Journal of Innovation & Knowledge 9 (2024) 100542

Journal of Innovation & Knowledge

https://www.journals.elsevier.com/journal-of-innovation-and-knowledge

Digital infrastructure and innovation: Digital divide or digital dividend?

Zhuo-Ya Du[a], Qian Wang[b,*]

[a] School of Economics, Jilin University, Qianjin Street 2699, Changchun, Jilin 130012, PR China
[b] Public Sector Research Center KRI, School of Economics, Jilin University, Qianjin Street 2699, Changchun, Jilin 130012, PR China

ARTICLE INFO

Article History:
Received 12 December 2021
Accepted 7 August 2024
Available online 12 August 2024

Keywords:
Digital infrastructure
Digital divide
Regional heterogeneity
Mediating effect model
Threshold regression model

JEL classification:
O350
H730
O31
O38

ABSTRACT

With more activities being moved online during the COVID-era, digital infrastructure, as a public service, is now playing a greater role in influencing innovation and making the symbiotic relationship between innovation subjects closer. While the surge in patenting in China is associated with a significant innovation gap, there is noticeable regional disparity in digital infrastructure. This study investigates whether the digital infrastructure divide widens the innovation gap in the context of the innovation ecosystem. Based on the entropy weight method, a comprehensive index of digital infrastructure was constructed using provincial panel data from China for the years 2013 to 2018. The findings suggest that the digital infrastructure divide widens the innovation gap; however, this gap can be narrowed by upgrading the industrial structure. The relationship between different regions in China involves both competitive and reciprocal symbiosis. The mediating effect of the industrial structure in the eastern region is smaller than that in the non-eastern region. Moreover, the digital infrastructure divide has a disadvantage for late adopters when digital infrastructure falls below a specific threshold. Once this threshold is crossed, its impact changes from a digital divide to a digital dividend.

These findings have several theoretical implications. In digital economy literature, our support for comprehensively assessing the level of digital infrastructure is noteworthy. In innovation ecosystem literature, the broad framework that encompasses the evolution of innovation, including digital infrastructure and industrial structure, is significant. This study highlights the digitization of the innovation ecosystem and offers practical implications for narrowing the innovation gap between researchers, individuals, and policymakers.

Introduction

Under an innovation-driven development strategy, China has experienced a surge in patenting in recent years (Hu et al., 2017). In 2018, the number of domestic patents granted in China reached 2319,209, with an average annual growth rate of 20.22% over the past six years. According to the Patent Cooperation Treaty released by the World Intellectual Property Organization on March 2, 2021, although scientific and technological research and development have been affected by the COVID-19 pandemic, the number of patent applications in China increased by 16.1% year-on-year in 2020, ranking first in the world. However, there is a significant imbalance in regional innovation capability in China. Its regional innovation capability exhibits characteristics of geographical agglomeration, with patent licensing concentrated primarily in the eastern region, as shown in Fig. 1. The figure illustrates that the deepest shade of reddish-brown represents provinces with over 100,000 patents, all of which lie in the eastern region. Furthermore, the number of provinces with over 100,000 patents in this region has been increasing annually. Outside of the eastern region, only Sichuan falls within the second tier, with patent counts ranging from 50,000 to 100,000. The remaining non-eastern provinces indicate minimal growth in patent numbers over the years. The number of patents granted in the eastern region of China accounts for 71.82% of the total, but there is significant heterogeneity in digital infrastructure across the country. In 2018, the number of internet broadband access ports and computers in the eastern region of China was 43.47% higher than that in the non-eastern region. From 2013 to 2018, an average of 85,818 patents were granted annually in the eastern region, compared to 17,818 in the non-eastern region.

Innovation thrives in a peaceful environment with favorable economic conditions and material guarantees (Wang & Du, 2022). Studies have revealed the factors that foster innovation by examining aspects such as intellectual property protection (Furukawa, 2010; Gangopadhyay & Mondal, 2012), spillover effects of foreign direct investment (Cheung & Lin, 2004), democracy (Gao et al., 2017), emigration of skilled individuals (Thomas et al., 2020), and applied research institutions (Pfister et al., 2021). However, it is worth noting that the digital environment also plays a crucial role in influencing

* Corresponding author.
E-mail address: wangqian@jlu.edu.cn (Q. Wang).

https://doi.org/10.1016/j.jik.2024.100542

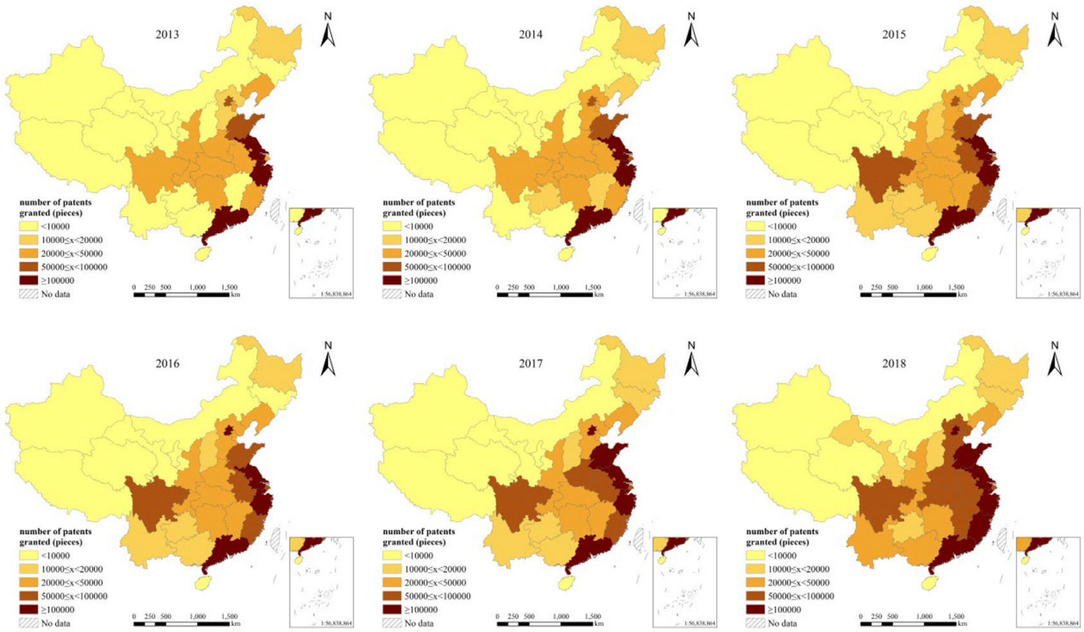

Fig. 1. Number of patents granted by provinces in China (2013 - 2018).

innovation. It serves as a key factor in re-engineering business processes, products, and services (Sestino et al., 2020), but there is scant discussion on this topic within academia.

China has implemented a new infrastructure program to promote the development of its digital economy. However, there are significant variations in the level of investment and development of new infrastructure between the eastern and non-eastern regions, which can be attributed to differences in economic development, factor inputs, and resource endowments. For instance, according to data from the National Bureau of Statistics of China, Beijing, a highly developed eastern province, achieved a cumulative total of 7003.73 billion yuan in telecommunications services from 2019 to 2022, while Guangxi accumulated only 531.8 billion yuan during the same period.

Numerous studies have demonstrated that regional economic foundations play a crucial role in shaping the digital divide (Cruz-Jesus et al., 2018; Dewan et al., 2010). The impact of digital infrastructure on traditional economies and societies has been extensively examined (Ahn, 2020; Ardito et al., 2018). Innovation is a fundamental driver of economic growth. Therefore, understanding whether digital infrastructure widens or narrows the innovation gap is important to bridge the gap in economic growth. The evident disparities in digital infrastructure and innovation across different regions in China provide valuable opportunities to study the impact of digital infrastructure on innovation from the perspective of regional heterogeneity. Hence, this study investigates whether the digital infrastructure divide widens the innovation gap and whether this gap can be bridged or continues to expand. What policies should the Chinese government formulate to narrow this innovation gap? To explore these questions, this study provides a fresh perspective on the interaction between digital infrastructure and innovation, serving as a foundation for analyzing the evolution of innovation in the process of digitalization. This research holds both policy and economic significance, as it offers valuable insights into China's transition toward an innovation-based economic growth model and its new infrastructure program, which primarily focuses on constructing digital infrastructure.

This study makes three key contributions to existing literature. This is the first empirical study on the impact of digital infrastructure on the innovation gap. In contrast to the literature (Huang & Liu, 2020; Jiao et al., 2015; Li et al., 2020), which typically employs a single indicator to measure digital infrastructure, we propose a comprehensive index of the digital infrastructure level using the entropy weight method. This approach lays the groundwork for explaining the evolution of digital infrastructure. While other studies focus on human capital, government support (Hsu et al., 2014; Seyoum et al., 2015), and the Internet (Audretsch et al., 2015; McGuire et al., 2012), this study introduces a new perspective by considering digital infrastructure as a public good in the context of an innovation ecosystem. Our findings reveal that the promotional effect of digital infrastructure on innovation in the eastern region is higher than in the non-eastern region, indicating that the digital infrastructure divide widens the innovation gap in China.

Second, we find that the Matthew effect of the digital infrastructure divide on the innovation gap can be mitigated by upgrading the industrial structure. The mediating effects of industrial structure in the eastern region were lower than those in the non-eastern region. This enhances the theoretical understanding of innovation by analyzing the mediating effect of industrial structure.

Third, unlike linear analyses of innovation, we examine nonlinear relationships. Our findings demonstrate that the innovation gap can narrow after the digital infrastructure crosses a certain threshold. In the east region, the fostering impact of digital infrastructure on innovation slows down after the threshold, while in the non-east region, the fostering impact of digital infrastructure on innovation increases after the threshold. This suggests that the development of a digital infrastructure can alter co-evolution within the innovation ecosystem and narrow the innovation gap. Therefore, digital infrastructure has emerged as a new driving force in the evolution of innovation ecosystems in China, complementing the theory of innovation ecosystems.

The remainder of this study is organized as follows. Section 2 presents the study's theoretical framework and hypotheses. Section 3 describes our research methodology. Section 4 presents and discusses the empirical results. Section 5 presents the conclusions and policy suggestions.

Literature review and research hypotheses

The technology evolution theory believes that innovation is the main feature of the development and evolution of human society

(Coccia, 2021), and that innovation and industrial change are driven by disruptive technologies (Coccia, 2017). These topics have emerged through the co-evolution of problems and have been presented by scientific research institutions (Schaeffer et al., 2021). The innovation ecosystem model seizes important opportunities and addresses environmental threats (Ardito et al., 2021; Miteva, 2022). In recent years, there have been more discussions on innovation ecosystems based on the technological evolution theory (Granstrand & Holgersson, 2020).

The innovation ecosystem consists of core enterprises, upstream and downstream participants, users, and their environments, emphasizing the relationships among innovation subjects (Cozzolino et al., 2021). According to the literature, the relationships among subjects in an innovation ecosystem are mainly classified into three types: competition coexistence, parasitic symbiosis, and reciprocal symbiosis (Adner & Kapoor, 2010; Bacon et al., 2020). Some scholars argue that parasitic and reciprocal symbioses coexist, complement each other, and jointly promote enterprises' continuous innovation (Hou & Shi, 2021). Although some scholars have proposed that an innovation ecosystem is an incorrect analogy of natural ecosystems and that the term ecosystem should be avoided (Oh et al., 2016), this study holds that the logical relationship is tenable.

With the ongoing advancement of a new round of technological revolution, digital information has become a critical production factor that is significantly influencing and participating in the innovation ecosystem. The foundation of innovation ecosystem technology resides in digital platform technology, which offers dynamic knowledge exchange opportunities for subjects requiring intensive knowledge (Siaw & Sarpong, 2021). In recent years, digital infrastructure has formed a core-periphery structure (Rodon & Eaton, 2021) that is highly open and unique (Inoue, 2021). It not only ensures the competitive advantage of the subjects but also generates a technological spillover effect.

The impact of the digital infrastructure on innovation activities is reflected in the following points. First, a digital communication platform can mitigate the impact of uncertainty propagation (Gomes et al., 2021) and help the government understand the overall business ecosystem (Kim, 2021). Second, digitalization has reshaped the value co-creation method between innovation subjects and expanded innovation ecosystem theory because it requires all participants to use interactive service software systems to handle complex product processes (Ceccagnoli et al., 2012; Kamalaldin et al., 2021). Third, digitization manages the assets of other linear infrastructures and promotes the flow of goods and services (Kraus et al., 2021), and serves as a kind of infrastructure that participates in the urban metabolic cycle (D'Amico et al., 2022), ensures the full use of resources, and innovates urban development models. Fourth, digital infrastructure is conducive to reducing transaction costs and improving innovation efficiency (Kleis et al., 2012; Song & Song, 2010). The rapid development of digital infrastructure has accelerated the speed of information flow, reduced the cost of obtaining and exchanging information, and enabled innovative subjects to easily and quickly access the most advanced technical information (Bharadwaj, 2000). It also accelerates research and development (R&D), improves technical capability, and brings economic benefits such as profitability and competitive advantage (Wang & Wang, 2012). Thus, related enterprises have become leaders in innovation (Leidner et al., 2010). The high flow of information supported by digital infrastructure helps production factors to flow to areas with a higher marginal rate of return, thereby avoiding resource mismatches and improving innovation efficiency. Innovation activities generally have a long return cycle that requires a large amount of R&D investment, indicating a relatively high risk (Hall, 2002). Fifth, the digital infrastructure breaks the time and space constraints of economic activities. This enables entrepreneurs to benefit from long-tail effects, such as financing through crowdfunding and selling in larger markets. Regions with a higher level of information infrastructure construction have greater technological convenience, thereby improving productivity and accelerating the realization of technological change (Niebel, 2018). However, suburban and rural areas are often excluded from digital social innovation because of the low level of digital infrastructure, which limits innovation participants, reduces the network diffusion range, and increases information acquisition costs (Kaletka & Pelka, 2015).

Economic foundations and talent reserves are considered important factors affecting the digital divide. Construction costs are a significant constraint in promoting digital infrastructure (Cruz-Jesus et al., 2018; Dewan et al., 2010), and those who benefit from digital infrastructure typically have economic advantages (Hsieh et al., 2008). The application of deeper and more complex digital technologies requires users to have a certain degree of financial literacy and knowledge reserves. Digital infrastructure can play an important role in areas with more scientific and technological talent, digital infrastructure can fully play its role (Chinn & Fairlie, 2007; Wilson et al., 2003). Considering the economic foundation and talent reserves, a substantial gap exists between China's eastern and non-eastern regions, and the digital divide further exacerbates the imbalance in innovation levels in different regions.

Hypothesis 1. *Digital infrastructure promotes innovation and its promotion impact in regions where better digital infrastructure is greater.*

Major technological infrastructures play a significant role in promoting innovation by leading technological frontiers, forming emerging strategic industries, and incubating innovative talent. Some scholars believe that information technology is the driving force behind innovation performance, and that its impact on innovation performance is influenced by other organizational factors, such as developmental culture, absorptive capacity, and competitive intensity (Chen et al., 2015). The use of the internet improves the utilization efficiency of production factors in various traditional industries, promoting them to enhance supply quality, upgrade industrial structures, and realize intelligent production and high-value-added manufacturing processes (Lee et al., 2017). Internet usage generates new products and formats (Rehm et al., 2016) and accelerates the emergence of new industries (Iansiti & Lakhani, 2014).

Industrial upgrading requires higher demand for Internet services in R&D departments, forcing them to engage in technological innovation and industrial upgrading (Martínez et al., 2010; Shahiduzzaman & Alam, 2014). In an open economy, industrial upgrades push a country's products and industries into the international market and integrate them into the global value chain. Enterprises gain foreign knowledge spillovers and technology diffusion (Liu et al., 2020) and enhance their independent innovation capabilities through technology absorption and re-innovation.

Fig. 2 shows the channels through which the digital infrastructure affects regional innovation. Digital infrastructure directly affects regional innovation by enabling access to more information, accelerating the flow of goods, and reducing market frictions. Additionally, it indirectly influences innovation by facilitating industrial upgrading.

Digital infrastructure provides a profitable market and a solid foundation for the development of information communication technology (ICT). In turn, the ICT industry drives the digital transformation of the economy and upgrades its industrial structure. The specialization and diversification of provincial regional industrial structures can promote regional innovation performance, leading to regional heterogeneity (Li et al., 2014). Prosperous regions that typically exhibit better digital infrastructures usually have higher digitalization in their industries and economies. A reasonable industry structure aligns with the law of resource endowment (Duarte & Restuccia, 2010). When prosperous regions are close to their reasonable industry structure with the support of digital infrastructure, the upgrading effects of digital infrastructure on industry structure slow

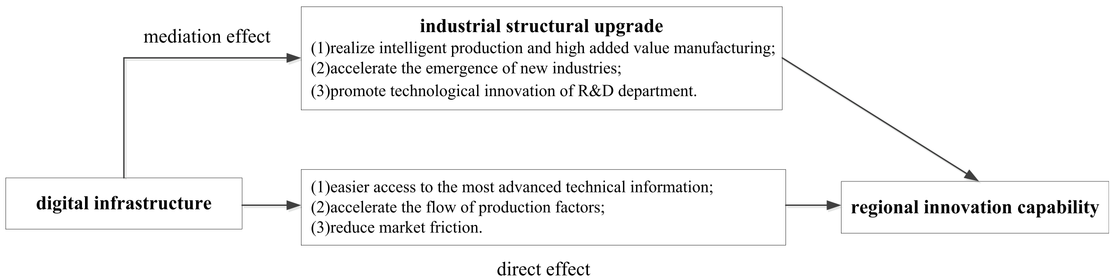

Fig. 2. Conceptual framework of digital infrastructure on innovation.

under the law of marginal decrease. This leads to the following hypotheses:

Hypothesis 2. *The mediating effect of industrial structure in digital infrastructure promoting innovation in the east region is lower than that in the non-east region.*

The network effects of digital infrastructure, combined with the cumulative effects of science and technology, lead to a nonlinear impact of digital infrastructure on innovation. As the depth and breadth of Internet usage continue to expand, an increasing number of enterprises are embarking on digital transformation, resulting in growing complexity of both digital infrastructure and actual services (Tassey et al., 2009). Once the digital infrastructure reaches a certain threshold, it can create a profitable market for the rapid development of the Internet of Things (IoT) industry, thereby fostering collaborative innovation (Hou & Li, 2020). Consequently, initial investments in the digital infrastructure can accelerate innovation. However, when the supply scale of the digital infrastructure reaches saturation, such as when each person owns more than one computer, the marginal positive impact decreases. The impact of digital infrastructure on innovation is nonlinear, and its nonlinear effects depend on the level of infrastructure. This leads to the following hypotheses:

Hypothesis 3. *The promotion of digital infrastructure on innovation exhibits threshold effect, and after the threshold the difference between the east and non-east region narrows.*

Model, variables, and data

Research settings, sample, and data

This study used panel data from 30 administrative provinces in China, covering the 2013−2018 period and resulting in a total of 180 observations. To discuss the impact of digital infrastructure divide on innovation gap, we divide the 30 provinces into eastern and non-eastern regions according to their economic level and geographic location. The eastern coastal provinces of China have higher digital infrastructure and economic levels than non-eastern provinces.

Patent-granted data were obtained from the China Science and Technology Statistical Yearbook. Patent case data were obtained from the annual statistical reports of the State Intellectual Property Office. The data on secondary and tertiary industry employment were taken from the China Labour Statistical Yearbook and China's Tertiary Industry Statistical Yearbook. Data for the other variables were obtained from the China Statistical Yearbook.

Variable selection

The number of patent grants is considered a more accurate reflection of the quality of innovation output (Graham et al., 2015). Thus, we use the number of patent grants in each year as a metric to gage the level of innovation within a provincial administrative region.

The level of digital infrastructure is the core explanatory variable and the threshold variable. At present, the Chinese government has not disclosed a comprehensive index of the digital infrastructure level, which has led some scholars to adopt a single indicator, such as aggregates of the post and telephone communications business (Huang & Liu, 2020), the number of telephone users per capita (Li et al., 2020), and corporate computer usage (Jiao et al., 2015), and other indicators. The Internet is a complex system. Although a single indicator is an important embodiment of digital infrastructure, it is not sufficiently comprehensive. Certain indicators are limited in their ability to fully capture the realities of China's digital infrastructure development and thus may not provide an accurate representation of its true level. Following the entropy weight method (Cui et al., 2021), we calculated the provincial digital infrastructure variables using four sub-indicators.

Assume that the value of the *j*th indicator data of the *i*th province is $(x_{ij})_{mn}$ i = 1, 2, . . ., m, j = 1, 2, . . ., n. First, the dimensionless processing of the raw data yields:

$$r_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{1}$$

and the entropy of the *j*th indicator is defined as:

$$e_j = -k\sum_{i=1}^{m} p_{ij} \ln p_{ij} \quad j = 1, 2, ..., n \tag{2}$$

Here, $p_{ij} = r_{ij}/\sum_{i=1}^{m} r_{ij}$, $k = 1/\ln m$, p_{ij}=0 and $p_{ij} \ln p_{ij}$=0. The weight of the j^{th} indicator is defined as

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n}(1 - e_j)} \tag{3}$$

Here, $0 \le w_j \le 1, \sum_{j=1}^{n} w_j = 1$. We then can get the comprehensive value of digital infrastructure:

$$DIG_i = w_1 x_{i1} + w_2 x_{i2} + w_3 x_{i3} + w_4 x_{i4}, i = 1, 2, ...30 \tag{4}$$

The indicators of China's digital infrastructure level and the corresponding weights designed in this study are shown in Table 1.

Industrial structure (*IS*): We use the ratio of added value between the tertiary and secondary industries as a metric to measure *IS*, which serves as a mediating variable. The other driving factors for innovation were controlled to estimate the impact of digital infrastructure on innovation.

Economic openness: Foreign direct investment (*FDI*) can increase total factor productivity (*TFP*) (Herzer & Donaubauer, 2018), *TFP* is the main indicator to measure technological progress, which can improve regional innovation capacity. We use the percentage of *FDI* within *GDP* of each provincial region to gage its level of economic openness. The valuation of *FDI* is denominated in RMB, using the average exchange rate of *USD* for each year. This index is relative and unaffected by price factors. A higher value indicated a higher level of economic openness.

Human capital: Advancement of innovation is closely intertwined with investment in human capital. Developing human capital can significantly enhance a company's internal capabilities and knowledge-

Table 1
China's digital infrastructure indicators and corresponding weights.

indicators	indicators description	weight					
		2013	2014	2015	2016	2017	2018
Number of computers at the end of year	Reflect the construction level of regional digital equipment	0.316	0.321	0.311	0.314	0.320	0.328
Number of internet broadband access port	Reflect the utilization of digital hardware equipment in the region	0.176	0.185	0.183	0.173	0.178	0.182
Number of internet broadband access users	Reflect the regional Internet penetration rate	0.187	0.194	0.206	0.210	0.201	0.184
Number of websites owned by the company	Reflect the allocation ability of regional Internet information resources	0.320	0.300	0.299	0.303	0.300	0.306

Table 2
Variable definitions and data sources.

Variable type	Variable name	symbol	Variable definitions	Data sources
Dependent variable	Innovation output	*PG*	The logarithm of the number of patents granted	China Statistical Yearbook
Core independent variable	Digital infrastructure	*DIG*	The logarithm of digital infrastructure index	
Intermediary variable	Industrial structure	*IS*	Added value of tertiary industry/added value of secondary industry (%)	
Industrial structure control variables	Labor	*IE*	Employment in the tertiary industry/ employment in the secondary industry (%)	China Labor Statistical Yearbook and China's Tertiary Industry Statistical Yearbook
	Social purchasing power	*SPP*	Total social retail sales/*GDP* (%)	China Statistical Yearbook
Regional innovation control variables	Human capital	*HC*	Population with college degree or above/ total permanent population at the end of the year (%)	
	R&D investment	*R&D*	R&D investment/*GDP* (%)	
	Intellectual Property Protection	*IPP*	Number of patent dispute cases closed/ Number of patent dispute cases (%)	Statistical annual report of the State Intellectual Property Office
	Marketization process	*MP*	State-owned industrial enterprise profit/ total industrial enterprise profit (%)	China Statistical Yearbook
Common control variables	Economic openness	*FDI*	*FDI*/*GDP* (%)	

creation potential (Zahedi & Naghdi Khanachah, 2021). The acquisition of new skills and perspectives through human capital plays a pivotal role in facilitating fundamental innovation (D'Este et al., 2016). To measure the level of human capital within a region, we use the ratio of individuals with college degrees or higher to the permanent resident population at the end of each year.

R&D investment: Most studies show that *R&D* input can break the financial constraints of innovation subjects, bring about more innovation output (Beneito et al., 2014; Xu et al., 2020), and help innovation subjects improve innovation efficiency. (Carayannis & Sagi, 2002) believe that *R&D* expenditure is a key factor in promoting innovation in a country. Other scholars hold different opinions. (Ejermo et al., 2011) state that *R&D* investment, as an input, adheres to the law of decreasing marginal returns, and increasing *R&D* input does not transform into ideal innovation output. The impact *R&D* investments on innovation varies. We use the percentage of *R&D* in *GDP* to measure the level of *R&D* investment in the region.

Intellectual property protection: Intellectual property protection is crucial in safeguarding the fruits of innovation and plays a pivotal role in fostering regional innovation. Intellectual property rights, such as trademarks, patents, and copyrights, are an important part of innovation and development in any country (Furukawa, 2010; Gangopadhyay & Mondal, 2012). Some scholars have used the *GP* index to measure intellectual property protection. (Ginarte & Park, 1997) construct a country's *GP* index based on five criteria: coverage of patent law, signing of international patent agreements, provisions of rights protection, implementation of measures, and duration of protection. However, this method often overlooks the impact of law enforcement on intellectual property rights protection when measuring developing countries and fails to account for noticeable regional disparities in intellectual property rights. We used the proportion of closed patent dispute cases within a year (*IPP*) to measure the level of regional knowledge property rights protection. Patent disputes encompass infringements and other legal disputes.

Marketization process: Following (Huang & Liu, 2020), we use the proportion of state-owned industrial enterprises profits in total industrial enterprises profits (*MP*) to measure the capability of regional marketization. To estimate the impact of digital infrastructure on upgrading industrial structure, confounded variables influencing industrial structure should be controlled.

Labor: Labor is always an important traditional factor in driving industrial value-added (Kujur, 2019). We use the ratio of tertiary industry employment to secondary industry employment (*IE*) in a region to control labor input.

Social purchasing power: Consumption plays an obvious role in promoting industrial upgrading (Yao et al., 2019). We use the proportion of total social retail sales in *GDP* (*SPP*) to measure regional social purchasing power.

Economic openness: We continue to use foreign direct investment (*FDI*) as a percentage of *GDP* in each provincial region to measure economic openness. By providing advanced technology, foreign enterprises can partially bridge the technological gap within the host country. This improves the productivity of domestic enterprises and promotes the upgrading of industrial structures. Some scholars have confirmed that *FDI* is beneficial for upgrading industrial structures in home countries (Xu & Liu, 2018). Definitions of the variables and data sources are listed in Table 2.

Model and data analysis procedures

To estimate the impact of digital infrastructure on regional innovation, we set the following regression model:

$$PG_{it} = \alpha_0 + \alpha_1 DIG_{it} + \phi X_{it} + \varepsilon_{it} \tag{5}$$

where subscript i is the province, subscript t is the year, PG_{it} represents the innovation of the i^{th} province in period t, and digital infrastructure is represented by DIG_{it}. X_{it} stands for the control variable.$\varepsilon$is the error term.

Table 3
The descriptive statistics of variables.

Variable	Eastern regression				non-Eastern regression			
	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max
PG	10.9626	1.3609	7.1937	13.0775	9.5932	1.1011	6.2186	11.3779
DIG	13.3150	0.9928	10.7564	14.8459	12.1837	0.7189	10.3059	13.3557
IS	1.5503	0.9697	0.6954	5.0221	1.0460	0.2801	0.6325	2.1861
IE	1.3031	1.1564	0.3473	4.5238	1.0570	0.4678	0.2544	3.7807
SPP	64.0600	47.4027	1.2873	168.1919	41.1637	35.4150	8.2163	180.7872
HC	0.5651	0.1218	0.3874	0.8940	0.4766	0.1315	0.2145	0.8426
R&D	1.5050	0.5967	0.1677	2.1721	0.7945	0.3421	0.2464	1.6142
IPP	13.7612	29.7015	0.0000	100.0000	11.5644	27.8654	0.0000	116.2162
MP	74.5189	19.5841	32.4652	108.9870	62.1563	33.9334	−190.2248	130.9806
FDI	70.1939	42.7695	12.0611	175.5564	17.7222	8.2384	4.8068	59.5147

To measure the intermediary effects of the industrial structure on the digital infrastructure level and regional innovation, the mediating effect model can be expressed as follows:

$$IS_{it} = \beta_0 + \beta_1 DIG_{it} + \phi X_{it} + \varepsilon_{it} \quad (6)$$

$$PG_{it} = \phi_0 + \phi_1 DIG_{it} + \phi_2 IS_{it} + \phi X_{it} + \varepsilon_{it} \quad (7)$$

Here, IS_{it} represents the industrial structure and is the mediating variable. A mediating effect must simultaneously meet the following three conditions: First, DIG_{it} significantly affects PG_{it} in Eq. (5) without IS_{it}; that is, the impact of the digital infrastructure level on innovation, as tested by the benchmark model. Second, the core explanatory variable DIG_{it} in Eq. (6) has a significant impact on the mediating variable IS_{it}, and the mediating variable IS_{it} has a significant impact on the explained variable PG_{it}. Finally, if the coefficient of DIG_{it} in Eq. (7) after adding the mediating variable IS_{it} compared with Eq. (5), there is a partial mediating effect. If the coefficient of DIG_{it} is not significant in Eq. (7) After adding the mediating variable IS_{it}, a complete mediating effect was observed.

Hansen's (1999) panel threshold model is used to test the nonlinear impact of digital infrastructure on innovation. On the basis of Eq. (7), the model is constructed as follows:

$$PG_{it} = \delta_0 + \delta_1 I(DIG_{it} \leq \gamma) + \delta_2 I(\gamma < DIG_{it}) + \delta_3 IS_{it} + \phi X_{it} + \varepsilon_{it} \quad (8)$$

Here, DIG_{it} represents the core explanatory and threshold variables. γ is the threshold value to be estimated. The other variables are defined similarly as in Eq. (7). γ can divide the provincial sample studied into two intervals. However, the regression coefficient values of the two sample intervals differ. I (•) is the indicator function. When the conditions were satisfied, the value was 1; otherwise, it was 0.

Results

Table 3 presents the variables' descriptive statistics. The descriptive statistics of the variables indicate that the Eastern region exhibits better economic development than the non-Eastern region. Except for the number of patents granted, all economic variables have higher average levels in the eastern region than in the non-eastern region.

Estimated results of the mediating effect

Before conducting panel data regression, we tested for multicollinearity between the explanatory variables. The VIF (variance inflation factor) test results indicated no multicollinearity among the variables. The regression results for the mediating effects are presented in Table 4.

Columns (1)–(3) show the regression results for the eastern region, whereas columns (4)–(6) display the regression outcomes for the non-eastern region. The regression results of the models in different regions yield the same conclusion; that is, the improvement of the digital infrastructure level is significantly conducive to the improvement of innovation and the upgrading of industrial structure. Upgrading industrial structures can promote innovation significantly. Thus, the existence of partial mediating effects signifies that the impact of digital infrastructure on innovation is partly realized through the mediating variable (*IS*).

By comparing the regression results in Table 4, it is evident that the coefficient of the digital infrastructure in the eastern region is greater than that in the non-eastern region. This suggests that the digital infrastructure in the eastern region exerts a more substantial influence on innovation. This discrepancy may be attributed to the earlier and superior construction of digital infrastructure in the eastern region compared with the non-eastern region, indicating a first-mover advantage in digital infrastructure development. The positive impact of digital infrastructure on innovation is more pronounced in regions with advanced digital infrastructure. The higher levels of digital infrastructure and innovation in the eastern region imply that the digital infrastructure gap widens the innovation disparity.

The indirect effect of digital infrastructure on innovation in the eastern region was 0.2166 (0.8088 × 0.2678). This implies that for every additional unit of digital infrastructure, regional innovation indirectly improves by 0.217 units, accounting for 11.549% (0.2166/1.8756) of the total effect. In the non-eastern region, the indirect effect and proportion of digital infrastructure on innovation are 0.0336 and 24.986%, respectively. This finding suggests that the positive indirect effect of digital infrastructure on innovation through industrial structure upgrading is greater in the non-eastern region than in the eastern region. One possible reason for this discrepancy is that industrial structure upgrading in the eastern region began earlier than in the non-eastern region, and the industrial structure in the eastern region has already reached a more optimal level, leading to the early release of the spillover dividend of the industrial structure on innovation. Consequently, the indirect effect of industrial structure on innovation (0.2678) in the eastern region is noticeably smaller than in the non-eastern region (0.4844). This indicates that upgrading the industrial structure can help reduce the Matthew effect of digital infrastructure divided by the innovation gap.

Estimated results of the threshold regression

To estimate the nonlinear impact of digital infrastructure divided by the innovation gap, a threshold regression model was used for the empirical analysis. Before conducting the estimation, we test for the existence of panel thresholds based on (Hansen, 1999)'s method. The test was performed using the bootstrap method in State15.0 statistical software. By repeatedly sampling 300 times, we obtained the p-value corresponding to the test statistic to determine the existence of a threshold effect. The results of the threshold effect test are presented in Table 5. The threshold variable (*DIG*) significantly passes

Table 4
Regression results of mediating effect.

VARIABLES	Eastern regression results			non-Eestern regression results		
	(1) *PG(FE)*	(2) *IS(FE)*	(3) *PG(FE)*	(4) *PG(FE)*	(5) *IS(FE)*	(6) *PG(RE)*
DN	1.8755***	0.8087***	1.5935***	1.6743***	0.8636***	1.2676***
	(6.40)	(3.32)	(4.93)	(5.24)	(5.68)	(10.88)
IS			0.2678*			0.4844***
			(1.87)			(4.37)
IE		0.8088***			0.0693	
		(3.32)			(1.55)	
SPP		0.0456			0.0047	
		(1.03)			(1.16)	
FDI	0.0018	0.0047***	0.0007	0.0097**	0.0043	0.0079**
	(1.46)	(4.25)	(0.53)	(2.40)	(1.35)	(2.27)
HC	1.7181		1.7734*	1.8056**		0.8803*
	(1.62)		(1.72)	(2.11)		(1.67)
R&D	0.0142		0.1187	0.1371		0.3331*
	(0.09)		(0.71)	(0.53)		(1.67)
IPP	0.0011		0.0011	0.0016*		0.0015**
	(1.30)		(1.39)	(1.76)		(2.00)
MP	−0.0017		−0.0013	0.0002		0.0005
	(−0.74)		(−0.59)	(0.34)		(0.73)
Constant	−15.0202***	−9.8507***	−11.8182***	−11.9814***	−9.8167***	−7.2290***
	(−3.87)	(−3.13)	(−2.85)	(−3.32)	(−5.52)	(−5.68)
Hausman test(P-value)	17.35(0.0039)	33.33(0.0000)	12.46(0.0864)	13.14(0.0221)	24.51(0.0001)	2.34(0.9383)
Observations	66	66	66	114	114	114
R-squared	0.751	0.677	0.768	0.728	0.509	0.751

Notes:FE stands for Fixed Effects Model; RE stands for Random Effects Model; t-statistics in parentheses;.
*** $p < 0.01$,.
** $p < 0.05$,.
* $p < 0.1$.
PG stands for innovation output; *DIG* stand for Digital infrastructure; *IS* stand for Industrial structure; *IE* stand for Labor; *SPP* stand for Social purchasing power; *HC* stand for Human capital; *R&D* stand for *R&D* investment; *IPP* stand for Intellectual Property Protection; *MP* stand for Marketization process; *FDI* stand for Economic openness.

Table 5
Threshold effect test results.

area	Threshold number	F-statistics	P-value	10%	5%	1%
Eastern	Single threshold	14.34	0.010	8.713	10.067	14.265
non-Eastern	Single threshold	36.01	0.000	16.077	18.742	26.931

Notes:10% stands for 10% critical value; 5% stands for 5% critical value; 1% stands for 1% critical value.

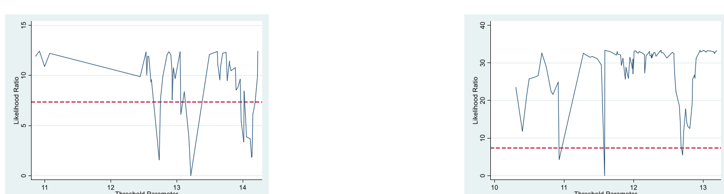

Fig. 3. Likelihood ratio function graphs of threshold regression model.Notes: From left to right are the Likelihood Ratio Function graphs of the eastern and non-eastern regions.

the single threshold test, but fails the double and triple threshold tests. Hence, only one threshold is present in the samples.

According to the test results, the corresponding threshold values for the eastern and non-eastern regions were 13.2129 and 11.5834, respectively. From the threshold model theory, the threshold estimated value is the corresponding γ value when the likelihood ratio statistic LR approaches 0. Fig. 3 shows the likelihood ratio function graphs for the estimated threshold values within the 95% confidence interval for both eastern and non-eastern regions. The true threshold is indicated by the lowest point of the LR statistic in the images, and the dotted line represents the critical value corresponding to the 95% confidence interval. Given the critical value of 7.35 is significantly higher than the threshold, we conclude that the threshold is valid and reliable. Table 6 presents the threshold regression results.

The regression results in Table 6 show that both before and after the threshold, the effect of digital infrastructure on regional innovation is significantly positive in the eastern and non-eastern regions. The results validate Hypothesis 1, which states that digital infrastructure construction improves innovation capacity.

The results revealed that the impact of digital infrastructure on regional innovation in the non-eastern region significantly increased after crossing the threshold. The coefficient in the non-eastern region increased from 1.3118 to 1.3418. However, the promotional effect of digital infrastructure in the eastern region decreased significantly after crossing the threshold, dropping from 2.4929 to 1.3345. This can be attributed to the fact that the Eastern region already possesses a strong foundation for digital infrastructure and has reached a stage of intensive development. At this stage, improving the efficiency of

Table 6
Threshold regression results.

VARIABLES	(2) Eastern	(3) non-Eastern
$I\ (DIG_{it} \leq \gamma)$	2.4929***	1.3118***
	(6.27)	(4.09)
$I\ (\gamma < DIG_{it})$	1.3345***	1.3418***
	(4.40)	(4.22)
IS	0.2390*	0.3868***
	(1.84)	(2.98)
FDI	0.0004	0.0068*
	(0.31)	(1.74)
HC	1.8929**	1.4539*
	(2.01)	(1.74)
R&D	0.0420	0.3965
	(0.27)	(1.54)
IPP	0.0014*	0.0018**
	(1.81)	(1.99)
MP	−0.0016	0.0004
	(−0.77)	(0.53)
Constant	−14.7934***	−8.2816**
	(−3.82)	(−2.31)
Observations	66	114
R-squared	0.813	0.761

Notes:.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.
PG stands for innovation output; *DIG* stand for Digital infrastructure; *IS* stand for Industrial structure; *IE* stand for Labor; *SPP* stand for Social purchasing power; *HC* stand for Human capital; *R&D* stand for *R&D* investment; *IPP* stand for Intellectual Property Protection; *MP* stand for Marketization process; *FDI* stand for Economic openness.

the input factors becomes more crucial for enhancing innovation output than simply increasing the input factors. Therefore, with an increase in investment in digital infrastructure, innovation output will show diminishing marginal utility. After crossing the threshold, the coefficient of digital infrastructure in the eastern region remained positive, but was smaller.

In contrast, the non-eastern region has weaker innovation capabilities and is yet to make a leap towards intensive development. For them, increasing innovation output still relies on driving factors such as fixed asset investments, including digital infrastructure construction. Considering the significant digital infrastructure divide between the eastern and non-eastern regions, the results of the threshold regression indicate that China's new infrastructure program has the potential to narrow the innovation gap caused by the digital infrastructure divide. This program can accelerate the crossing of thresholds for digital infrastructure. The higher promotional effect observed in the non-eastern region after crossing the threshold, coupled with the slowdown of the promotional effect in the eastern region after crossing the threshold, provides an opportunity for the non-eastern region to catch up. In the long run, narrowing the innovation gap can be achieved by improving the digital infrastructure.

Once digital information is integrated into the innovation ecosystem, it fundamentally transforms the interactions between the original subjects and the evolution of the innovation system. Through the deep integration of traditional subjects with digital technology, the delineation of product and industrial boundaries has become less distinct (Kozonogova & Dubrovskaya, 2022). Digital information possesses the characteristics of being shareable and reusable, enabling the transmission and verification of data at zero marginal cost. This low-cost input leads to a rapid increase in output levels, thereby facilitating the realization of scale effects. Consequently, once the digital infrastructure of the non-eastern region crosses the threshold of 11.5834, its impact is significantly amplified.

The sustainability of the scale effects is not guaranteed indefinitely. This is because digital technology is dynamic and can effectively respond to evolving external demands, thus driving the iterative innovation of technology and evolution of the ecosystem. When most external demands for digital infrastructure are met, the marginal effect of digital infrastructure construction diminishes. Similarly, after the digital infrastructure in the eastern region crosses the threshold of 13.2129, although it continues to have a positive impact on innovation, this impact diminishes.

Within the digital innovation ecosystem, the impact of the digital infrastructure is dynamic and evolves in response to construction and changes in the external environment. The non-eastern region is experiencing rapid initial development, while the eastern region is subject to diminishing marginal effects, resulting in differing performance between the two. Digitization enriches and enhances the intricate relationship between innovation subjects and the innovation ecosystem, ultimately promoting an overall enhancement of innovation capability and efficiency.

Robust test

To address the endogeneity problem caused by the bidirectional causal relationship between digital infrastructure and innovation output, this study employs the first lag phase of digital infrastructure (DIG_{-1}) as an instrumental variable to reexamine the original model. Using DIG_{-1} as an instrument, we establish a robust and reliable estimation of the causal effect of digital infrastructure on innovation output.

As shown in Table 7, the first-stage regression results illustrate that the instrumental variables were significantly and positively correlated with digital infrastructure. The second-stage regression results revealed a similar significant positive correlation between digital infrastructure (*DIG*) and innovation output (*PG*). Furthermore, the under-identification test yielded significant Kleibergen-Paap rk LM statistics at the 1% significance level, decisively rejecting the original hypothesis of insufficient identification of the instrumental variables. The weak identification test indicated that the Cragg-Donald Wald F-statistic exceeded the critical value of 10%, refuting the original hypothesis of weak instrumental variable. These tests collectively validate the reliability of the instrumental variables. The results support Core Hypothesis 1, which is valid after considering the endogeneity problem.

To ensure the reliability and robustness of the empirical results, we replaced the explained and core explanatory variables. The proportion of industrial Internet services, represented by cloud computing, IDC, IoT, and big data, in the telecommunications business has steadily increased over time. The upgrading of telecommunications IoT platforms reflects the development of the digital economy infrastructure (Zhang et al., 2020). This study uses the logarithm of the total telecom business volume (*TBV*) as a substitute variable for digital infrastructure and the logarithm of patent applications as a substitute variable for innovation to conduct a robustness test. The robustness test results are listed in Table 8.

The promotional effects of digital infrastructure on innovation are conducive to improvements in innovation. Moreover, partial mediating effects were observed, suggesting that the impact of digital infrastructure on innovation is partly realized through the mediating variable of industrial structure. Similarly, the indirect effect of digital infrastructure on innovation is greater in the non-eastern region than in the eastern region. These results are consistent with the estimated results when the digital infrastructure composite index was the core explanatory variable. This verified that the results were robust.

The empirical results presented above shed light on the pathways and nonlinear impacts of digital infrastructure on regional innovation, considering regional heterogeneity. Using the mediating effect and threshold regression models, we find that the promotional effect of digital infrastructure on innovation is greater in the eastern region than in the non-eastern region. This can be attributed to the early development of the digital infrastructure in the eastern region, which

Table 7
Endogenous test results.

VARIABLES	Eastern regression results		non-Eastern regression results	
	(1) *DIG*	(2) *PG*	(3) *DIG*	(4) *PG*
DIG-1	0.7615***		0.6138***	
	(14.4590)		(4.6342)	
DIĜ		3.0819***		2.9353***
		(6.0930)		(4.0554)
FDI	0.0008**	−0.0011	0.0021*	0.0013
	(2.6804)	(−0.7301)	(1.5695)	(0.2507)
HC	−0.3653	1.7138	0.3686	0.0058
	(−1.0358)	(1.1357)	(0.9066)	(0.0036)
R&D	0.0364	0.0398	−0.0304	0.1613
	(1.0643)	(0.2951)	(−0.3542)	(0.3771)
IPP	−0.0005	−0.0327	0.0022	−0.0128
	(−0.0270)	(−0.3494)	(0.3530)	(−0.3900)
MP	−0.0006	−0.0016	0.0002	0.0001
	(−1.2233)	(−0.8299)	(1.3889)	(0.0850)
Underidentification test		13.651***		8.871***
Weak identification test		62.604		56.975
R-squared		0.604		0.545
F value	67.45***	15.63***	34.07***	19.38***

Notes:.
*** $p < 0.01$,.
** $p < 0.05$,.
* $p < 0.1$.
PG stands for innovation output; *DIG* stand for Digital infrastructure; *IS* stand for Industrial structure; *IE* stand for Labor; *SPP* stand for Social purchasing power; *HC* stand for Human capital; *R&D* stand for *R&D* investment; *IPP* stand for Intellectual Property Protection; *MP* stand for Marketization process; *FDI* stand for Economic openness.

Table 8
Robust test results for the mediating effects.

VARIABLES	Eastern regression results			non-Eastern regression results		
	(1) *PG(FE)*	(2) *IS(FE)*	(3) *PG(RE)*	(4) *PG(FE)*	(5) *IS(FE)*	(6) *PG(FE)*
TBV	0.2438***	0.0923**	0.1753**	0.1819***	0.1190***	0.1051*
	(3.5444)	(2.2407)	(2.3366)	(3.2803)	(3.9234)	(1.7886)
IS			0.3796*			0.4637***
			(1.9999)			(3.0431)
IE		0.0548			0.0856*	
		(1.1856)			(1.7843)	
SPP		0.0055**			0.0093**	
		(2.0860)			(2.2041)	
FDI	0.0051***	0.0062***	0.0031*	0.0107**	0.0093***	0.0087**
	(3.2857)	(6.4303)	(1.7664)	(2.4462)	(2.9863)	(2.0349)
HC	1.2264		1.4952	2.6706***		2.1235**
	(0.8547)		(1.0685)	(3.1357)		(2.5451)
R&D	0.2922		0.4319*	0.6062**		0.8029***
	(1.3619)		(1.9664)	(2.1146)		(2.8498)
IPP	−0.0011		−0.0005	−0.0015*		−0.0008
	(−1.1056)		(−0.5035)	(−1.7545)		(−0.9187)
MP	0.0062*		0.0060*	0.0015*		0.0015*
	(1.9852)		(1.9583)	(1.8845)		(1.9137)
Constant	7.9625***	0.2515	7.6218***	7.1315***	0.0539	7.2625***
	(8.2035)	(1.1595)	(7.9601)	(19.9482)	(0.3047)	(21.0702)
Hausman test(P-value)	45.78(0.0000)	36.57(0.0000)	214.95(0.0000)	31.19(0.0000)	140.23(0.0000)	32.63(0.0000)
Observations	66	66	66	114	114	114
R-squared	0.620	0.642	0.649	0.665	0.431	0.697

Notes:FE stands for Fixed Effects Model; RE stands for Random Effects Model; t-statistics in parentheses;.
*** $p < 0.01$,.
** $p < 0.05$,.
* $p < 0.1$.
TBV stands for the total telecom business volume; *IS* stand for Industrial structure; *IE* stand for Labor; *SPP* stand for Social purchasing power; *HC* stand for Human capital; *R&D* stand for *R&D* investment; *IPP* stand for Intellectual Property Protection; *MP* stand for Marketization process; *FDI* stand for Economic openness.

aligns well with the economic foundation, talent pool, and technological advantages, thereby enabling it to play a more substantial role. The digital infrastructure divide has a latecomer disadvantage, widening the innovation gap. In the non-eastern region, the promotion of digital infrastructure for innovation significantly increases after crossing a certain threshold. By contrast, in the eastern region, the promotion effect slowed after surpassing the threshold. This could be because the eastern region has reached a stage of intensive development or has approached saturation. At this stage, increasing innovation output relies more on improving the efficiency of the input elements than on increasing the input elements themselves. Therefore, as investment in digital infrastructure increases, marginal utility in terms of innovation output diminishes. Although the digital infrastructure divide may widen the innovation gap, less prosperous regions can narrow this gap by augmenting digital infrastructure investment and upgrading their industrial structures.

Conclusions

According to the theory of innovation evolution, digital technology is an indispensable factor in innovation ecosystems. China's implementation of the new infrastructure program aims to promote digital economic growth, but there are significant variations in the level and investment of new infrastructure between eastern and non-eastern regions. This disparity has led to a noticeable innovation gap, reflected in the surge of patent filings in China. The stark contrast between digital infrastructure and innovation levels in China provides a valuable opportunity to examine the impact of digital infrastructure on innovation from a regionally heterogeneous perspective. This study investigated whether the digital infrastructure divide widens the innovation gap. The findings of this study offer a fresh perspective on the Darwinian evolution of innovation in the context of digitalization.

This study contributes to several theoretical and empirical perspectives. First, we propose a comprehensive index for the digital infrastructure level using the entropy weight method. In contrast to other studies that rely on single indicators to measure digital infrastructure, this study presents a holistic digital infrastructure index to elucidate the evolution of digital infrastructure.

Second, we introduce a new perspective to explain the evolution of innovation and the mediating effect of industrial structure by incorporating digital infrastructure as a public good within the innovation ecosystem. The results derived from the mediating effect and threshold regression model, utilizing provincial panel data from China from 2013 to 2018, indicate that the digital infrastructure divide widens the innovation gap, but also suggest that this gap can be narrowed. Most academic research on the factors influencing regional innovation has focused on dimensions such as human capital and government support (Hsu et al., 2014; Seyoum et al., 2015). However, our study endeavors to broaden this scope by emphasizing the pivotal role of digital infrastructure in shaping regional innovation dynamics.

Third, our findings reveal that the promotional effect of digital infrastructure on innovation is greater in the eastern region than in the non-eastern region. Additionally, the mediating effect of the industrial structure is smaller in the eastern region than in the non-eastern region. Most studies on innovation have primarily utilized linear regression models and overlooked the potential nonlinear effects arising from the cumulative impact of digital transformation. Our study recognizes the importance of considering these nonlinear effects and their implications for regional innovation dynamics. The relationships between different regions in China can be characterized as both competitive and reciprocal symbiosis. The divide in digital infrastructure generates latecomer disadvantage effects when digital infrastructure levels fall below a certain threshold. Once this threshold is surpassed, the impact of digital infrastructure shifts from a digital divide to a digital dividend. Thus, the development of digital infrastructure has the potential to reshape co-evolution within an innovation ecosystem and narrow the innovation gap. Overall, digital infrastructure serves as a new driving force for the evolution of China's innovation ecosystem, transforming dynamics and fostering greater innovation across regions.

These findings have significant policy implications. First, it is crucial to address the innovation gap and promote the integration of technological innovation to prevent further regional disparities during digitalization. To narrow the innovation gap, non-eastern regions should focus on improving their digital infrastructure and upgrading their industrial structures to enable them to provide better external resources for open innovation.

Second, it is important to foster the development of markets with technological dynamism to support industrial changes within the innovation ecosystem's digitization process. To facilitate these developments, it is recommended to establish a digital infrastructure industry development fund and digital technology incubation center. These initiatives can guide social capital investment in the core areas and key fields of digital infrastructure.

Third, in addition to greater investment in digital infrastructure, policies should address the spillover effects of technology space to promote collective progress among regions. Moreover, it is essential for innovation management and technological dynamism to evolve alongside the innovation ecosystem's digitization process. This ensures that the implemented policies and strategies align with the changing digital transformation landscape.

Ample opportunities exist for further research in this field. First, the measurement method for assessing digital infrastructure should be enhanced, as it is evident that the four current sub-indicators are insufficient to fully capture the level of regional digital infrastructure. The framework should be adjusted according to the evolving IT landscape of information technology. Furthermore, the empirical research presented in this study focused solely on the regional level.

Second, future studies could delve deeper into and engage in a comprehensive analysis of the three key innovation stakeholders: enterprises, universities, and scientific research institutions. These entities play pivotal roles in driving innovation. Thus, exploring their specific contributions in the context of digital infrastructure would provide valuable insights.

Third, public infrastructure is widely acknowledged to have spatial spillover effects. This aspect can be further explored to better understand the implications and impacts of digital infrastructure development across regions (Ahlfeldt & Feddersen, 2018; Bronzini & Piselli, 2006; Zhang et al., 2020). Finally, whether there is a spatial spillover effect of digital infrastructure warrants further research.

CRediT authorship contribution statement

Zhuo-Ya Du: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Qian Wang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

References

Adner, R., & Kapoor, R. (2010). Value creation in innovation ecosystems: How the structure of technological interdependence affects firm performance in new technology generations. *Strategic Management Journal*, *31*(3), 306–333. doi:10.1002/smj.821.

Ahlfeldt, G. M., & Feddersen, A. (2018). From periphery to core: Measuring agglomeration effects using high-speed rail. *Journal of Economic Geography*, *18*(2), 355–390. doi:10.1093/jeg/lbx005.

Ahn, S. J. (2020). Three characteristics of technology competition by IoT-driven digitization. *Technological Forecasting and Social Change*, (C), 157. https://ideas.repec.org//a/eee/tefoso/v157y2020ics0040162519322395.html.

Ardito, L., Coccia, M., & Messeni Petruzzelli, A. (2021). Technological exaptation and crisis management: Evidence from COVID-19 outbreaks. *R&D Management*, *51*(4), 381–392. doi:10.1111/radm.12455.

Ardito, L., D'Adda, D., & Messeni Petruzzelli, A. (2018). Mapping innovation dynamics in the Internet of Things domain: Evidence from patent analysis. *Technological Forecasting and Social Change*, *136*, 317–330. doi:10.1016/j.techfore.2017.04.022.

Audretsch, D. B., Heger, D., & Veith, T. (2015). Infrastructure and entrepreneurship. *Small Business Economics*, *44*(2), 219–230. doi:10.1007/s11187-014-9600-6.

Bacon, E., Williams, M. D., & Davies, G. (2020). Coopetition in innovation ecosystems: A comparative analysis of knowledge transfer configurations. *Journal of Business Research*, *115*, 307–316. doi:10.1016/j.jbusres.2019.11.005.

Beneito, P., Rochina-Barrachina, M. E., & Sanchis, A. (2014). Learning through experience in research & development: An empirical analysis with Spanish firms.

Technological Forecasting and Social Change, *88*, 290–305. doi:10.1016/j.techfore.2013.10.009.
Bharadwaj, A. S. (2000). a resource-based perspective on information technology capability and firm performance: An empirical investigation. *MIS Quarterly*, *24*(1), 169. doi:10.2307/3250983.
Bronzini, R., & Piselli, P. (2006). Determinants of long-run regional productivity: The role of R&D, human capital and public infrastructure. *SSRN Electronic Journal*. doi:10.2139/ssrn.935010.
Carayannis, E. G., & Sagi, J. (2002). Exploiting opportunities of the new economy: Developing nations in support of the ICT industry. *Technovation*, *22*(8), 517–524. doi:10.1016/S0166-4972(01)00046-3.
Ceccagnoli, F., Huang, & Wu (2012). Cocreation of value in a platform ecosystem! The case of enterprise software. *MIS Quarterly*, *36*(1), 263. doi:10.2307/41410417.
Chen, Y., Wang, Y., Nevo, S., Benitez-Amado, J., & Kou, G. (2015). IT capabilities and product innovation performance: The roles of corporate entrepreneurship and competitive intensity. *Information & Management*, *52*(6), 643–657. doi:10.1016/j.im.2015.05.003.
Cheung, K., & Lin, P. (2004). Spillover effects of FDI on innovation in China: Evidence from the provincial data. *China Economic Review*, *15*(1), 25–44. doi:10.1016/S1043-951X(03)00027-0.
Chinn, M. D., & Fairlie, R. W. (2007). The determinants of the global digital divide: A cross-country analysis of computer and internet penetration. *Oxford Economic Papers*, *59*(1), 16–44. doi:10.1093/oep/gpl024.
Coccia, M. (2017). Sources of technological innovation: Radical and incremental innovation problem-driven to support competitive advantage of firms. *Technology Analysis & Strategic Management*, *29*(9), 1048–1061. doi:10.1080/09537325.2016.1268682.
Coccia, M. (2021). Technological innovation. G. Ritzer (Ed.), *The blackwell encyclopedia of sociology* G. Ritzer (Ed.). (1st ed.). (pp. 1–6). Wiley. doi:10.1002/9781405165518.wbeost011.pub2.
Cozzolino, A., Corbo, L., & Aversa, P. (2021). Digital platform-based ecosystems: The evolution of collaboration and competition between incumbent producers and entrant platforms. *Journal of Business Research*, *126*, 385–400. doi:10.1016/j.jbusres.2020.12.058.
Cruz-Jesus, F., Oliveira, T., & Bacao, F. (2018). The global digital divide: Evidence and drivers. *Journal of Global Information Management*, *26*(2), 1–26. doi:10.4018/JGIM.2018040101.
Cui, X., Zhao, T., & Wang, J. (2021). Allocation of carbon emission quotas in China's provincial power sector based on entropy method and ZSG-DEA. *Journal of Cleaner Production*, *284*, 124683. doi:10.1016/j.jclepro.2020.124683.
D'Amico, G., Arbolino, R., Shi, L., Yigitcanlar, T., & Ioppolo, G. (2022). Digitalisation driven urban metabolism circularity: A review and analysis of circular city initiatives. *Land Use Policy*, *112*, 105819. doi:10.1016/j.landusepol.2021.105819.
D'Este, P., Amara, N., & Olmos-Peñuela, J. (2016). Fostering novelty while reducing failure: Balancing the twin challenges of product innovation. *Technological Forecasting and Social Change*, *113*, 280–292. doi:10.1016/j.techfore.2015.08.011.
Dewan, S., Ganley, D., & Kraemer, K. L. (2010). Complementarities in the diffusion of personal computers and the internet: Implications for the global digital divide. *Information Systems Research*, *21*(4), 925–940. doi:10.1287/isre.1080.0219.
Duarte, M., & Restuccia, D. (2010). The role of the structural transformation in aggregate productivity *. *Quarterly Journal of Economics*, *125*(1), 129–173. doi:10.1162/qjec.2010.125.1.129.
Ejermo, O., Kander, A., & Svensson Henning, M. (2011). The R&D-growth paradox arises in fast-growing sectors. *Research Policy*, *40*(5), 664–672. doi:10.1016/j.respol.2011.03.004.
Furukawa, Y. (2010). Intellectual property protection and innovation: An inverted-U relationship. *Economics Letters*, *109*(2), 99–101. doi:10.1016/j.econlet.2010.09.004.
Gangopadhyay, K., & Mondal, D. (2012). Does stronger protection of intellectual property stimulate innovation? *Economics Letters*, *116*(1), 80–82. doi:10.1016/j.econlet.2012.01.006.
Gao, H., Ru, H., Townsend, R. M., & Yang, X. (2017). Rise of bank competition: Evidence from banking deregulation in China. *SSRN Electronic Journal*. doi:10.2139/ssrn.3087081.
Ginarte, J. C., & Park, W. G. (1997). Determinants of patent rights: A cross-national study. *Research Policy*, *26*(3), 283–301. doi:10.1016/S0048-7333(97)00022-X.
Gomes, L. A., de, V., Facin, A. L. F., & Salerno, M. S. (2021). Managing uncertainty propagation in innovation ecosystems. *Technological Forecasting and Social Change*, *171*, 120945. doi:10.1016/j.techfore.2021.120945.
Graham, S. J. H., Marco, A. C., & Myers, A. F. (2015). Patent transactions in the marketplace: Lessons from the USPTO patent assignment dataset. *SSRN Electronic Journal*. doi:10.2139/ssrn.2489153.
Granstrand, O., & Holgersson, M. (2020). Innovation ecosystems: A conceptual review and a new definition. *Technovation*, *90–91*, 102098. doi:10.1016/j.technovation.2019.102098.
Hall, B. H. (2002). The financing of research and development. *Oxford Review of Economic Policy*, *18*(1), 35–51. doi:10.1093/oxrep/18.1.35.
Hansen, B. E. (1999). Threshold effects in non-dynamic panels: Estimation, testing, and inference. *Journal of Econometrics*, *93*(2), 345–368. doi:10.1016/S0304-4076(99)00025-1.
Herzer, D., & Donaubauer, J. (2018). The long-run effect of foreign direct investment on total factor productivity in developing countries: A panel cointegration analysis. *Empirical Economics*, *54*(2), 309–342. doi:10.1007/s00181-016-1206-1.
Hou, H., & Shi, Y. (2021). Ecosystem-as-structure and ecosystem-as-coevolution: A constructive examination. *Technovation*, *100*, 102193. doi:10.1016/j.technovation.2020.102193.
Hou, J., & Li, B. (2020). The evolutionary game for collaborative innovation of the IoT industry under government leadership in China: An IoT infrastructure perspective. *Sustainability*, *12*(9), 3648. doi:10.3390/su12093648.
Hsieh, R., & Keil (2008). Understanding digital inequality: Comparing continued use behavioral models of the socio-economically advantaged and disadvantaged. *MIS Quarterly*, *32*(1), 97. doi:10.2307/25148830.
Hsu, P. H., Tian, X., & Xu, Y. (2014). Financial development and innovation: Cross-country evidence. *Journal of Financial Economics*, *112*(1), 116–135. doi:10.1016/j.jfineco.2013.12.002.
Hu, A. G. Z., Zhang, P., & Zhao, L. (2017). China as number one? Evidence from China's most recent patenting surge. *Journal of Development Economics*, *124*, 107–119. doi:10.1016/j.jdeveco.2016.09.004.
Huang, X., & Liu, J. (2020). Regional economic efficiency and its influencing factors of Beijing-Tianjin-Hebei metropolitans in china based on a heterogeneity stochastic frontier model. *Chinese Geographical Science*, *30*(1), 30–44. doi:10.1007/s11769-019-1089-0.
Iansiti, M., & Lakhani, K. (2014). Digital ubiquity: How connections, sensors, and data are revolutionizing business. *Harvard Business Review*. *https://www.semanticscholar.org/paper/Digital-Ubiquity%3A-How-Connections%2C-Sensors%2C-and-Are-Iansiti-Lakhani/602a975237ea35fb4348c440d256159afc299f97*.
Inoue, Y. (2021). Indirect innovation management by platform ecosystem governance and positioning: Toward collective ambidexterity in the ecosystems. *Technological Forecasting and Social Change*, *166*, 120652. doi:10.1016/j.techfore.2021.120652.
Jiao, H., Koo, C. K., & Cui, Y. (2015). Legal environment, government effectiveness and firms' innovation in China: Examining the moderating influence of government ownership. *Technological Forecasting and Social Change*, *96*, 15–24. doi:10.1016/j.techfore.2015.01.008.
Kaletka, C., & Pelka, B. (2015). Digital) social innovation through public internet access points. M. Antona & C. Stephanidis (Eds.), *Universal access in human-computer interaction. Access to today's technologies:* M. Antona & C. Stephanidis (Eds.). *9175* (pp. 201−212). Springer International Publishing. doi:10.1007/978-3-319-20678-3_20.
Kamalaldin, A., Sjödin, D., Hullova, D., & Parida, V. (2021). Configuring ecosystem strategies for digitally enabled process innovation: A framework for equipment suppliers in the process industries. *Technovation*, *105*, 102250. doi:10.1016/j.technovation.2021.102250.
Kim, D. (2021). Network analysis of robot ecosystems using national information systems. *Technological Forecasting and Social Change*, *170*, 120855. doi:10.1016/j.techfore.2021.120855.
Kleis, L., Chwelos, P., Ramirez, R. V., & Cockburn, I. (2012). Information technology and intangible output: The impact of IT investment on innovation productivity. *Information Systems Research*, *23*(1), 42–59. doi:10.1287/isre.1100.0338.
Kozonogova, E., & Dubrovskaya, J. (2022). Assessing the convergence of the digital infrastructure development in the RF regions: Spatial analysis. T. Antipova (Ed.), *Comprehensible science:* T. Antipova (Ed.). *315* (pp. 118−129). Springer International Publishing. doi:10.1007/978-3-030-85799-8_11.
Kraus, S., Jones, P., Kailer, N., Weinmann, A., Chaparro-Banegas, N., & Roig-Tierno, N. (2021). Digital transformation: An overview of the current state of the art of research. *SAGE Open*, *11*,(3) 21582440211047576. doi:10.1177/21582440211047576.
Kujur, S. K. (2019). Use of traditional inputs and advanced industrial technology in value-added within the pulp and paper industry in India. *Journal of Sustainable Forestry*, *38*(6), 542–557. doi:10.1080/10549811.2019.1598439.
Lee, C. K. M., Zhang, S. Z., & Ng, K. K. H. (2017). Development of an industrial Internet of things suite for smart factory towards re-industrialization. *Advances in Manufacturing*, *5*(4), 335–343. doi:10.1007/s40436-017-0197-2.
Leidner, D. E., Preston, D., & Chen, D. (2010). An examination of the antecedents and consequences of organizational IT innovation in hospitals. *The Journal of Strategic Information Systems*, *19*(3), 154–170. doi:10.1016/j.jsis.2010.07.002.
Li, J., Sutherland, D., Ning, L., & Wang, Y. (2014). Firm ownership, industrial structure, and regional innovation performance in China's provinces. *Technology Analysis & Strategic Management*, *26*(9), 1001–1022. doi:10.1080/09537325.2014.943714.
Li, Z., Hu, M., & Wang, Z. (2020). The space-time evolution and driving forces of county economic growth in China from 1998 to 2015. *Growth and Change*, *51*(3), 1203–1223. doi:10.1111/grow.12412.
Liu, J., Chang, H., Forrest, J. Y. L., & Yang, B. (2020). Influence of artificial intelligence on technological innovation: Evidence from the panel data of china's manufacturing sectors. *Technological Forecasting and Social Change*, *158*, 120142. doi:10.1016/j.techfore.2020.120142.
Martínez, D., Rodríguez, J., & Torres, J. L. (2010). ICT-specific technological change and productivity growth in the US: 1980−2004. *Information Economics and Policy*, *22*(2), 121–129. doi:10.1016/j.infoecopol.2009.07.001.
McGuire, T., Manyika, J., & Chui, M. (2012). Why big data is the new competitive advantage. *Ivey Business Journal*, *76*(4), 1–4.
Miteva, N. (2022). COVID-19 pandemic as an impetus for development of 5G networks in Bulgaria: A case study. T. Ahram & R. Taiar (Eds.), *Human interaction, emerging technologies and future systems v* T. Ahram & R. Taiar (Eds.). (pp. 651−657). Springer International Publishing. doi:10.1007/978-3-030-85540-6_82.
Niebel, T. (2018). ICT and economic growth − comparing developing, emerging and developed countries. *World Development*, *104*, 197–211. doi:10.1016/j.worlddev.2017.11.024.
Oh, D. S., Phillips, F., Park, S., & Lee, E. (2016). Innovation ecosystems: A critical examination. *Technovation*, *54*, 1–6. doi:10.1016/j.technovation.2016.02.004.
Pfister, C., Koomen, M., Harhoff, D., & Backes-Gellner, U. (2021). Regional innovation effects of applied research institutions. *Research Policy*, *50*,(4) 104197. doi:10.1016/j.respol.2021.104197.

Rehm, S. V., Goel, L., & Junglas, I. (2016). Information management for innovation networks—An empirical study on the “who, what and how” in networked innovation. *International Journal of Information Management*, *36*(3), 348–359. doi:10.1016/j.ijinfomgt.2015.11.004.

Rodon, M. J., & Eaton, B. (2021). Digital infrastructure evolution as generative entrenchment: The formation of a core−periphery structure. *Journal of Information Technology*, *36*(4), 342–364. doi:10.1177/02683962211013362.

Schaeffer, P. R., Guerrero, M., & Fischer, B. B. (2021). Mutualism in ecosystems of innovation and entrepreneurship: A bidirectional perspective on universities’ linkages. *Journal of Business Research*, *134*, 184–197. doi:10.1016/j.jbusres.2021.05.039.

Sestino, A., Prete, M. I., & Piper, L. (2020). Internet of Things and Big Data as enablers for business digitalization strategies. *Reponame:EXpeditio Repositorio Institucional UJTL*. doi:10.1016/j.technovation.2020.102173.

Seyoum, M., Wu, R., & Yang, L. (2015). Technology spillovers from Chinese outward direct investment: The case of Ethiopia. *China Economic Review*, *33*, 35–49. doi:10.1016/j.chieco.2015.01.005.

Shahiduzzaman, Md., & Alam, K. (2014). Information technology and its changing roles to economic growth and productivity in Australia. *Telecommunications Policy*, *38*(2), 125–135. doi:10.1016/j.telpol.2013.07.003.

Siaw, C. A., & Sarpong, D. (2021). Dynamic exchange capabilities for value co-creation in ecosystems. *Journal of Business Research*, *134*, 493–506. doi:10.1016/j.jbusres.2021.05.060.

Song, L. Z., & Song, M. (2010). The role of information technologies in enhancing R&D-marketing integration: an empirical investigation. *Journal of Product Innovation Management*, *27*(3), 382–401. doi:10.1111/j.1540-5885.2010.00723.x.

Tassey, G., Gallaher, M. P., & Rowe, B. R. (2009). Complex standards and innovation in the digital economy: The Internet Protocol. *International Journal of Technology Management*, *48*(4), 448. doi:10.1504/IJTM.2009.026689.

Wang, Q., & Du, Z. Y. (2022). Changing the impact of banking concentration on corporate innovation: The moderating effect of digital transformation. *Technology in Society*, *71*, 102124. doi:10.1016/j.techsoc.2022.102124.

Wang, Z., & Wang, N. (2012). Knowledge sharing, innovation and firm performance. *Expert Systems with Applications*, *39*(10), 8899–8908. doi:10.1016/j.eswa.2012.02.017.

Wilson, K. R., Wallin, J. S., & Reiser, C. (2003). Social stratification and the digital divide. *Social Science Computer Review*, *21*(2), 133–143. doi:10.1177/0894439303021002001.

Xu, J., & Liu, K. (2018). Exploration on the indirect economic effects of foreign direct investment. *Journal of Discrete Mathematical Sciences and Cryptography*, *21*(6), 1229–1234. doi:10.1080/09720529.2018.1525905.

Xu, K., Geng, C., Wei, X., & Jiang, H. (2020). Financing development, financing constraint and R&D investment of strategic emerging industries in China. *Journal of Business Economics and Management*, *21*(4), 1010–1034. doi:10.3846/jbem.2020.12727.

Yao, Lu, & Sun (2019). Venture capital and industrial structure upgrading from the perspective of spatial spillover. *Sustainability*, *11*(23), 6698. doi:10.3390/su11236698.

Zahedi, M. R., & Naghdi Khanachah, S. (2021). The effect of knowledge management processes on organizational innovation through intellectual capital development in Iranian industrial organizations. *Journal of Science and Technology Policy Management*, *12*(1), 86–105. doi:10.1108/JSTPM-11-2019-0113.

Zhang, J., Zhang, D., Li, L., & Zeng, H. (2020). Regional impact and spillover effect of public infrastructure investment: An empirical study in the Yangtze River Delta, China. *Growth and Change*, *51*(4), 1749–1765. doi:10.1111/grow.12427.