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Digital economy and urban innovation level: A quasi-natural experiment from the strategy of "Digital China"

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The digital economy is an essential engine of the innovation-driven development strategy and plays a valuable role in promoting the high-quality development of the regional economy. Based on the panel data of 286 cities in mainland China with the help of the digital economy strategic plans issued by local governments as a quasi-natural experiment, we use the multi-temporal double-difference (DID) method to examine the impact of the digital economy on the urban innovation level. Findings show that the digital economy can significantly improve the urban innovation level. After a series of robustness tests, such as parallel trend test, updating sample and period, and repeated placebo test, the innovation-driving effect generated by the development of the digital economy remains significant. Results of the mechanism analysis indicate that the digital economy enhances the level of innovation through upgrading industrial structures. In addition, we find through the heterogeneity test that the digital economy has a stronger effect on improving the quality of innovation. Meanwhile, the innovation output in the Middle Eastern region is more significantly affected by the "Digital China" strategy than the Western region. Therefore, we should accelerate the implementation of the local digital economy development strategy to realize the high-quality development of the regional economy.

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Introduction

With the continuous change and development of the economy and society, the scale of China's digital economy has grown from 11 trillion yuan to 45.5 trillion yuan (China Academy of Information and Communications Technology, White Paper on the Development of China's Digital Economy [2023]). Moreover, the scale of China's digital economy development has increased from 20.9% to 39.8% of the GDP. The breadth and depth of the integration of the digital economy with all aspects of the economy and society are further extended; this development also plays a pivotal role in economic growth in terms of improving quality and efficiency while benefiting people's livelihoods (Liu et al. 2023; Ren et al. 2023). In its planning documents, the Chinese government has proposed accelerating the construction of "Digital China" and promoting the digital economy's development strategy, which subsequently promotes the deep integration of the digital and the real economies. The "Overall Layout Plan for the Construction of Digital China" issued by the state points out that the construction of "Digital China" is an essential engine for promoting Chinese modernization in the digital era. At the same time, China's economy is shifting gears from an investment-driven growth model to an innovation-driven development model, and the digital economy has been recognized as a new kinetic energy for China's innovation drive (Qinqin et al. 2023; Wang et al. 2023). Characterized by the development of big data and the Internet, the digital economy has a development pattern distinct from that of the previous industrial revolution period; as such, the importance of the data element in promoting the development of the local economy requires emphasis (Tao et al. 2023). Thus, in the context of the in-depth implementation of the innovation-driven development strategy, how to build the digital economy further as a new engine to promote innovation and development has become a widely discussed topic by the government and all sectors of society (Sun and You, 2023; Liu et al. 2023; Wang et al. 2023).

Digital economy refers to a series of economic activities based on modern information networks and information and communication technology with the production, transmission, and use of data and information as the primary technical means. The digital economy has now become a central key force driving the national economic development of major countries in the world (Zhang and Ran, 2023; Wang et al. 2022). It plays an influential role from the perspectives of economic growth, efficiency improvement, and structural upgrading. Specifically, the integration between the digital economy and the real economy has much room for improvement, and it can still contribute to economic growth, inclusive growth, and high-quality development (Daud, 2023; Myovella et al. 2020). In addition, the development of the digital economy improves labor allocation efficiency, capital allocation efficiency, and total factor productivity, subsequently ensuring a rational allocation of resources (Zhang and Dong, 2023). From a structural perspective, the digital economy can promote the upgrading of industrial structure and quality optimization in the manufacturing industry (Liu et al. 2023; Ding et al. 2022).

While the development of the digital economy, technological advances, and economic transformation has brought excellent opportunities to society, they have also been accompanied by a series of challenges. The development of the digital economy has led to the phenomenon of the digital divide, leaving gaps in digital technology and access to information between different regions and groups. As the scale of the digital economy continues to expand, data collection and use become increasingly widespread. This scenario can raise concerns on personal privacy and data security, especially in areas such as big data and artificial intelligence. In addition, as technological innovation is a critical factor in promoting high-quality urban development, studying the relationship between the role of the digital economy and technological innovation has profound significance. In this regard, this paper is based on the analysis regarding the impact of the "Digital China" strategy on urban innovation and the mechanism of its role in providing a certain policy basis and reference for promoting sustainable urban development. It also effectively verifies the critical role of policy implementation in promoting innovation and development.

Literature review

Despite the rapid development of the research on the digital economy, researchers have yet to produce extensive results on how the digital economy affects science and technological innovation in the academic world. The current research on this topic faces three problems. First, related research faces the problem of measuring the digital economy, and scholars need assistance in reaching a consensus on measuring the level of development of the digital economy (Xin et al. 2023). Existing measurements are synthesized from a variety of sub-indicators. When the sub-indicators are inconsistent, the estimated composite indicators are also inconsistent. Thus, such composite indicators constantly face the problem of representativeness. Specifically, some scholars have measured the level of digitization using the following four dimensions: digital access, equipment, platform construction, and application. They found that only the level of digital access can promote regional innovation, while the remaining three dimensions show an inverted U-shaped relationship with innovation (Zhao et al. 2023; Hui et al. 2023). Some scholars have also synthesized the index of the digital economy development level at the provincial level by using digital infrastructure and application level; they have also empirically examined the promotion effect of the digital economy on innovation with provincial panel data (Song et al. 2023). In addition, some scholars have measured the level of the digital economy from two levels of direct and indirect effects which both demonstrated empirical evidence that the digital economy promotes technological innovation (Zhang et al. 2023). Moreover, relevant scholars have re-analyzed the digital economy from two perspectives: Internet development and digital financial inclusion, thus confirming that the digital economy can effectively promote green technological innovation (Chen et al. 2023). Second, although some related studies have examined the impact of the digital economy on innovation, they have focused on the impact of informatization and the Internet on innovation (Wang et al. 2022). Despite informatization and the Internet being closely related to the digital economy, they are fundamentally different. The 13th Five-Year National Informatization Plan sets "achieving significant results in the construction of a Digital China" as the overall goal of China's informatization development, which clarifies that informatization is one of the specific paths to achieve a "Digital China." However, a need may arise to go beyond merely viewing the digital economy from the perspective of informatization. Specifically, the relevant literature can be divided into the following three levels: macro, meso, and micro. At the macro level, Varian (2010) argues that information technology effectively promotes innovation spillovers. By constructing an inter-provincial Internet development index, some scholars have found that the Internet can promote regional innovation efficiency through various channels, such as accelerated human capital accumulation, financial development, and inter-provincialization of industries (Luo et al. 2023). Studies that used provincial data have also found that the Internet can significantly promote technological progress (Lee and Wang, 2022).

At the meso level, studies using industry-level data have found that informatization can promote technological innovation efficiency in the industrial sector (Xi et al. 2022). At the micro level, the Internet was found to promote technological complexity and manufacturing product upgrading at the firm level. Internet use was found to increase the probability of household entrepreneurship (Clarysse et al. 2022). Finally, endogeneity exists between the two. As in the case of bi-directional causality, more innovative regions also generally develop their digital economy. Thus, a logical chain of urban innovation may influence the digital economy's development, such as measurement error. As such, the measurement of the digital economy and the measurement of urban innovation may need some fixing. Then, variables are omitted because many factors can affect urban innovation, which may have yet to be listed in the empirical studies. Notably, most of the literature needs to provide in-depth studies on endogeneity in the form of policy assessments.

In the face of the problems discussed earlier, the academic community is naturally called upon to study the impact of the digital economy on science, technology, and innovation using the paradigm of policy evaluation. However, the literature on the effect of the digital economy on policy evaluation is relatively scarce, especially regarding the impact of the digital economy on urban innovation from a holistic perspective. The current research focuses on the "Broadband China" policy. This policy primarily focuses on network infrastructure construction, which is only a localized policy and perspective of the digital economy (Wang et al. 2022). Related studies have found that the "Broadband China" pilot policy can promote the total factor productivity of the pilot regions and the rationalization and advanced level of industrial structure as well as the diffusion of innovations at the enterprise level, thus promoting high-quality development (Zhang et al. 2022; Hong et al. 2023). The digital economy is a critical element in the development of China's economy. With the introduction of corresponding digital economy strategic plans by local governments, new development momentum is provided for the regional development of the digital economy. This local similar strategy implementation provides a valuable opportunity to study the impact of the digital economy on urban innovation from a holistic perspective. Hence, this study adopts a multi-temporal DID approach with the help of natural experiments of the digital economy strategies introduced by local governments. It also examines the impact effect, mechanism of action, and heterogeneity performance of digital economy on urban technological innovation.

The possible marginal contributions of this research are as follows: (1) From the level of research perspective, this paper studies the digital economy not only from the unilateral perspective of informatization, network infrastructure, and so on but also adopts a holistic vision compared with previous literature. The local government issued the corresponding digital economy strategic plan, which is a holistic development plan covering a comprehensive aspect. It not only considers the construction of digital infrastructure but also the protection of intellectual property rights related to the digital economy, talent training and concentration, credit financing policy optimization, and so on. This planning helps enrich and deepen the theoretical research on the development of the digital economy. (2) By including digital economy strategies and technological innovation in a unified analytical framework, we provide new empirical evidence on the innovation effects of digital economy-related policy implementation.

Institutional background and research hypotheses

Development history of regional "Digital China" strategy. In 2016, the Chinese government issued the Outline of the 13th Five-Year Plan, which proposed to accelerate the construction of "Digital China" and promote the deep integration of information technology and economic and social development. The government's planning documents emphasized the need to "promote the deep integration of the Internet, big data, artificial intelligence, and the real economy." Ministries and commissions have also issued policies and guidelines to encourage the development of the digital economy and related industries. For example, the Ministry of Commerce formulated the "Internet + Circulation" Action Plan, the Ministry of Education formulated the "13th Five-Year Plan for Education Informatization," and the Ministry of Industry and Information Technology formulated the "Plan for the Development of the Big Data Industry (2016–2020)" and other important policies. Guided by the central policy, provinces, autonomous regions, and municipalities directly under the central government have also issued supporting policies in accordance with the national strategy. For example, Zhejiang formulated the Five-Year Multiplication Plan for Zhejiang Digital Economy in 2018, which proposes that the added value of the province's digital economy should be doubled by 2022 compared with 2017. Furthermore, Tianjin released the Tianjin Action Program for Promoting the Development of the Digital Economy (2019–2023), which proposes to enhance the digital economy's "going out" and "bringing in" to realize the mutual benefit and win-win situation of the digital economy. In a meeting held in China, the government once again emphasized "accelerating the construction of Digital China," which also means that the construction of "Digital China" has once again increased in quantity and quality.

In general, "Digital China" is the strategic layout of the Chinese government's overall planning. It has a programmatic, dominant, and directional role in the overall construction of the digital economy. Moreover, the policies for the development of the digital economy at the provincial and municipal levels are centered on the core proposition of the digital economy and its sub-topics, such as the Internet, informatization, intelligent manufacturing, and smart cities (Liu et al. 2023; Luo et al. 2021). The construction of "Digital China" covers a wide range of fields and involves many aspects. In recent years, major countries and regions in the world have taken digital development as the main direction to enhance their comprehensive strength. In addition, we have carried out an all-round layout in facility construction and technological innovation. Notably, the competition in the digital environment with policies as an important means has become increasingly fierce. Thus, "Digital China," which is structured centrally and locally, seeks to enhance the development of China's digital economy at the global level.

Research hypotheses. From the point of view of the "Digital China" strategy itself introduced by localities, the following aspects of institutional mechanisms incentivize the development of the local digital economy. First, these mechanisms improve the digital economy industrial policy. As such, a policy system must be established to provide comprehensive support for the development of the digital economy industry in terms of finance, access mechanisms, and negative lists. Second, the protection of intellectual property rights related to the digital economy must be strengthened. The mechanism for rights protection and assistance also needs improvement, and the protection of digital economy innovations must be reinforced. In line with these policies, financial support should also increase. The government should oversee the comprehensive use of special funds, equity investment, loan subsidies, and other ways to establish a diversified incentive for the development of the digital economy through the government's financial investment mechanism. In relation to these aspects, the digital economy products of government procurement should be increased. Moreover, a new investment financing system related to the digital economy must be built. This new model should involve digital economy investments and financing through the cooperation between government finance and social capital. In addition, credit support for enterprises related to the digital economy should be increased. Finally, the development of digital economy-related talents should be strengthened to improve the working mechanism for nurturing, attracting, retaining, and serving talents in the digital economy.

The "Digital China" strategy promotes the growth of the digital economy, and the digital economy itself has an innovation incentive effect. On the one hand, the "Digital China" strategy promotes the development of the underlying technology of the digital economy. The core underlying technology of the digital economy lies in artificial intelligence, blockchain, cloud computing, big data, and so on, which belong to the field of high knowledge density and can thus promote innovation in cities. On the other hand, the dissemination of knowledge is hindered by geographical distance (Shaw and Gilly, 2000). However, informationization and the Internet can break the limitations of this distance. The "Digital China" strategy plays an important role in promoting core technological innovation in the field of information, the construction of a new generation of information infrastructure, and the popularization and speed-up of broadband networks. These developments can help break down the physical barriers to information, accelerate the speed of knowledge dissemination, improve knowledge dissemination efficiency, reduce information asymmetry, improve supply chain efficiency, and reduce the cost of enterprises (Peng and Luxin, 2022; Lau, 2023). The digital economy enhances the accuracy and timeliness of the transmission and acquisition of information on the demand and supply sides. Furthermore, the information between the supply and demand sides becomes increasingly symmetrical, which compresses the length of the industrial chain, improves the efficiency of the industrial chain, and reduces the transaction costs, thus promoting the enhancement of the level of urban innovation (Akbar and Tracogna, 2022). Therefore, this study proposes the following hypothesis:

Hypothesis 1: The digital economy has a driving effect on urban innovation.

After proposing the "Digital China" strategy, local governments have implemented a series of important initiatives to grasp industrial digitalization and digital industrialization construction, which have strongly promoted the industrial structure upgrade in various places. The current study argues that such an upgrade is an important conduction mechanism for the digital economy to influence urban science and technological innovation. Industrial structure upgrading is an inherent power of China's high-quality economic development. Strategies aimed toward the digital economy promote its development; moreover, the digital economy not only has a direct impact on science and technological innovation by virtue of its own qualities but also indirectly affects science and technological innovation through industrial upgrading (Peng et al. 2023). On the one hand, the digital economy has led to the tremendous development of information technology, which is conducive to the transformation and upgrading of the traditional manufacturing industry to strengthen the fusion of information technology. In turn, this fusion enhances the production efficiency and the digital transformation of industries. The digitalization of industries not only improves the efficiency of the value of commodities and the efficiency of industrial production but also optimizes the mode of industrial organization. On the other hand, the intrinsic characteristics of the digital economy have given rise to many new and emerging industries developed around information technology. These emerging industries developed around information technology, such as artificial intelligence, big data, cloud computing, blockchain, and other digital industries, are developing rapidly (Pisano et al. 2015). In addition, digital industrialization will promote industrial upgrading through the linkage effect, spillover effect, and diffusion effect (Heo and Lee, 2019). Together, industrial digitization and digital industrialization promote overall industrial structure upgrading, which strongly promotes local independent innovation (Madanaguli et al. 2023).

Hypothesis 2: Digital economy can promote science and urban innovation through the industrial upgrading effect.

Research design

Modeling. To mitigate endogeneity, this paper adopts a multi-temporal double-difference approach to identify the impact of the digital economy on China's science and technology innovation by using the urban "Digital China" strategy as a quasi-natural experiment. Compared with natural experiments, quasi-natural experiments need not satisfy the random assignment assumption (Fetzer and Graeber, 2021); thus, social and political forces (e.g., policies) can be viewed as quasi-natural experiments, and the implementation of the urban "Digital China" strategy can be regarded as a "quasi-natural experiment." The implementation of the urban "Digital China" strategy can be regarded as a "quasi-natural experiment." Double-difference (DID) is commonly used in social sciences for causal inference and policy evaluation. Its basic idea is to construct a double-difference statistic by comparing the differences between the control and experimental groups before and after the implementation of a policy to reflect the effect of the policy. Moreover, the theoretical framework of DID is built on the basis of natural and quasi-natural experiments. The theoretical framework of the double difference method is based on natural and quasi-natural experiments. However, the traditional DID model is generally designed for policy evaluation in the same period of policy implementation. Otherwise, it will lead to a biased estimation of the coefficients. Therefore, this paper draws on previous work (Shen and Sun, 2023) and adopts a multi-temporal DID (also known as progressive DID) approach. Multi-temporal DID is suitable for evaluating the differential impacts of a policy on the implementation group at different time points and has been widely adopted. The effect of the Digital Economy Development Plan ("Digital China" Strategy) on urban innovation is twofold. On the one hand, a "time effect" varies naturally over time or with the overall economic situation. On the other hand, a "time effect" results from the Digital Economy Development Plan (DEDP). On the one hand, the "time effect," is a natural change over time or the overall economic situation. On the other hand, the "policy treatment effect" is caused by the "Digital Economy Development Plan." The next step is how to separate the "time effect" to study the pure "policy treatment effect." This paper identifies two sources of change in the strategy: one is the "Digital Economy Development Plan" ("Digital China" Strategy) of each region, and the other is the "policy treatment effect." This paper identifies two sources of policy change. First, the time change before and after the implementation of the "Digital Economy Development Plan" ("Digital China" Strategy) in each region serves as a variable for the change before and after the implementation of our policy. Second, the implementation or non-implementation of the "Digital Economy Development Plan" ("Digital China" Strategy) in different regions serves as a grouping variable for the experimental and control groups. In other words, the implementation of the Digital Economy Development Plan ("Digital China" Strategy) in different regions is used as the treatment group, and the non-trial regions are used as the control group. The aim is to examine the differences between the control group and treatment groups before and after the policy treatment and to determine the "effect of the policy treatment." This paper constructs the following multi-temporal DID (also called progressive DID) model to verify the impact of the digital economy on urban innovation:

$$\mathrm{Innovation}_{it} = \alpha + \beta \mathrm{DID}_{it} + \varphi \mathrm{controls}_{it} + \mu_i + \lambda_t + \varepsilon_{it}. \quad (1)$$

In Eq. (1), the explanatory variable $\mathrm{Innovation}_{it}$ denotes urban innovation, which is measured by patent applications per 10,000 people in this study. The subscripts i and t represent the city and year, respectively; and μ_i and λ_t denote city fixed effects and time fixed effects, respectively. The core explanatory variable DID_{it} indicates whether city i is affected by the city's Digital China strategy in year t. DID_{it} is equivalent to the interaction term of two dummy variables, that is, whether the host province has released a major policy on the digital economy (1 if yes; otherwise, 0) and whether the host province has released a major policy on the digital economy (1 if yes; otherwise, 0). DID_{it} is equivalent to the interaction term of two dummy variables, that is, whether the province has released a major policy on digital economy (1 for yes; otherwise, 0) and whether it is after the policy year (1 for t ≥ the year of policy release; otherwise, 0). The coefficient β measures the impact of the city's "Digital China" strategy on science and technological innovation. If the coefficient β is significantly positive, the digital economy promotes science and technological innovation in Chinese cities. $\mathrm{controls}_{it}$ is a control variable. Specific definitions of variables are provided later in the section "3.2 Data sources and variable descriptions."

The premise of using the DID method should satisfy the parallel trend assumption. The foundation of "Digital China" strategy implementation, the lag of policy effect, and the strength of policy implementation are not the same in different places. Therefore, this study refers to Beck et al. (2010) and constructs the test model of parallel trend as follows:

$$\mathrm{Innovation}_{it} = \alpha + \sum_{\gamma=-1}^{\gamma=-4} \beta_\gamma \mathrm{Before} + \sum_{\rho=-1}^{\rho=-4} \beta_\rho \mathrm{After} + \beta_\delta \mathrm{Current} + \varphi \mathrm{controls}_{it} + \mu_i + \lambda_t + \varepsilon_{it}. \quad (2)$$

In Eq. (2), $\mathrm{Innovation}_{it}$, which is the indicator for urban innovation, represents the number of patent applications per 10,000 people. Before represents a set of counterfactual dummy variables for a set of experimental group cities in year γ prior to the release of the policy. β_γ measures the policy effect on urban innovation when the digital economy policy is released in year γ prior to the release year. When city i is located in a province that releases an important digital economy policy in year t, then, the city is assigned a value of 1 for Before and 0 for the rest of the years $t-1$, $t-2$, $t-3$, and $t-4$ in that order. After represents a set of counterfactual dummy variables for the experimental group of cities in the ρth year after the release of the policy. β_ρ measures the policy effect on urban innovation in the ρth year after the year of the release of the digital economy policy. When the policy effect urban innovation, that is, when City i's province releases a significant digital economy policy in year t, then, the city sequentially releases the policy in years $t+1$, $t+2$, $t+3\ldots$, $t+7$ years. After is assigned a value of 1, and the rest are 0. Currently represents a dummy variable for the experimental group of cities, which has a value of 1 in the year when the digital economy policy is released and 0 in all the rest of the years.

Data sources and variable descriptions. In December 2015, China's national leaders proposed for the first time that China would promote the construction of Digital China. Along with the release of policies related to the "Digital China" strategy at the central level, local governments have also issued development plans, outline documents, important notices, and other policy documents on the digital economy. The successive release of these policy documents provides a valuable opportunity to identify the impact of the digital economy on science and technological innovation. Therefore, the current study utilizes city panel data from 2008 to 2018 to assess the impact of the digital economy on urban science and technological innovation using a multi-temporal DID method.

Core explanatory variables. The core explanatory variable (DID) of this study is the implementation of the "Digital China" strategy at the level of each prefecture-level city. According to the previous section, based on this strategy at the central level, the major digital economy policies that have actually been implemented by provincial governments, such as the "Outline for the Construction of Digital Hunan," should be referred to as Digital Hunan in theory. For the sake of name unification, this study collectively refers to them as the "Digital China" strategy. Specifically, if the province/autonomous region issued a digital economy development plan, action program, important notice, and other policy documents after 2015, the variable is assigned a value of 1 for the year after the release and 0 for the rest of the year. Meanwhile, after sorting out the local digital economy policies, we found that (1) although some prefecture-level cities have separately issued a digital economy policy titled, "Digital + Municipal Name," the variable is assigned a value of 1, and the rest of the variables are assigned a value of 0. "Digital + City Name" is the title of the development strategy (e.g., Digital Hangzhou). However, considering the relatively small number, the follow-up support is imperfect, and other reasons have emerged. Thus, we have selected the provincial/autonomous region level as the criterion to judge the introduction of digital economy policies, which is more general and comparative, as well as the provincial/autonomous region level. (2) The selected sample only covers up to 2018 but considers that the country formulated a series of important digital economy strategies in 2015, which is regarded as the official start of the "Digital China" strategy. In addition, most provinces started to formulate specific digital economy policies afterwards. Hence, we take the period after 2015, 2018, and before as the period of the "Digital China" strategy. Meanwhile, we use the period after 2015, 2018, and before as the basis for judging whether the city's province has introduced policies that meet the criteria. Therefore, we use whether the province where the city is located has introduced a digital economy policy that meets the criteria as the criterion for determining whether the city belongs to the treatment group.

The data for the core explanatory variables are manually screened, verified, and organized on the basis of the content of the official website of each local government, Beida Faber, and other web pages. Referring to the convention, the samples of municipalities were excluded. After removing missing values, the final sample includes 286 prefecture-level cities with 3123 observations. Among them, the experimental group contains 137 prefectural-level cities, including Jilin, Zhejiang, Anhui, Fujian, Sichuan, Guizhou, Hunan, Guangxi, Guangdong, Gansu, and Shaanxi Provinces, totaling 11 provinces; and the control group contains 149 cities.[1]

Other variables. 1. Explained variable: urban innovation (Innovation). This study uses the number of patent applications per 10,000 people to measure the level of science and technological innovation in a city. The measures of urban innovation in existing studies have two main types: innovation inputs and innovation outputs. Considering the availability of R&D expenditures at the prefecture-level city level, we use the number of patents applied to measure the innovation output of cities. The data come from the China Urban Statistical Yearbook of past years.

Table 1 Descriptive statistics of the main variables.

Variable name	Type	Sample	Average value	Standard deviation	Minimum	Maximum
Innovation	Explanatory variable	3123	10.320	24.580	0.027	371.500
"Digital China" Strategy	Core explanatory variables	3123	0.102	0.303	0.000	1.000
GDP	Control variables	3123	16.320	0.916	13.540	19.310
Pop		3123	5.853	0.677	2.975	7.298
Industry		3123	48.380	10.620	12.190	90.970
Finr		3123	13.640	1.064	10.170	17.380
Fine		3123	14.540	0.765	11.330	17.640
Tec		3123	9.995	1.318	6.254	15.530
Invest		3123	15.980	0.943	12.792	19.690
Fdi		3123	9.456	2.691	0.000	14.150

2. Control variables. We refer to the relevant literature (Liu et al. 2022; Liu et al. 2023; Liu et al. 2023; Ding et al. 2023) and select four types of control variables affecting urban innovation: first, the variables reflecting the level of economic development and fiscal capacity, including the gross domestic product (GDP), the general budgetary revenue (finr), the general budgetary expenditure (fine), and the proportion of the value added of the secondary industry to GDP (SGDP); second, the variables reflecting the level of investment, with the gross regional product (GDP), the local fiscal revenue (finr), local financial general budget expenditure (fine), and the proportion of value added of the secondary industry to GDP (industry); third, variables reflecting the level of investment with the amount of investment in fixed assets (invest) and the amount of foreign investment actually used (fdi); fourth, variables reflecting the population with the total number of people at the end of the year (pop); and fifth, variables reflecting the science and technology investment in the city with the city-level science and technology expenditure (tec) selected. All of the above variables are in logarithmic form except for the share of secondary industry. The data of all the control variables come from the China Urban Statistical Yearbook and the statistical bulletins of each city in the past years.

3. Mechanism variables: industrial structure upgrading (ins). Referring to the previous literature (Pan et al. 2023), this study adopts the proportion of the output value of the secondary and tertiary industries as a measure of industrial structure upgrading.

In addition, the two indicators of the per capita sales revenue of new products above scale and the ratio of the sales revenue of new products above scale to the main business income in the robustness test of this study come from the China Science and Technology Yearbook of past years.

Table 1 shows the descriptive statistics of the main variables. The relevant variables were logarithmized. Partial missing data are processed using interpolation. According to the descriptive statistical results of the variables, the standard deviation of the explanatory variables is 24.580, indicating that the difference between most of the values and their mean values is relatively large. Moreover, the number of patents owned by different regions substantially varies. The standard deviation of the other variables is relatively small, indicating that the fluctuation trend of the variables is not obvious.

Empirical results and analysis

Benchmark regression analysis. We examine the impact of the digital economy on urban innovation. The empirical strategies are all based on two-way fixed-effects models, and the samples are prefecture-level cities from 2008 to 2018. Table 2 reports the results of the benchmark regression. The core explanatory variable is the implementation of the "Digital China" strategy, and the explanatory variables are all the number of patent applications per 10,000 people measured. Column (1) is the result of OLS estimation without adding any control variables. Column (2) adds time and city fixed effects. Column (3) adds the level of economic development of the city, economic structure, and demographic-related variables. Column (4) continues to add control variables for fiscal capacity and science and technology expenditures. Column (5) includes the variables for the level of investment. The results in Table 2 show that the implementation of the "Digital China" strategy promotes the level of science, technology, and innovation in the city. With the addition of the control variables, this promotion effect decreases but eventually stabilizes and remains significant at the 5% level. The magnitude of the final coefficient indicates that the "Digital China" strategy introduced by each local government can significantly promote the output of innovation patents in cities, that is, increase the number of patent applications per 10,000 people by 2.32 applications. From the results of the control variables, GDP and population have a positive impact on innovation. The scale of the regional economy and population is conducive to the improvement of urban innovation. The higher the proportion of the secondary industry, the worse the city's technological innovation ability, indicating that the innovation growth may be concentrated in the secondary industry during the sample period, and the innovation of the traditional manufacturing industry is insufficient. The impact of fiscal revenue is significantly negative, indicating that fiscal revenue may be transformed into the burden of corporate fiscal taxation, which will inhibit the level of urban innovation. Meanwhile, the impact of science expenditure is significantly positive, which suggests that the output of science and technological innovation can be significantly enhanced by increasing investment in science and technological innovation. The impact of fixed asset investment is significantly negative, and the amount of real foreign investment is insignificant, which indicates a crowding-out effect of fixed asset investment on urban science and technological innovation.

Parallel trend test. For multi-temporal DIDs, the parallel trend assumption should also be satisfied, and the difference between it and the traditional DID parallel trend test lies in the technical aspects of practical operation. The main difference between it and the traditional DID parallel trend test is that for the traditional DID method, considering that it has the same time point of policy intervention, it only needs to generate the interaction terms of the policy dummy variable and the dummy variable of each period, select one of the interaction items as the control group, and observe the coefficients of each interaction term to obtain the dynamic effect of the policy. For multi-temporal DID, despite the absence of a unified policy time, given that the time point of each individual entering the experimental group is determined, we can compare the current year with the individual's policy time. In addition, we can obtain the individual's pre-N to post-N periods to observe the dynamic policy effect.

Table 2 Impact of the digital economy on technological innovation in cities.

Variable	(1)	(2)	(3)	(4)	(5)
DID	4.841***	2.726***	1.950**	2.049**	2.323**
	(1.450)	(0.957)	(0.951)	(0.950)	(0.950)
GDP			6.286***	3.415	7.868***
			(2.332)	(2.684)	(2.907)
pop			34.891***	32.804***	32.193***
			(4.243)	(4.250)	(4.244)
industry			−0.266***	−0.244***	−0.253***
			(0.069)	(0.069)	(0.069)
finr				−2.724**	−2.201*
				(1.317)	(1.327)
fine				−1.084	−0.250
				(1.708)	(1.717)
tec				3.158***	3.335***
				(0.552)	(0.553)
invest					−3.281***
					(0.841)
fdi					−0.0551
					(0.179)
Constant	9.822***	3.559***	−285.120***	−207.911***	−243.623***
	(0.463)	(0.625)	(34.573)	(38.681)	(39.672)
N	3123	3123	3123	3123	3123
R-squared	0.004	0.199	0.229	0.238	0.242
Urban Effect	NO	YES	YES	YES	YES
Time Effect	NO	YES	YES	YES	YES

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively, with robustness standard errors in parentheses below.

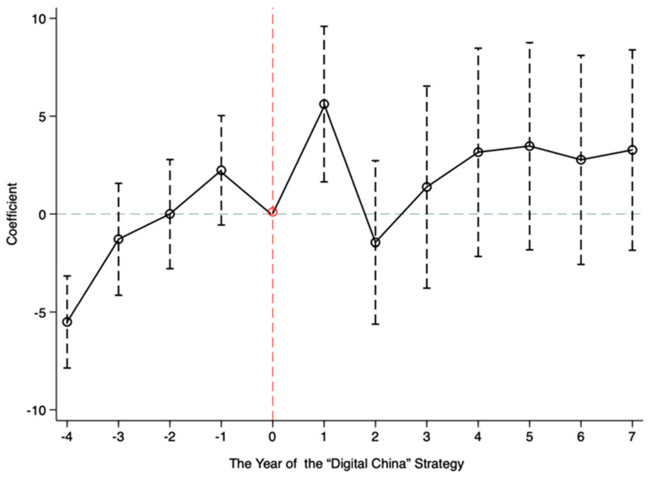

Fig. 1 Parallel trend test for "Digital China" strategies. It reflects the positive effect of policy implementation on the city's science and technological innovation after the implementation of the "Digital China" strategy.

The parallel trend is tested and plotted according to the regression results shown in Fig. 1. The results in the figure show no significant difference in the level of science and technological innovation between the cities in the experimental group and the cities in the control group before the provinces began to implement the "Digital China" strategy. After the cities in the experimental group introduced the "Digital China" strategy, the level of science and technological innovation represented by the number of patent applications per 10,000 people in the cities in the experimental group increased significantly in the first year, thus forming a significant difference with the control group cities that did not implement the "Digital China" strategy. Despite the certain tendency of the difference to fall back in the later period, considering the lag of the policy, the overall upward trend still indicates that the digital economy has a facilitating effect on the city's science and technological innovation.

Robustness test. The previous analysis in this study suggests that the digital economy has a significant role in promoting urban science and technological innovation. However, this conclusion may be disturbed by various types of factors. Therefore, a series of robustness tests are conducted on the above results.

Consideration of sample selectivity and exclusion of confounding policies. Columns (1)–(3) of Table 3 show the results of the robustness tests considering the sample selectivity issue and excluding disruptive policies. Column (1) is the regression result after excluding the cities included in Fujian Province. The special characteristics of Fujian Province are considered. Moreover, Fujian Province started to implement the "Digital Fujian" strategy as early as 2002 and subsequently issued the "Notice of the People's Government of Fujian Province on Issuing the 12th Five-Year Plan of Fujian Province on Digital Fujian" (2011–2015). Table 3 shows the regression results after removing the cities included in Fujian Province. Considering its specificity, this study conducts a regression after deleting the samples of Fujian cities. The result in Column (1) shows that the significance of the coefficient of the impact of the digital economy slightly decreases after the exclusion of Fujian cities. However, the coefficient does not change much, and it only decreases by 0.13. Column (2) is the regression result of the cities included in Hunan Province (Hunan Province's "Construction of Digital Hunan" <2011–2015>, which covers 2015) and Fujian Province. The regression results for the included cities remain positive and significant, thus supporting the core conclusion of this study that the digital economy can promote urban innovation in China. Column (3) shows the regression results for the sample considering only 2016 and before. The reason for doing so is that in 2016, the central government issued a series of policy and outline documents related to the digital economy, such as the Outline of the National

Table 3 Robustness test.

Variable	Panel 1: Consider sample selection and exclusion policies			Panel 2: Substitution of explanatory variables			Panel 3: Replacement of control variables
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
DID	2.199**	3.632***	3.686**	0.127***	0.043***	3.514***	1.382**
	(0.903)	(1.061)	(1.739)	(0.044)	(0.006)	(0.738)	(0.790)
Control variable	YES	YES	YES	YES	YES	YES	YES
N	3024	2881	2552	3112	2552	3,123	2,552
R-squared	0.407	0.410	0.280	0.794	0.645	0.280	0.461
Urban Effect	YES	YES	YES	YES	YES	YES	YES
Time Effect	YES	YES	YES	YES	YES	YES	YES

, and * indicate significance at the 10%, 5%, and 1% levels, respectively, with robustness standard errors in parentheses below.

Informatization Development Strategy, the National Informatization Plan for the 13th Five-Year Plan, and the Three-Year Action Program for the Construction of Major Projects of Information Infrastructure (2016–2018), which may overlap with the strategic objectives of "Digital China" and overestimate the policy effects of this study. Here, we regress the sample before 2016 to exclude the interference of other policies. The significance of the regression coefficients has not changed remarkably to support the role of the digital economy in promoting science and technological innovation.

Robustness test for replacement variables. To remove the impact of the selection of indicators of urban innovation on the robustness of the core findings of this study, three additional different indicators of urban innovation are added and re-estimated. Columns (4)–(6) in Table 3 are the results of the robustness test for substituting the explanatory variables. The explanatory variable in Column (4) replaces the urban innovation index, and the data come from the "China Urban and Industrial Innovation Report 2017" published by the Industrial Development Research Center of Fudan University (He et al. 2018; Jin et al. 2019), and the regression results still strongly support the core conclusion of this paper, that is, the digital economy can significantly increase the urban innovation index. Column (5) demonstrates that the replacement of the dependent variable for each province above-scale new product sales revenue accounted for the proportion of the main business income (new product rate) (Liu et al. 2023). The regression results show that the digital economy on new product sales revenue accounted for the proportion of the main business, which has a significant role in enhancing the new product sales revenue that accounted for 4.25 percentage points. The above regression results show that the results after substituting the urban innovation indicator variables remain robust and thus support the core conclusion that the digital economy promotes urban science and technological innovation. Column (6) is re-regressed using the number of granted patents per capita as a substitute for the explanatory variables, and the empirical results show that the coefficients of the core independent variables are all positively significant at the 1% level, which further supports the main research hypothesis of this paper. In addition, Column (7) changes the form of control variables, thus replacing the natural logarithmic form with the per capita variable. The results remain significantly positive, thus supporting the research hypothesis of this study.

Placebo test. To test the randomness of the implementation of the digital economy policy with reference to the relevant studies of Cantoni et al. (2017) in recent years, the method of repeated experiments is adopted to conduct the placebo test. The specific

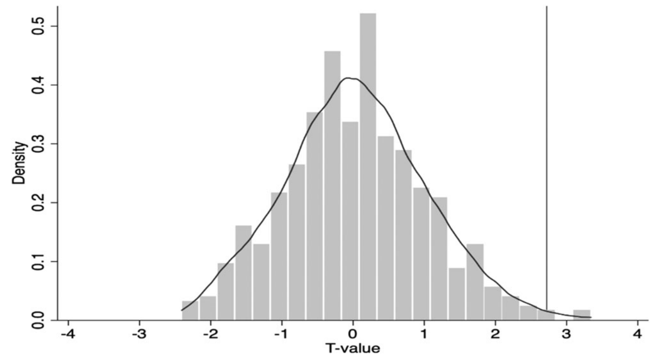

Fig. 2 Regression coefficient t-value of digital economy on technological innovation in cities in 500 regressions. It suggests that only 1% of random shocks in randomly generated experiments have a significant positive effect on urban innovation and that the probability of falsification errors in this study is extremely low.

test steps are as follows. According to the real experimental group of individuals, 500 pairs of hypothetical experimental and control groups are randomly generated. Then, 500 regressions are conducted. The t-value of the coefficient of the core explanatory variables of each regression is counted. Finally, the true t-value of the benchmark regression in Column (5) of Table 2 ($2.45 = 2.323/0.95$) is used to compare these 500 instances of random t-values. As shown in Fig. 2, only 1% of the 500 randomly generated regressions for the experimental group have random t-values greater than the coefficient t-values in the true regression. This outcome suggests that only 1% of the random shocks in the randomly generated experiments have a significant positive effect on urban innovation. The data results show that the probability of making a falsification error in this study is extremely low. This result further supports the core conclusion of this study, that is, the policy effects of the digital economy on urban technological innovation are robust.

Heterogeneity analysis. For the high-quality development of cities, the improvement of urban innovation quality is also key. Thus, we examine the heterogeneity of the impact of the digital economy on innovation quality. Owing to the unbalanced regional economic development in China, spatial differences exist in the development level of different location areas. Thus, we also examine the heterogeneity of the impact of location traits on the innovation incentive effect of the digital economy. This paper also conducts further heterogeneity analysis of innovation types and location traits as shown in Table 4 below.

Table 4 Heterogeneity analysis of the digital economy affecting technological innovation in cities.

Variable	(1) Substantive innovation	(2) Non-substantive innovation	(3) Western Region	(4) Eastern and Central region
DID	1.255**	1.068	−0.482	2.751**
	(0.624)	(0.938)	(0.631)	(1.134)
Control variable	YES	YES	YES	YES
N	3123	3123	880	2,243
R-squared	0.256	0.191	0.620	0.444
Urban Effect	YES	YES	YES	YES
Time Effect	YES	YES	YES	YES

** indicates significance at the 10%, 5%, and 1% levels, respectively, with robustness standard errors in parentheses below.

The digital economy may have a heterogeneous impact on different types of innovation. Columns (1) and (2) in Table 4 reveal the impact of the digital economy on various types of innovation. Patent innovation behavior can be divided according to the type of patents, which can be generally classified into two categories. The first category regards invention patents as a type of substantive innovation that is more disruptive and more oriented toward the quality of innovations. The second category regards non-invention patents (including utility models and design patents), which are less disruptive, as a type of strategic innovation that is oriented toward the number of innovations. Correspondingly, the explanatory variables in Columns (1) and (2) are patent applications per 10,000 inventions and non-invention patent applications per 10,000 non-inventions, respectively, with the former representing substantive innovation and the latter strategic innovation. The positive and significant regression coefficient of Column (1) indicates that the implementation of the "Digital China" strategy significantly promotes substantive innovation or the quality of innovation in the city. The non-significant coefficient of Column (2) indicates that strategic innovation is insignificantly affected compared with the significant promotion of digital economy on substantive innovation. This outcome indicates that the current "Digital China" strategy in China plays an enhancing role in the quality of technological innovation.

Given the unbalanced regional economic development in China, obvious spatial differences exist in the development level of different regions. Therefore, the incentive effect of the implementation of the "Digital China" strategy on urban technological innovation may vary due to differences in geographic location. In accordance with the relevant criteria, this study conducts regressions on the samples of cities in the central and eastern parts of the country and the samples of cities in the western part of the country, respectively. The regression results in Columns (3) and (4) in Table 4 indicate that the digital economy significantly promotes technological innovation in cities in the east-central region but has no impact on the western region. Therefore, the "Digital China" strategy in the east-central region is powerful in promoting the technological innovation process in cities. However, the promotion of the "Digital China" strategy in the western region does not produce good results.

Extensibility analysis: Examining the mechanisms by which the "Digital China" strategy influences urban innovation

Mechanism test analysis. The previous section has verified that the "Digital China" strategy can promote technological innovation in cities. Therefore, we must consider the path mechanism through which the digital economy affects technological innovation. Referring to the previous study (Liu et al. 2023; Ding et al. 2022), we construct the following mechanism testing model on top of the baseline regression model:

Table 5 Identification of mechanisms of "Digital China" strategy affecting urban innovation: Upgrading of industrial structure.

Variable	(1) Urban innovation	(2) Ins	(3) Urban innovation
DID	2.323** (0.950)	0.025** (0.013)	1.819*** (0.774)
ins			3.237*** (1.071)
Control variable	YES	YES	YES
N	3123	3123	3123
R-squared	0.242	0.721	0.679
Urban Effect	YES	YES	YES
Time Effect	YES	YES	YES

, and * indicate significance at the 10%, 5%, and 1% levels, respectively, with robustness standard errors in parentheses below.

$$\mathrm{Innovation}_{it} = \alpha + \beta \mathrm{DID}_{it} + \gamma \mathrm{ins}_{it} + \varphi \mathrm{controls}_{it} + \mu_i + \lambda_t + \varepsilon_{it}. \tag{3}$$

Among them, ins_{it} represents the level of industrial structure upgrading, which is measured by using the proportion of tertiary industry to secondary industry output. Other variables and coefficients represent meanings consistent with those in Eq. (1). Table 5 shows the mechanism test in this part. Column (1) shows the regression results of Column (5) in Table 2, and Column (2) is the regression of digital economy on industrial structure upgrading. The coefficient is significantly positive at the 5% level, which suggests that the "Digital China" strategy leads to the upgrading of the industrial structure of the region. Column (3) further reports the results of regressing the level of technological innovation in the city with the inclusion of the core independent variable and the mediator variable. The estimated coefficient of industrial structure upgrading (mediating variable) is found to be positive and significant, thus indicating that industrial structure upgrading promotes technological innovation in cities. Meanwhile, after adding the mediator variable, the coefficient of digital economy on urban technological innovation remains significantly positive, and the coefficient and significance level are increased. This outcome indicates that industrial structure upgrading plays a mechanism role in "Digital China" strategy and urban technological innovation, that is, the digital economy leads to the optimization and upgrading of industrial structure, which promotes regional technological innovation in China. Hence, Hypothesis 2 can be verified.

Table 6 Comparative test of the measurement methods of substitution mechanism variables.

Variable	(1) ins1	(2) ins2	(3) ins3
DID	0.025** (0.013)	0.556** (0.280)	1.380** (0.633)
Control variable	YES	YES	YES
N	3123	3123	3123
R-squared	0.721	0.779	0.387
Urban Effect	YES	YES	YES
Time Effect	YES	YES	YES

** indicates significance at the 10%, 5%, and 1% levels, respectively, with robustness standard errors in parentheses below.

Comparative analysis of replacement variable. To strengthen the practice of using the proportion of secondary and tertiary industries as a criterion for industrial upgrading, we further adopt the comparative analysis approach of replacing variable measures. First, this paper adopts the proportion of output value of the secondary and tertiary industries as a measure of industrial structure upgrading in the mechanism analysis part. It specifically corresponds to Column (1) in Table 6. Second, to increase the standardization of industrial structure upgrading, we took the proportion of the added value of the tertiary industry to GDP as a new industrial structure upgrading measurement index and then carried out a regression as shown in Column (2) in Table 6. Finally, referring to the practice of previous studies (He et al. 2018; Liu et al. 2023), we adopted "1*Primary industry share + 2*Secondary industry share + 3*Tertiary industry share" as the new industrial structure upgrading measurement index and then carried out the regression (see Column (3) in Table 6). The regression results show that industrial structure upgrading can effectively play the role of intermediary promotion regardless of the type of indicators used for measurement. This finding further confirms the rationality of the results of the mechanism test.

Conclusions and policy recommendations

The digital economy is an essential engine for innovation-driven development. This study examines the impact of the digital economy on urban technological innovation by adopting a multi-temporal DID method and a natural experiment of the local government's "Digital China" strategy. The study finds that this strategy has an incentive effect on urban innovation. Additionally, the strategy enhances urban innovation through the upgrading of industrial structures. Moreover, the digital economy has a more substantial effect on enhancing substantive innovation in terms of the types of innovation. The urban innovation-driven effect of the "Digital China" strategy is more pronounced in the Central and Eastern regions than in the Western regions.

Apart from providing a series of empirical evidence to assess the innovation incentive effect of the digital economy, the conclusions of this study also have the following implications.

(1) Under the reality that the digital economy has become an essential engine for innovation-driven development, the actual implementation of the urban "Digital China" strategy should be accelerated. Priority must be given to the establishment of strategic investment in the field of artificial intelligence, big data, cloud computing, blockchain, and other underlying technologies; the industrial fund must be expanded and strengthened to support the innovative development of the digital economy; the new mode of government guidance, enterprise participation, social crowdfunding, and cooperation between public financial funds and social capital must be explored; a multi-level high-quality digital economy investment system must be built; the strength of talent attraction must be increased in the digital economy, furthermore, the establishment of a new mechanism of multi-party cooperation in talent training needs exploration, various types of educational resources needs integration, and the training of digital economy-related professional education and practical talents needs further strengthening. We should explore the establishment of a new mechanism for multi-party cooperation in nurturing talents, integrate all kinds of educational resources, and strengthen the education of digital economy-related professions and practical talent cultivation; we should build a multi-method digital economy talent attraction system with open selection, market recruitment, and flexible talent attraction; we should further strengthen the construction of talent supporting services to retain talents; we should establish a multi-level exchange and cooperation mechanism and set up a database of experts in the field of the digital economy to form a variety of forms of exchanges, cooperation, and the intelligence introduction mechanism. In addition, a necessity arises to protect the digital economy's intellectual property rights, provide multiple financing channels for digital economy enterprises, and vigorously promote the construction of digital infrastructure.

(2) From the perspective of mechanism analysis, industrial structure upgrading is an important path mechanism for the "Digital China" strategy to promote urban innovation. Therefore, the development level of digital industrialization and industrial digitization must be improved to encourage the upgrading of industrial structures, which can further bolster urban innovation. In addition, the deep integration of the digital economy with the real economy and the transformation and upgrading of traditional industries must be promoted. New industries, business forms, and models must also be cultivated. Further improvements in industrial policies and establishing a coordinated review mechanism for industrial policies on the digital economy are also necessary. Moreover, the inclusiveness of industrial negative lists for emerging industries, such as the digital economy, must be increased.

(3) We should improve the quality of innovation and ensure that the digital economy has a remarkable effect on enhancing the quality of regional innovation. The digital economy has a strong promotional effect on the quality of innovation and maintains a favorable momentum in endorsing high-quality innovation. From the point of view of regional heterogeneity, a differentiated "Digital China" strategy should be implemented to reinforce the positive role of the digital economy in reducing the imbalances of regional development.

Future research directions

This paper uses a multi-temporal DID model to empirically test the role of strategic planning for the digital economy in influencing technological innovation. A room for further expansion and deepening of future research remains in this area. First, in terms of data granularity, microenterprises data can be further utilized to enrich the relevant content of digital economy policies. Second, as a new form of economic growth, the digital economy can be subjected to further analysis by constructing theoretical models of digital economy and technological innovation. In terms of indicator measurement, the expression of technological innovation can be further enriched, and new measurement methods can be explored.

Data availability

The datasets generated during and/or analyzed during the current study are not publicly available. Making the full data set publicly available could potentially breach the privacy that was promised to participants when they agreed to take part, in particular for the individual informants who come from a small, specific population, and may breach the ethics approval for the study. The data are available from the corresponding author on reasonable request.

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Note

1 Fujian and Hunan Provinces are special in that the documents for the digital economy development planning issued by these two provinces before 2015, i.e., Fujian Province's "Notice of the People's Government of Fujian Province on the Issuance of Fujian Province's 'Twelfth Five-Year' Special Plan for Digital Fujian" (2011–2015) and Hunan Province's "Construction of Digital Hunan" (2011–2015), which both cover 2015. For the sake of uniformity, we identify the time of the digital economy strategies of these two provinces as 2011. In addition, we conducted a correlation test in the robustness test for the exclusion of the samples from Fujian and Hunan, which does not affect the core regression results of this study.

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Author contributions

Chong Zhang: The first draft of the manuscript. Baoliu Liu: Material preparation, data collection, and Formal analysis. Yuhan Yang: Material preparation, data collection, and Formal analysis.

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The authors declare no competing interests.

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