could employ the dynamic QCA method to investigate the variations in the demand for traditional and digital resources and capabilities at different stages of regional digital innovation ecosystem development. Second, there is a need for further research on the differentiated configurational pathways across different regions. This study conducted a comprehensive analysis using a sample of 30 provinces and cities. However, it did not perform a differentiated analysis of the pathways for enhancing resilience in the digital innovation ecosystem in different regions. Future research could consider regional variations, such as dividing regions into eastern, central, and western parts or distinguishing between coastal and noncoastal areas.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Adner R (2006) Match your innovation strategy to your innovation ecosystem. Harv Bus Rev 84:98
Akter S, Michael K, Uddin MR, McCarthy G, Rahman M (2022) Transforming business using digital innovations: The application of AI, blockchain, cloud and data analytics. Ann Oper Res 308:7–39. https://doi.org/10.1007/s10479-020-03620-w
Amit R, Han X (2017) Value creation through novel resource configurations in a digitally enabled world. Strateg Entrep J 11:228–242. https://doi.org/10.1002/sej.1256
Baert C, Meuleman M, Debruyne M, Wright M (2016) Portfolio entrepreneurship and resource orchestration. Strateg Entrep J 10:346–370. https://doi.org/10.1002/sej.1227
Balland P-A, Rigby D, Boschma R (2015) The technological resilience of US cities. Camb J Reg Econ Soc 8:167–184. https://doi.org/10.1093/cjres/rsv007
Beltagui A, Rosli A, Candi M (2020) Exaptation in a digital innovation ecosystem: the disruptive impacts of 3D printing. Res Policy 49:103833
Bittencourt BA, dos Santos DAG, Mignoni J (2021) Resource orchestration in innovation ecosystems: a comparative study between innovation ecosystems at different stages of development. Int J Innov 9:108–130. https://doi.org/10.5585/iji.v9i1.18076
Brand F (2009) Critical natural capital revisited: ecological resilience and sustainable development. Ecol Econ 68:605–612
Camarinha-Matos LM, Afsarmanesh H, Galeano N, Molina A (2009) Collaborative networked organizations–concepts and practice in manufacturing enterprises. Comput Ind Eng 57:46–60
Chen H, Cai S (2023) Research on evaluation and influencing factors of regional digital innovation ecosystem resilience—Empirical research based on panel data of 30 provinces and cities in China. Sustainability 15:10477. https://doi.org/10.3390/su151310477
Chen J, Li X, Zhu Y (2024) Shock absorber and shock diffuser: the multiple roles of industrial diversity in shaping regional economic resilience after the Great Recession. Ann Reg Sci 72:1015–1045
Chesbrough HW, (2003) Open innovation: The new imperative for creating and profiting from technology. Harvard Business Press
Constantinides P, Henfridsson O, Parker GG (2018) Introduction—platforms and infrastructures in the digital age. Inf Syst Res 29:253–523. https://doi.org/10.1287/isre.2018.0794
Cooke P (2017) Complex spaces: global innovation networks & territorial innovation systems in information & communication technologies. J Open Innov Technol Mark Complex 3:9. https://doi.org/10.1186/s40852-017-0060-5
Fiss PC (2011) Building better causal theories: a fuzzy set approach to typologies in organization research. Acad Manag J 54:393–420
Gligor D (2018) Performance implications of the fit between suppliers' flexibility and their customers' expected flexibility: a dyadic examination. J Oper Manag 58:73–85. https://doi.org/10.1016/j.jom.2018.05.002
Hao W, Zhang J (2021) The reality, risk and governance of regional innovation ecosystems under digital transformation background. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, p 022052
Hervas-Oliver J-L, Gonzalez-Alcaide G, Rojas-Alvarado R, Monto-Mompo S (2021) Emerging regional innovation policies for industry 4.0: analyzing the digital innovation hub program in European regions. Compet Rev Int Bus J 31:106–129
Holling CS (1973) Resilience and stability of ecological systems. Annu Rev Ecol Syst 4:1–23. https://doi.org/10.1146/annurev.es.04.110173.000245
Holling CS (1996) Engineering resilience versus ecological resilience. Eng Ecol Constraints 31:32
Hopkins MM, Crane P, Nightingale P, Baden-Fuller C (2019) Moving from non-interventionism to industrial strategy: The roles of tentative and definitive governance in support of the UK biotech sector. Res Policy 48:1113–1127. https://doi.org/10.1016/j.respol.2019.01.008
Jacobides MG, Cennamo C, Gawer A (2018) Towards a theory of ecosystems. Strateg Manag J 39:2255–2276
Jian X, Du D, Liang D (2024) Scale or effectiveness? The nonlinear impact of talent agglomeration on high-quality economic development in China. Heliyon. https://doi.org/10.1016/j.heliyon.2024.e30121

Keeble D, Lawson C, Smith HL, Moore B, Wilkinson F (1998) Internationalisation processes, networking and local embeddedness in technology-intensive small firms. Small Bus Econ 11:327–342. https://doi.org/10.1023/A:1007942612220

Khurana I, Dutta DK, Ghura AS (2022) SMEs and digital transformation during a crisis: the emergence of resilience as a second-order dynamic capability in an entrepreneurial ecosystem. J Bus Res 150:623–641

Kraus S, Ribeiro-Soriano D, Schüssler M (2018) Fuzzy-set qualitative comparative analysis (fsQCA) in entrepreneurship and innovation research—the rise of a method. Int Entrep Manag J 14:15–33. https://doi.org/10.1007/s11365-017-0461-8

Li Y, Wang Y, Wang L, Xie J (2022) Investigating the effects of stakeholder collaboration strategies on risk prevention performance in a digital innovation ecosystem. Ind Manag Data Syst 122:2045–2071

Li X, Rao M (2023) Research on the development path of the regional digital innovation ecosystem: Configuration analysis based on fsQCA. J. Ind. Eng. Eng. Manag. 37:20–31. https://doi.org/10.13587/j.cnki.jieem.2023.06.003. (**in Chinese**)

Liang L, Li Y (2023) How does government support promote digital economy development in China? The mediating role of regional innovation ecosystem resilience. Technol Forecast Soc Change 188:122328

Liu H, Wei S, Ke W, Wei KK, Hua Z (2016) The configuration between supply chain integration and information technology competency: a resource orchestration perspective. J Oper Manag 44:13–29

Martin R, Sunley P, Gardiner B, Tyler P (2016) How regions react to recessions: resilience and the role of economic structure. Reg Stud 50:561–585

Pappas IO, Woodside AG (2021) Fuzzy-set Qualitative Comparative Analysis (fsQCA): Guidelines for research practice in Information Systems and marketing. Int J Inf Manag 58:102310

Pickett ST, Cadenasso ML (2002) The ecosystem as a multidimensional concept: meaning, model, and metaphor. Ecosystems 5:1–10

Pimm SL (1984) The complexity and stability of ecosystems. Nature 307:321–326

Pistorio A, Gastaldi L, Corso M others (2018) The Development of Digital Innovation Ecosystem: The Key Role of Policymakers, in: 40th R&D Management Conference "R&Designing Innovation: Transformational Challenges for Organizations and Society." pp. 1–17

Roundy PT, Bradshaw M, Brockman BK (2018) The emergence of entrepreneurial ecosystems: a complex adaptive systems approach. J Bus Res 86:1–10

Russell MG, Smorodinskaya NV (2018) Leveraging complexity for ecosystemic innovation. Technol Forecast Soc Change 136:114–131

Simmie J, Martin R (2010) The economic resilience of regions: towards an evolutionary approach. Camb J Reg Econ Soc 3:27–43

Sirmon DG, Hitt MA, Ireland RD (2007) Managing firm resources in dynamic environments to create value: Looking inside the black box. Acad Manag Rev 32:273–292. https://doi.org/10.5465/amr.2007.23466005

Stathaki C, Xenakis A, Skayannis P, Stamoulis G (2020) Studying the role of proximity in advancing innovation partnerships at the dawn of industry 4.0 era, In: European Conference on Innovation and Entrepreneurship. Academic Conferences International Limited, pp 651–XXII

Suoniemi S, Meyer-Waarden L, Munzel A, Zablah AR, Straub D (2020) Big data and firm performance: the roles of market-directed capabilities and business strategy. Inf Manage 57:103365. https://doi.org/10.1016/j.im.2020.103365

Suseno Y, Laurell C, Sick N (2018) Assessing value creation in digital innovation ecosystems: A Social Media Analytics approach. J Strateg Inf Syst 27:335–349. https://doi.org/10.1016/j.jsis.2018.09.004

Theodoraki C, Catanzaro A (2022) Widening the borders of entrepreneurial ecosystem through the international lens. J Technol Transf 47:383–406

Troy AS, Willroth EC, Shallcross AJ, Giuliani NR, Gross JJ, Mauss IB (2023) Psychological resilience: an affect-regulation framework. Annu Rev Psychol 74:547–576

Urbinati A, Manelli L, Frattini F, Bogers ML (2022) The digital transformation of the innovation process: orchestration mechanisms and future research directions. Innovation 24:65–85. https://doi.org/10.1080/14479338.2021.1963736

Wang X, Luo Y (2020) Has technological innovation capability addressed environmental pollution from the dual perspective of FDI quantity and quality? Evid China J Clean Prod 258:120941

Wang J, Wang B, Dong K, Dong X (2022a) How does the digital economy improve high-quality energy development? The case of China. Technol Forecast Soc Change 184:121960

Wang Y, Tian Q, Li X, Xiao X (2022b) Different roles, different strokes: how to leverage two types of digital platform capabilities to fuel service innovation. J Bus Res 144:1121–1128. https://doi.org/10.1016/j.jbusres.2022.02.038
Wen Y, Zhao M, Zheng L, Yang Y, Yang X (2023) Impacts of financial agglomeration on technological innovation: a spatial and nonlinear perspective. Technol Anal Strateg Manag 35:17–29
Xie X, Wang H (2020) How can open innovation ecosystem modes push product innovation forward? An fsQCA analysis. J Bus Res 108:29–41
Xie W, Zhang Q, Lin Y, Wang Z, Li Z (2024) The effect of big data capability on organizational innovation: a resource orchestration perspective. J Knowl Econ 15:3767–3791. https://doi.org/10.1007/s13132-023-01208-w
Xu S, Wu F, Cavusgil E (2013) Complements or substitutes? Internal technological strength, competitor alliance participation, and innovation development. J Prod Innov Manag 30:750–762. https://doi.org/10.1111/jpim.12014
Xu A, Qiu K, Jin C, Cheng C, Zhu Y (2022) Regional innovation ability and its inequality: measurements and dynamic decomposition. Technol Forecast Soc Change 180:121713. https://doi.org/10.1016/j.techfore.2022.121713
Xu L, Zhong H, Huang X, Zhu X (2023) Innovation target responsibility system, capital allocation and regional innovation capacity: evidence from China☆. Finance Res Lett 58:104662
Xu X, Yang X, Lian H (2024) How does tax revenue sharing affect local government governance?—Empirical evidence from Chinese cities. Finance Res Lett 64:105473. https://doi.org/10.1016/j.frl.2024.105473
Yang G, Deng F, Wang Y, Xiang X (2022a) Digital paradox: Platform economy and high-quality economic development—New evidence from provincial panel data in China. Sustainability 14:2225
Yang W, Lao X, Zhou Q, Zhang L (2022b) The governance niche configurations for the resilience of regional digital innovation ecosystem. Stud. Sci. Sci. 40:534–544. https://doi.org/10.16192/j.cnki.1003-2053.20210723.003. (**in Chinese**)
Yi C, Ma L, Liu Z, Liang K, Huang X (2023) Cultivating regional innovation ecosystems in the digital age: case studies of four cites in China. Sci Technol Soc 28:191–212
Zamora D, Barahona JC, Palaco I (2016) Case: digital governance office. J Bus Res 69:4484–4488
Zhang M, Cheng R, Fei J, Khanal R (2024) Enhancing Digital Innovation Ecosystem Resilience through the Interplay of Organizational, Technological, and Environmental Factors: A Study of 31 Provinces in China Using NCA and fsQCA. Sustainability 16:1946
Zheng Q, Gu D, Liang C, Fang Y (2020) Impact of a firm's physical and knowledge capital intensities on its selection of a cloud computing deployment model. Inf Manag 57:103259. https://doi.org/10.1016/j.im.2019.103259
Zhu X, Li Y (2023) The use of data-driven insight in ambidextrous digital transformation: How do resource orchestration, organizational strategic decision-making, and organizational agility matter? Technol Forecast Soc Change 196:122851