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Research article

Digital finance, spatial spillover and regional innovation efficiency: New insights from China

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Abstract: Digital finance, as a new financial model, is increasingly attracting attention for its potential influence on regional innovation. By focusing on the nexus between digital finance and regional innovation efficiency, we first analyze the mechanism by which digital finance affects regional innovation efficiency, and then we empirically investigate its spatial spillover effect by employing the dynamic spatial Durbin model on the basis of a sample set of 31 Chinese provinces from 2011 to 2020. The results reveal that regional innovation efficiency had a significant spatial correlation and time dependence, globally, during the study period. Digital finance significantly contributes to regional innovation efficiency improvement, and such an effect has a significant positive spatial spillover. The spatial effect decomposition results report that the spatial spillover effect of digital finance affecting regional innovation efficiency is stronger than the direct effect. Besides, all three sub-dimensions of digital finance have spatial spillover effects, and the heterogeneity between eastern and central-western regions is mainly reflected in the spatial spillover effects of digital finance.

Keywords: regional innovation efficiency; digital finance; dynamic Durbin model; spatial spillover

1. Introduction

Innovation is the primary engine that drives economic development. The Chinese government has realized that there is an urgent need to shift the dynamics of current economic development from factor-driven and investment-driven to innovation-driven toward upgrading the industrial structure and achieving high-quality economic development by improving innovation efficiency. Meanwhile, the Chinese economy is transitioning from the high growth stage to the high-quality development stage. Given the issues like rising labor costs, escalating energy prices, tightening resource factors and declining marginal efficiency of capital, Chinese economic growth is gradually slowing down. An economic growth model that is driven by investment, factors and trade can no longer serve the need for continuous growth. And, economic growth urgently requires seeking new driving forces. Technological innovation, as the main source of economic growth, is not only the core force for improving local productivity and promoting high-quality economic development, but also the basic driving force for economic development. The Chinese government stated in 2017 that innovation is the primary engine leading economic growth and also a key pillar in constructing the economic system, signaling that the innovation-driven approach has reached a full implementation stage. By the end of 2019, China had input approximately 2 trillion (RMB) in various types of R&D, with a growth rate of 150% relative to 2011, maintaining rapid growth in investment in science and technology and ranking second in the world; investment intensity in R&D reached 2.23%, compared to only 1.84% in 2011; the full-time equivalent of R&D personnel exceeded 4.8 million, with the total number of R&D personnel ranking first in the world for seven consecutive years[1]. The Global Innovation Index 2020, published by the World Intellectual Property Organization, shows that China created the 6th highest innovation output with the 26th highest innovation input in 2020, reflecting the innovation system efficiency, while China ranked 14th in the overall innovation index[2]. In addition, relevant research results show that the conversion rate of China's R&D results is less than 10%, which is far lower than the 40% for developed countries[3]. There are problems such as a low conversion rate of R&D results, disconnection between the innovation chain and industry chain and insufficient financial support for technological innovation in various regions. Therefore, how to effectively enhance its innovation capacity has become a pressing topic [1–5].

Innovative activities require efficient and low-cost financial services support to meet the demand for funds in the R&D stage, the scientific transformation and technological outcome and the industrialization and application of new technologies [6–9]. As early as 1921, Schumpeter emphasized the importance of financial development to technological innovation when examining the contribution of finance to economic growth. Accordingly, during the next wave of a global technological revolution, the finance industry had organically combined with IT enterprises to form a new financial model, known as digital finance, with the development of digital technologies such as big data, cloud computing, artificial intelligence and 5G networks [10]. The rapid development of digital finance in China has given new impetus and vitality to innovative activities [11]. From the Digital Inclusive Finance Index, it is evident that China's digital finance business has developed by leaps and bounds since 2011, where the average value of the digital inclusive finance index in each province increased from 40 in 2011 to 340 in 2020, with an annual average growth rate of nearly 30%[4]. Undoubtedly, the

[1]See more detail: http://www.gov.cn/shuju/2020-08/27/content_5537848.htm
[2]See more detail: https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2020.pdf
[3]See more detail: http://www.gov.cn/zhengce/2014-11/20/content_2781195.htm
[4]See more detail: https://idf.pku.edu.cn/docs/20210421101507614920.pdf

application of digital finance will broaden the breadth and depth of financial services and bridge the deficiencies in traditional financial services with its digital features [12]. Digital finance also creates reachable financial services for market players excluded by traditional finance but have innovative potential. Moreover, emerging technologies and finances have been deeply integrated to develop and boost financial services efficiency and financial resource allocation efficiency. Meanwhile, it also affects the consumption behavior of regional residents, which will inevitably further influence the innovation efficiency of each region [13,14]. Then, some urgent issues concerning digital finance and regional innovation efficiency must be discussed: Does the development of digital finance in China drive regional innovation efficiency, as well as the inherent mechanism for its realization? Innovation activities among regions are associated due to the existence of factor flows, so does this impact of digital finance have spatial spillover? Therefore, it is of significant theoretical and practical significance to accurately evaluate the role of digital finance in regional innovation efficiency, explore digital finance development policies and boost regional innovation efficiency.

The possible research contributions of this paper are the following four aspects. First, digital finance and regional innovation efficiency are included in the same research framework, and the role of the mechanism of digital finance in regional innovation efficiency is analyzed systematically, thus diversifying the research content associated with digital finance and regional innovation efficiency. Second, considering the existence of spatial correlation of regional innovation efficiency, the impact of digital finance on regional innovation efficiency is studied from a spatial perspective by constructing a spatial correlation matrix based on two innovation factors, and the direct and total effects of digital finance affecting regional innovation efficiency are analyzed to deeply mine the spatial heterogeneity between the two, providing a novel perspective for future research on the two. Finally, from the perspective of regional imbalances and structural characteristics, we investigate the heterogeneity effect of digital finance on regional innovation efficiency to serve as a useful reference for differentiated policy implementation and precise policy enforcement with the aim of guiding the implementation of differentiated and targeted policies.

The rest of the paper is structured as follows. The second chapter presents a review of the relevant literature on financial development and innovation and digital financial and innovation. The third chapter presents the role of the mechanism of digital finance in regional innovation efficiency and related research hypotheses. The fourth chapter presents the research methodology, including the variables and the data collection and processing. The fifth chapter discusses the empirical findings of this research design and, on this basis, analyzes the intrinsic causes. The sixth section summarizes the conclusion and gives the corresponding recommended responses.

2. Literature review

As a new financial services model, digital finance is a digital transformation of the financial industry, which involves all electronic products and services in the financial sector [15]. Huang [16] pointed out that digital finance has not changed the essence of finance, and that it has three advantages over the traditional financial sector: payment channels, information matching and data. Through utilizing internet banking, mobile phones and digital payment platforms, digital finance has enriched modern financial activities by reducing financial exclusion, lowering the cost of financial services and improving information asymmetry [17,18].

The essence of digital finance is finance. Brown et al. and Matei argue that a vital channel of

finance's contribution to economic growth is support for R&D financing [19,20]. However, there is no unanimous academic conclusion on how financial development will affect innovation efficiency. Some scholars argue that financial development significantly contributes to innovation efficiency [21]. For example, Ayyagari et al. and Huang found that the higher the share of financing from banking institutions in a firm's investment expenditure, the more innovative the firm [22,23]. Hsu et al. [24] analyze that the degree of stock market development is closely related to innovation in high-tech industries. Hall et al. emphasized the role of financial development in technological innovation, arguing that, by providing financial support for innovation and efficiently allocating scarce resources, evaluating and monitoring innovation projects, overcoming moral hazards and adverse selection problems in the innovation process, financial development can reduce innovation costs, and thus reducing innovation costs, and driving innovation [25–28]. Yao et al. [29] explored the impact of financial technology on regional economies by using a sample of major Chinese cities, revealing that financial technology will indirectly enhance regional technological innovation. Chowdhury and Maung [30] found that financial market development can enhance the effectiveness of an area's investment in innovation; while there is information asymmetry, financing institutions may misallocate resources, leading to inefficient technological innovation. Dirk and Liu confirmed that the financial mismatch and financing constraints arising from financial development are major constraints on investment in basic, high-technology R&D, and they will inhibit innovation efficiency to the detriment of local total factor productivity [31,32]. Song and Wu [33] estimated that the total factor productivity loss in China after 2000 due to financial mismatch was at least 20%. In addition, risk aversion, a prominent feature of traditional financial institutions such as banks when conducting lending operations, is detrimental to companies undertaking innovative business projects [34]. When investigating Chinese firms, Li et al. [28] found that the increase in the level of financialization of firms showed some differentiation in their R&D innovation. For state-owned enterprises, the effect of the level of financialization of firms on R&D innovation was generally inhibitory, but its inhibitory effect gradually decreased as the level of financialization increased.

It is thus clear that, in terms of the traditional perspective on finance, there is a wide divergence of findings across different elements and dimensions, and the relationship between finance and innovation efficiency cannot be generalized. As a further complement to and development of the financial sector, studying whether digital finance enhances regional innovation efficiency may help to deepen research, and the literature that is most closely aligned with this study currently focuses on discussing the impact of digital finance on regional innovation output and innovation activity.

Some scholars have pointed out that traditional financial markets are characterized by a large number of investors who are "many, small and loose" [35]. Digital finance, supported by artificial intelligence and other "ABCDI" technologies, expands the breadth, depth and accessibility of financial services [36]. On the one hand, it is possible to absorb idle social capital at a lower cost and risk. On the other hand, it helps to alleviate the financing constraints faced by the various technological innovation agents and ultimately provides the necessary financial support for the innovation activities of the innovation themes [37]. For firms, adequate financial support and financing capacity are necessary to promote technological innovation [38]. Ketterer's [36] study also shows that the development of digital finance has increased the forms of financial services and expanded access to finance for businesses. Some scholars explore the digital features of digital finance and argue that digital finance will expand its service base through digital technology [39], a streamlined approval process [40], mitigating information asymmetry [41], improving credit evaluation systems [42] and

other ways to ease the financing constraints faced by the region. In turn, it promotes regional levels of technological innovation [43]. In addition, Zhai et al. [44] argues from the perspective of demand for digital services that increased digital demand will "push" financial institutions to provide advanced digital banking services, which provides a favorable financial ecosystem for regional innovation. Some scholars believe that the financial cycle fluctuations led by digital financial development will also have a positive impact on innovation activities [45–47]. The development of digital finance will promote the prosperity of regional trade activities and stimulate the innovation behavior of local enterprises [48,49]. In this process, the digital information characteristics of digital finance will promote the disclosure of corporate information and force them to assume more social responsibilities. In turn improving the total factor productivity and innovation enthusiasm of enterprises [50,51]. Some scholars believe that the financial agglomeration caused by digital financial development and investment in local infrastructure will promote local green technology innovation [52,53].

To sum up, the above literature has shown that digital finance has a vital impact on innovation activities, but there are still some omissions. First, the existing relevant studies mainly focus on the impact of digital finance on regional innovation levels, represented by the technological innovation level, and few consider the impact of digital finance on regional innovation efficiency. Second, innovation activities between regions are linked due to the existence of factor flows; then, the spatial linkage effect of innovation activities is most likely to lead to the existence of an obvious spatial correlation of regional innovation; however, few scholars have considered the spatial spillover of digital finance affecting regional innovation efficiency. As such, we first analyze the mechanism by which digital finance affects regional innovation efficiency, and then we empirically investigate its spatial spillover effect by employing the dynamic spatial Durbin model on the basis of a sample set of 31 Chinese provinces from 2011 to 2020.

3. Mechanistic analysis and research hypothesis

By playing to its strengths, digital finance optimizes the internal and external conditions that influence regional innovation activity. Digital finance contributes to the efficiency of regional innovation. First, digital finance can alleviate financing constraints. The financial sector is a crucial channel for external financing, and the problem of a "moral hazard" and "adverse selection" arising from information asymmetry often exposes firms to financing constraints and inhibits their motivation for R&D and innovation [54]. The development of digital finance, however, can effectively alleviate financing constraints and stimulate R&D and innovation in enterprises. First, digital finance uses the internet platform to effectively integrate financial resources [55], forming a P2P-like investment trading platform, providing multi-channel financing options for innovative projects and meeting the funding needs of R&D and innovation. Second, digital finance uses big data technology to screen and disclose valid information, improve information transparency and effectively alleviate information asymmetry [44], thus reducing the cost of manpower, time and risk management in the financing process. Finally, the application of digital technology establishes a multi-dimensional credit evaluation system for enterprises, enabling investors to identify the creditworthiness of enterprises in a timely and efficient manner, thus reducing the approval process and improving the efficiency of financing [56] and facilitating the timely investment and development of R&D and innovation. Second, digital finance creates new business models. The emergence of digital finance has transformed traditional consumption patterns, especially mobile

payment services that make online transactions possible, resulting in the emergence of new business models and industrial chains similar to online car-hailing, digital education and digital healthcare, forming a multi-dimensional economic ecosystem. The emergence of new business models places new demands on the appearance, functionality and applicability of products, stimulating the development of new technologies and products in these areas. At the same time, new business models have broad market prospects. In the face of the constant entry of new companies, companies will increase their investment in R&D and actively promote autonomous innovation to ensure their core competitiveness. Third, it improves the financial ecosystem. On the one hand, digital finance has improved the universality and accessibility of financial services, and by actively playing the "long-tail effect" to include marginal groups in the investment and innovation markets, it has effectively compensated for the lack of coverage of "long-tail users" in the traditional financial market. This not only increases the scale of finance available for R&D innovation, but it also has an incentive effect on R&D innovation by private enterprises and Micro, Small, and Medium Enterprises (MSMEs). On the other hand, digital finance has also impacted the traditional financial sector, intensifying competition among banks; the spread of internet technology and the use of mobile clients has also increased the demand for digital services, forcing financial institutions to provide advanced digital banking services, forcing the banking sector to transform and upgrade and improving financial resource allocation efficiency, thus providing a favorable financial ecological environment for regional innovation efficiency. As such, this paper proposes the following hypothesis.

Hypothesis 1: Digital finance has a positive contribution to regional innovation efficiency.

According to the theory of spatial externalities, economic activities in each region are not completely independent, but are linked in some way; thus, local innovation activities are inevitably influenced by the financial activities of neighboring regions [57]. This implies that the spatial spillover effect of digital finance is an important factor affecting the efficiency of regional innovation. First, digital technology has enabled technical support for the cross-regional flow of digital finance, while the construction of infrastructure has provided physical dependence on it. With the dual guarantee of technology and infrastructure, digital finance has strong geographical penetration and can provide digital financial services across regions, enriching the financial resources available for innovation activities in specific regions and thus promoting regional innovation efficiency. Second, when digital finance works for R&D innovation in neighboring places, it creates a demonstration effect on the local area. Learning from neighboring areas' advanced use of digital finance and sound management experience can effectively enhance the efficiency of the local use of digital finance, which in turn influences local regional innovation efficiency. Finally, as a carrier of digital finance, the increasing frequency of information transmission and financial product circulation dilutes inter-regional boundaries and strengthens information exchange between regions, thus promoting the scale and level of knowledge spatial spillover. As a result, this paper puts forward the following hypothesis:

Hypothesis 2: Digital finance development has a positive spatial spillover effect on regional innovation efficiency. That is, regional innovation efficiency will be influenced not only by local digital finance, but also by digital finance in neighboring areas.

4. Research design

4.1. Construction of the spatial econometric model

4.1.1. Spatial correlation test

Before the spatial econometric regression, a spatial correlation test is required. In this paper, the global Moran's I index is used for the spatial correlation test, calculated as follows:

$$Moran'sI = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}(x_i-\overline{x})(x_j-\overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}\sum_{i=1}^{n}(x_i-\overline{x})^2} \quad (1)$$

In Eq (1), w_{ij} is the spatial weight matrix, i and j denote regions and x is the regional innovation efficiency. $\overline{x}$ denotes the average value for regional innovation efficiency.

4.1.2. Settings of the spatial econometric model

In spatial econometric models, the spatial autoregressive model (SAR) examines the spatial effects generated by the explanatory variables themselves, captured as spatial lag terms, and the spatial error model examines the spatial effects of other random shocks, captured as spatial error terms. In reality, both of these spatial effects may exist, and ignoring one of them may result in biased estimation results [58]. This work combines a spatial lag model and a spatial error model, incorporating spatial interaction effects into the linear model to build a spatial Durbin model (SDM) suitable for this study. In addition, considering that regional innovation efficiency may be influenced by the previous period, the lagged period of the explanatory variables is incorporated into the model to construct a dynamic spatial Durbin model to better examine the impact of digital finance on regional innovation efficiency. The specific model was constructed as follows:

$$eff_{it} = \alpha_0 + \rho\sum_{j=1}^{n}w_{ij}eff_{it} + \alpha_1 eff_{it-1} + \alpha_2 ifi_{it} + \alpha_3\sum_{j=1}^{n}w_{ij}\,ifi_{it} + \alpha_4 Z_{it} +$$

$$\alpha_5\sum_{j=1}^{n}w_{ij}\,Z_{it} + \mu_i + \theta_t + \varepsilon_{it} \quad (2)$$

In Eq (2), i and t denote the region and time, respectively; eff_{it} is the regional innovation efficiency; eff_{it-1} is the lagged one-period term of regional innovation efficiency; ifi_{it} is digital finance; Z_{it} is the control variable; α represents the parameters to be estimated; w_{ij} is the spatial weight matrix; ρ is the coefficient of the spatial lagged term of regional innovation efficiency; μ_i and θ_t are individual fixed effects and time fixed effects, respectively, and ε_{it} is the random disturbance term [59,60]. To mitigate heteroskedasticity and multicollinearity, some variables are treated by taking the natural logarithm in this work [61].

The effect of the explanatory variables on the explained variables cannot be simply accounted for by estimating the coefficients due to the presence of a spatial lag term. In contrast, the partial differential decomposition method proposed by LeSage and Pace [62] showed that one can accurately account for the effect of the explanatory variables on the explained variables by decomposing the total effect into a direct effect and an indirect effect (spatial spillover effect), where the direct effect is the average effect of the local explanatory variable on the local area, the indirect effect is the average effect

of the neighboring explanatory variable on the local area and the total effect is the average effect of the explanatory variable on the global area.

4.1.3. Spatial weight matrix construction

The commonly used spatial weight matrices are the geographic adjacency matrix, geographic distance matrix and economic distance matrix [63,64]. As for the innovation factors as the carriers of innovation activities, there will be deep-level connections among regional innovation systems due to the flow of innovation factors, so studying the spatial correlation of regional innovation efficiency in China from the perspective of innovation factor flow can reflect the correlation of innovation efficiency among regions more rigorously. A simplified gravity model is applied to construct the R&D funding matrix and R&D personnel matrix in China [65]. The R&D funding matrix is calculated using the following equation:

$$w = \begin{cases} \frac{KP_iP_j}{D_{ij}}, & i \neq j \\ 0, & i = j \end{cases} \tag{3}$$

In Eq (4), w is the R&D funding matrix, K is a constant term taking the value of 1 and i and j denote two different regions; P_i and P_j are the R&D funding stocks of the regions i and j, respectively, and the R&D funding stocks are estimated using the perpetual inventory method; D_{ij} is the distance between the geographical centers of the regions i and j. The same formula is used for the R&D matrix.

4.2. Variable selection and description

4.2.1. Explained variables

Regional innovation efficiency (eff). This paper uses the input-output-based stochastic frontier approach (SFA) to measure regional innovation efficiency. In general, the inputs to regional innovation activities include both labor and capital. The labor input indicator was chosen as the full-time equivalent of R&D personnel because, compared to the number of R&D personnel, the full-time equivalent of R&D personnel can more accurately reflect the actual level of labor input. Capital input is usually measured by internal R&D expenditure, but considering that current R&D expenditure may affect future R&D output, we chose to use the stock of R&D expenditure as the capital input indicator for regional innovation activities. For the output indicators of regional innovation activities, the number of patent applications granted is used to measure innovation output. Using Frontier 4.1 software, two types of production functions, i.e., the beyond logarithm and Cobb-Douglas functions, were measured, and the generalized likelihood ratio was used to test which production function was used. The results show that the LR statistic is greater than the critical value of the mixed chi-square distribution at the 5% significance level, indicating that the use of the transcendental logarithmic function as the production function is more suitable for measuring regional innovation efficiency.

4.2.2. Explanatory variables

Digital financial (ifi). The Peking University Digital Inclusive Finance Index has been used by

many scholars in recent years to study digital finance and its economic effects. The index system uses a total of 33 indicators, consisting of three dimensions: coverage breadth ($ifi1$), coverage depth($ifi2$) and digitization degree ($ifi3$). Its synthesis is based on the dimensionless processing of the indicators; using a layer-by-layer arithmetic weighted average synthetic model, it employs the coefficient of variation method and the hierarchical analysis method to respectively find the weights of the indicator layer on the criterion layer and the weights of the criterion layer on the upper target layer on which the digital inclusive finance development of each province is derived. We use the natural logarithm of this index as the level of digital financial development of each region. In addition, three dimensions of the index are also collected and used to study the impact of structural characteristics of digital finance on regional innovation efficiency.

4.2.3. Control variable

Following Su et al. [66], the control variables were selected to include government intervention, level of openness, industrial structure and human capital. Government intervention is expressed as the ratio of local government expenditure to GDP; openness is measured as the ratio of total imports and exports to GDP after exchange rate treatment; industrial structure is expressed as the share of industrial value added to GDP, and human capital is measured as the natural logarithm of the average number of years of schooling of the population aged six and above.

4.3. Data sources

This work applied panel data from 31 provinces (cities and districts) in China from 2011 to 2020; Hong Kong, Macao and Taiwan were not considered based on the availability of data. Data on digital finance are from the Peking University Digital Inclusive Finance Index. Other data were obtained from the China Statistical Yearbook, the China Science and Technology Statistical Yearbook and the official website of the National Bureau of Statistics. Table 1 shows the descriptive statistical analysis.

Table 1. Descriptive statistical analysis.

Variable	Symbol	Sample database	Average value	Standard deviation	Median	Maximum value	Minimum value
Innovation efficiency	eff	310	310	0.424	0.180	0.404	0.927
Digital finance	ifi	310	310	5.212	0.677	5.410	6.068
Coverage breadth	ifi1	310	310	5.060	0.844	5.284	5.984
Coverage depth	ifi2	310	310	5.195	0.651	5.313	6.192
Digitization degree	ifi3	310	310	5.510	0.698	5.778	6.136
Government intervention	gov	310	310	0.286	0.212	0.230	1.379
Openness	open	310	310	0.255	0.289	0.134	1.548
Industrial structure	inst	310	310	0.344	0.101	0.360	0.530
Human capital	hum	310	310	2.200	0.138	2.211	2.552

5. Empirical results and analysis

5.1. Spatial correlation analysis

The R&D funding matrix and R&D personnel matrix were introduced using Stata 15 software for spatial correlation tests. Table 2 presents the Moran's I index of regional innovation efficiency and digital finance in China from 2011 to 2020 for the two spatial matrices. From Table 2, it can be seen that the Moran's I index is significantly positive for both spatial weight matrices. On the one hand, it indicates the applicability of using spatial econometric models. On the other hand, it reveals that there are significant positive spatial correlations and spatial clustering phenomena for regional innovation efficiency and digital finance in China.

Table 2. Moran's I index.

Year	R&D funding matrix		R&D personnel matrix	
	Innovation efficiency	Digital finance	Innovation efficiency	Digital finance
2011	0.365***	0.627***	0.496***	0.492***
2012	0.367***	0.621***	0.495***	0.482***
2013	0.369***	0.635***	0.494***	0.491***
2014	0.37***	0.594***	0.493***	0.449***
2015	0.371***	0.513***	0.491***	0.373***
2016	0.371***	0.573***	0.488***	0.431***
2017	0.370***	0.598***	0.486***	0.482***
2018	0.370***	0.624***	0.483***	0.515***
2019	0.368***	0.579***	0.476***	0.464***
2020	0.365***	0.569***	0.470***	0.458***

Note: ***, ** and * denote significance at the 1, 5 and 10% levels, respectively.

5.2. Baseline estimation results and discussion

The random effects model, the individual fixed effects model and the two-way fixed-effects model under the non-spatial panel were first regressed separately (see Columns (1)–(3) of Table 3). Table 3 reports that the model fit was better (R^2) after controlling for two-way fixed effects; so, the dynamic spatial Durbin model controlling for two-way fixed effects were initially adopted in this work. In addition, to test whether the model can degenerate into a spatial error model or a spatial lag model, LR and Wald tests were performed on the model [67,68]. Columns (4) and (5) of Table 3 show the correlation estimation results for the two spatial weight matrices. The results show that both the LR and Wald tests indicate that the dynamic spatial Durbin model is more appropriate for this study. Table 3 reveals that, first, the spatial autocorrelation coefficient ρ is significantly positive for both innovation factors in the spatial correlation matrix, indicating that there is a significant spatial dependence between the regional innovation efficiency of each region. The increase in regional innovation efficiency in the "neighborhood" has a positive impact on the local area. It is important to note that this "neighborhood" is a spatially linked area of innovation formed by the movement of R&D funding and R&D personnel. The inter-regional mobility of R&D funds and R&D personnel increases the level of regional scale of innovation factors and knowledge spillover and optimizes the allocation of

innovation factor resources, which provides strong conditions for the improvement of regional innovation efficiency. Second, the estimated coefficients of regional innovation efficiency lagged by one period were all significantly positive, indicating that there is a strong path dependence of regional innovation efficiency in the time dimension, as well as a "snowball" effect. Third, compared to the non-spatial term, the estimated coefficients of digital finance were still significantly positive after considering the spatial interaction effect, but the coefficients were significantly smaller, indicating that the non-spatial model may ignore the spatial factor and lead to biased estimates. As mentioned earlier, to facilitate the analysis of the direct and spatial spillover effects for each variable, the partial differential method was used to decompose the effects of the results shown in Columns (4) and (5) of Table 3.

Table 3. Baseline estimation results.

Variable	Non-spatial panel RE (1)	Non-spatial panel FE (2)	Non-spatial panel FE (3)	R&D funding matrix SDM (4)	R&D personnel matrix SDM (5)
L.eff				1.051***	1.006***
				(111.52)	(105.51)
ifi	0.053***	0.049***	0.024***	0.015***	0.018***
	(11.78)	(12.04)	(3.09)	(5.39)	(6.39)
gov	-0.030	0.039	0.083**	0.025***	0.027***
	(-0.42)	(0.49)	(2.13)	(4.39)	(4.78)
open	-0.108***	-0.114***	-0.005	0.002	0.004**
	(-5.17)	(-5.74)	(-0.41)	(1.21)	(2.11)
inst	-0.715***	-0.720***	-0.000	0.011**	0.014***
	(-12.52)	(-13.85)	(-0.00)	(2.06)	(2.74)
hum	0.410***	0.474***	0.082**	0.005	0.009*
	(5.71)	(6.62)	(2.24)	(0.88)	(1.72)
W*ifi				0.189***	0.173***
				(6.77)	(6.33)
W*gov				0.892***	0.920***
				(13.19)	(14.19)
W*open				0.090***	0.091***
				(10.82)	(10.16)
W*inst				1.181***	1.213***
				(16.89)	(17.33)
W*hum				0.357***	0.487***
				(3.97)	(5.16)
ρ				0.362***	0.173***
				(5.87)	(6.33)
LRSAR				8.13	9.90*
LRSEM				84.32***	100.64***
WaldSAR				384.85***	412.29***
WaldSEM				383.28***	411.88***
City effect	NO	YES	YES	YES	YES
Year effect	NO	NO	NO	YES	YES
R2	0.900	0.901	0.979	0.962	0.962
N	310	310	310	279	279

Note: z-values in brackets; ***, ** and * denote significance at the 1, 5 and 10% levels, respectively.

5.3. Decomposition effects results and discussion

Table 4 presents the direct effects, indirect effects and total effects for the above-estimated results for the two spatial weight matrices. First, in terms of direct effects, there was a significant positive impact of digital finance on regional innovation efficiency for both spatial weighting matrices, indicating that local digital finance development has a significant contribution to local regional innovation efficiency, which validates Hypothesis 1. Our results support the findings of Qian et al. [69]. Digital finance in China not only improves the efficiency of capital allocation and promotes the enthusiasm of enterprises in R&D and innovation, but it also complements the shortcomings of the traditional financial market for the innovation market, especially, forming strong support for the innovation activities of small, medium and micro enterprises [70,71]. At the same time, the strengthening of government and industry regulations of digital finance in recent years has provided a strong guarantee for the efficiency of digital finance in promoting regional innovation. Such regulations include the Interim Measures on the Management of Business Activities of Online Lending Information Intermediaries issued by the CBRC in 2016, and the Financial Technology (FinTech) Development Plan (2019–2021) issued by the Central Bank in 2019 [72]. Second, in terms of indirect effects, the spatial spillover effects of digital finance affecting regional innovation efficiency are all positively significant, indicating that the development of digital finance in neighboring areas also plays a positive role in local regional innovation efficiency, and the empirical results significantly verify Hypothesis 2. In addition, the comparison reveals that the spatial spillover effect of digital finance affecting regional innovation efficiency is greater than the direct effect in both the R&D funding matrix and the R&D personnel matrix. On the one hand, relying on digital technology development, the geographical and spatial barriers to financial services have been gradually removed, making the provision of cross-regional financial services a feature and scope of the business of digital finance [69]. On the other hand, the saturation of the local financial market has prompted companies and digital finance to actively seek development outside of the region, and the use of the internet has provided a good platform for this demand, greatly improving the interface between local companies and digital finance, which in turn has stimulated regional innovation efficiency [73].

Finally, the total effect of digital finance is significantly positive, indicating that digital finance has a significant positive impact on regional innovation efficiency when the spatial spillover effect of digital finance is taken into account. In terms of control variables, both the direct and indirect effects of government intervention on regional innovation efficiency were significantly positive, indicating that innovation activities cannot be carried out without government support, and that government can actively compensate for market imperfections, eliminate innovation risks and stimulate innovation potential. Openness has a positive contribution to the efficiency of regional innovation, reflecting take-up of advanced technology and its ability to innovate independently in foreign economic activities. Industrial structure promotes regional innovation efficiency, which reflects the increasing demand for technological innovation in the process of industrial structure adjustment [74]. The indirect effects of human capital were all significantly positive, the direct effects were significantly positive for the R&D personnel matrix, and positive but not significant for the R&D funding matrix, indicating that the accumulation of human capital improves the level of knowledge and effectively promotes the improvement of regional innovation efficiency [75].

Table 4. Decomposition effects results.

Variable	R&D funding matrix			R&D personnel matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ifi	0.0196***	0.3049***	0.3245***	0.0204***	0.2401***	0.2606***
	(6.59)	(6.04)	(6.29)	(7.15)	(6.06)	(6.46)
gov	0.0481***	1.4055***	1.4536***	0.0426***	1.2485***	1.2911***
	(6.46)	(8.68)	(8.71)	(6.48)	(10.09)	(10.14)
open	0.0046**	0.1436***	0.1482***	0.0054***	0.1260***	0.1314***
	(2.42)	(6.35)	(6.33)	(2.95)	(6.95)	(6.98)
inst	0.0408***	1.8634***	1.9043***	0.0343***	1.6568***	1.6911***
	(3.91)	(7.24)	(7.15)	(3.96)	(8.33)	(8.21)
hum	0.0137**	0.5566***	0.5703***	0.0171***	0.6549***	0.6721***
	(2.34)	(4.82)	(4.82)	(2.97)	(6.40)	(6.42)

Note: z-values in brackets; ***, **and * denote significance at the 1, 5 and 10% levels, respectively.

5.4. Heterogeneity results and discussion

5.4.1. Structural characteristics heterogeneity results and discussion

The three dimensions of the digital finance index have different connotations based on their concepts and constituent indicators. Coverage breadth ($ifi1$) is reflected by the number of electronic accounts, reflecting the supply of digital financial services; coverage depth ($ifi2$) is measured by a combination of total actual use and active use of internet financial services, reflecting the effective demand for digital financial services; digitization $degree$ ($ifi3$) is marked by convenience, low cost and creditworthiness, reflecting the low cost, low threshold and high creditworthiness that digital technology brings to financial services. Table 5 shows the results of the decomposition of the effects of the structural characteristics of digital finance on regional innovation efficiency. In terms of the total effect, all three dimensions of digital finance have a significant positive impact on regional innovation efficiency, indicating that there is a "structural" driving effect of digital finance on regional innovation efficiency. In terms of direct effects, the coefficients of coverage breadth ($ifi1$), coverage depth ($ifi2$) and digitization $degree$ ($ifi3$) were all significantly positive. In terms of indirect effects, all three dimensions of digital finance have a positive spatial spillover effect on regional innovation efficiency, and their coefficients were larger than those for the direct effects. As mentioned in the previous analysis, Internet use to provide cross-regional financial services has become a characteristic and scope of business for digital finance, and this characteristic is also reflected in the dimensions of digital finance. Specifically, cross-regional financial services allow for an optimal mix of both supply and demand for digital finance, which greatly optimizes the efficiency of resource allocation and thus promotes the innovation capacity and motivation of enterprises, ultimately manifesting itself as positive support for regional innovation efficiency in terms of coverage breadth ($ifi1$) and coverage depth ($ifi2$), and as a spatial spillover effect over a direct driver effect. In contrast, digitization $degree$ ($ifi3$) is more dependent on digital technology; the development of digital technology continues to promote the penetration of digital finance into spatially connected areas, and its low-cost, low-threshold, and high-credit financial services effectively promote regional innovation efficiency. The digitization degree ($ifi3$) is more dependent on digital technology, the development of digital technology continues to promote the infiltration of digital finance into spatially related areas, and its low-cost,

low-threshold, high-credit financial services effectively promote regional innovation efficiency.

Table 5. Structural characteristics heterogeneity results.

Variable	R&D funding matrix			R&D funding matrix		
	ifi1	ifi2	ifi3	ifi1	ifi2	ifi3
L.eff	1.023***	1.025***	1.074***	1.023***	1.001***	1.128***
	(103.69)	(109.76)	(103.04)	(104.80)	(109.00)	(108.93)
ifi	0.006***	0.011***	0.002	0.005***	0.011***	0.005**
	(3.71)	(6.09)	(0.87)	(3.31)	(6.20)	(2.36)
gov	0.020***	0.014***	0.009	0.018***	0.015***	0.009
	(3.41)	(2.65)	(1.46)	(3.22)	(2.81)	(1.47)
open	0.003	0.003**	0.009***	0.004**	0.004***	0.011***
	(1.62)	(2.08)	(5.11)	(2.49)	(2.69)	(6.20)
inst	0.005	0.009*	0.011**	0.006	0.009*	0.017***
	(0.98)	(1.76)	(2.09)	(1.27)	(1.82)	(3.27)
hum	0.013**	0.003	0.018***	0.013**	0.003	0.016***
	(2.47)	(0.63)	(3.44)	(2.55)	(0.51)	(2.93)
W*ifi	0.051***	0.049***	0.133***	0.038**	0.035**	0.173***
	(3.20)	(2.80)	(7.84)	(2.37)	(2.04)	(10.15)
W*gov	0.817***	0.748***	0.775***	0.710***	0.581***	0.657***
	(12.15)	(11.65)	(11.75)	(11.20)	(9.91)	(10.61)
W*open	0.101***	0.103***	0.151***	0.092***	0.077***	0.166***
	(10.77)	(13.87)	(17.30)	(9.11)	(10.03)	(17.94)
W*inst	1.126***	1.050***	1.082***	1.006***	0.821***	1.129***
	(15.96)	(15.33)	(15.71)	(14.54)	(11.63)	(16.44)
W*hum	0.413***	0.328***	0.396***	0.519***	0.291***	0.595***
	(4.49)	(3.70)	(4.32)	(5.44)	(2.92)	(6.20)
ρ	0.373***	0.320***	0.607***	0.261***	0.223***	0.678***
	(5.94)	(4.96)	(9.13)	(4.20)	(2.71)	(10.46)
Direct effect	0.0072***	0.0121***	0.0106***	0.0057***	0.0112***	0.0203***
	(4.46)	(6.73)	(2.77)	(3.7)	(6.56)	(3.28)
Indirect effect	0.0862***	0.0766***	0.3551***	0.0539**	0.0485**	0.5764***
	(3.16)	(3.15)	(3.76)	(2.41)	(2.36)	(3.41)
Total effect	0.0934***	0.0886***	0.3657***	0.0596***	0.0597***	0.5968***
	(3.35)	(3.6)	(3.75)	(2.63)	(2.89)	(3.41)
City effect	YES	YES	YES	YES	YES	YES
Year effect	YES	YES	YES	YES	YES	YES

Note: z-values in brackets; ***, ** and * denote significance at the 1, 5 and 10% levels, respectively.

5.4.2. Regional heterogeneity results and discussion

There are significant differences in the development of digital finance and regional innovation capacity in different regions of China, so it is necessary to discuss them by region to examine the impact of digital finance development on regional innovation efficiency in different regions. Table 6 shows the results of the decomposition of the effect of digital finance on regional innovation efficiency in eastern and central and western regions. Regarding the total effect, whether in the eastern region or the central and western regions, digital finance has a significant positive impact on regional innovation efficiency. From the direct effect, it can be seen that, for the R&D funding matrix, the direct effect of the eastern

region is greater than that of the central and western regions, and the direct effect of the eastern region is greater than that of the central and western regions. In supporting scientific research, the eastern region pays attention to scientific and technological personnel, while the central and western regions pay attention to scientific research funds. From the indirect effect, it can be seen that there is obvious regional heterogeneity in the indirect effect of digital finance on regional innovation efficiency. Whether for the R&D funding matrix or the R&D personnel matrix, the indirect effect in the eastern region is greater than that in the central and western regions. Our results are similar to those of Yang and Wang, who argue that the impact of digital finance on regional innovation efficiency varies by region as well as by digital economy development level [73]. On the one hand, the eastern region has a high level of innovation activity, innovation capacity and technological implication, and can actively play a positive role in promoting the efficiency of regional innovation through digital finance, while the central and western regions are deficient in their innovation capacity and use of digital finance [69–74]. On the other hand, digital finance is not a pavilion in the sky, but it also needs the support of infrastructure construction, especially the construction of financial infrastructure and information infrastructure, in which the eastern region is ahead of the central and western regions; the shortcomings in infrastructure may make the spatial spillover effect of digital finance insignificant in the central and western regions [76].

Table 6. Regional heterogeneity results.

Variable	R&D Funding Matrix		R&D Funding Matrix	
	East	Central and western	East	Central and western
L.eff	1.125***	1.002***	2.259***	1.044***
	(100.34)	(36.24)	(181.96)	(38.00)
ifi	0.009	0.019***	-0.177***	0.021***
	(1.54)	(4.41)	(-28.24)	(4.80)
gov	0.030*	0.016**	-0.428***	0.004
	(1.92)	(2.47)	(-24.69)	(0.56)
open	0.010***	0.022***	0.081***	0.026***
	(3.63)	(4.65)	(27.92)	(5.68)
inst	0.045***	-0.002	0.552***	-0.003
	(4.37)	(-0.24)	(50.54)	(-0.47)
hum	-0.068***	0.004	-0.595***	0.006
	(-4.34)	(0.72)	(-33.97)	(1.11)
W*ifi	0.127***	0.155***	-0.291***	0.252***
	(4.89)	(3.27)	(-11.51)	(5.40)
W*gov	0.165**	0.154**	-2.369***	0.275***
	(2.29)	(2.40)	(-29.80)	(4.26)
W*open	0.028***	0.110**	0.229***	0.202***
	(3.29)	(2.11)	(23.98)	(3.59)
W*inst	0.294***	0.000	1.264***	0.081
	(4.28)	(0.00)	(17.28)	(1.40)
W*hum	0.193**	-0.018	-1.251***	-0.063
	(2.49)	(-0.20)	(-14.96)	(-0.74)
ρ	0.021	0.250	2.700***	1.490***
	(0.41)	(1.11)	(53.02)	(6.68)

Continued on next page

Variable	R&D funding matrix		R&D funding matrix	
	East	Central and western	East	Central and western
Direct effect	0.0092	0.0171***	0.0879***	0.0081*
	(1.60)	(3.91)	(4.63)	(1.72)
Indirect effect	0.1300***	0.1270***	0.1868***	0.1021***
	(4.76)	(2.81)	(11.57)	(4.87)
Total effect	0.1391***	0.1442***	0.2747***	0.1103***
	(4.57)	(3.07)	(16.07)	(5.43)
City effect	YES	YES	YES	YES
Year effect	YES	YES	YES	YES

Note: z-values in brackets; ***, ** and * denote significance at the 1, 5 and 10% levels, respectively.

5.5. Robustness tests results and discussion

To further verify the robustness of the model and estimation results, we conducted robustness tests with focus on replacing the explanatory variables and the spatial weight matrix. Specifically, the number of patent applications received is used as the output indicator, the SFA method is re-applied for the measurement of regional innovation efficiency and the spatial weight matrix is replaced with a geographical distance matrix (see Table 7). The results in Table 7 show that the sign direction of the core explanatory variables remains consistent with those in the previous section after endogeneity treatment and robustness tests, indicating the reliability of the model settings and estimation results.

Table 7. Robustness test results.

Variable	Changing explanatory variable		Changing matrix
	R&D funding matrix	R&D personnel matrix	Geographical distance matrix
L.eff	1.146***	1.077***	1.110***
	(96.13)	(90.60)	(115.48)
ifi	0.015***	0.014***	0.010***
	(5.94)	(5.61)	(3.30)
Wifi	0.100***	0.096***	0.035*
	(3.82)	(3.80)	(1.91)
ρ	1.135***	1.163***	0.807***
	(10.38)	(10.58)	(10.70)
Control variable	YES	YES	YES
City effect	YES	YES	YES
Year effect	YES	YES	YES

Note: z-values in brackets; ***, ** and * denote significance at the 1, 5 and 10% levels, respectively.

6. Conclusions and recommendations

Based on panel data from 31 provinces in China from 2011 to 2020, this work matches regional innovation efficiency measured via the SFA and employs a dynamic spatial Durbin model based on constructing an R&D funding matrix and an R&D personnel matrix to test the impact of digital finance on regional innovation efficiency and its spatial spillover effects. It was found that there is a positive spatial correlation between both digital finance and regional innovation efficiency, and that there is a path dependence of regional innovation efficiency in spatial and temporal distribution. Digital finance significantly contributes to regional innovation efficiency, and such effects exist in a positive spatial spillover. The decomposition effect results report that digital finance in neighboring areas is more

conducive to enhancing local regional innovation efficiency. Among the three sub-dimensions of digital finance, the direct and spatial spillover effects of coverage breadth, usage depth and digitization degree were significantly positive. The heterogeneity of digital finance affecting regional innovation efficiency is reflected in the spatial spillover effect, which is greater in the eastern region than in the central and western regions. Based on this, some beneficial policy recommendations are as follows.

1) Policymakers shall pay attention to the spatial linkage effect of regional innovation activities and give full play to the spatial advantages of regional innovation efficiency. For example, by actively building regional collaboration platforms and encouraging exchanges and cooperation between local enterprises and those in neighboring regions, the collaborative innovation capacity between regions can be improved; on the other hand, through the inter-regional flow of R&D personnel and R&D funds, the level of knowledge spillover and the allocation efficiency of innovation factors can be driven.

2) Local governments should actively promote the digital transformation of the financial sector, improving the ability of digital financial services to serve the real economy and realizing further support from digital finance for the efficiency of regional innovation. Policymakers shall encourage the deeper integration of digital technology with the financial sector through financial subsidies and tax breaks, thus promoting the development of digital finance. Second, they should establish a standardized investment trading platform, build a one-stop approval service and improve the financial supervision system for the flow of funds, information security and financing process to provide quality and safe financial services that improve regional innovation efficiency.

3) Policymakers should broaden digital finance coverage and develop differentiated measures to effectively facilitate regional innovation efficiency in more regions. On the one hand, the flow of talent, technology and capital will be guided through increased support and publicity to improve the efficiency and capacity of enterprises in the central and western regions to utilize digital finance. On the other hand, the "new infrastructure" will be used as an opportunity to strengthen the existing financial and information infrastructure in the eastern region, while the central and western regions will step up their efforts to complete the shortcomings in this area, thus ensuring that the spatial spillover effects of digital finance are fully utilized.

4) Although this paper analyzes the impact of digital finance on regional innovation efficiency in terms of spatial spillover, some research deficiencies and future research directions still deserved to be the focus. On the one hand, industrial structure, income gap and Internet infrastructure construction probably serve significant roles in the impact of digital finance on regional innovation efficiency. Therefore, future scholars can analyze the impact of digital finance on regional innovation efficiency from the above perspectives. On the other hand, this paper quantifies digital finance using the Digital Inclusive Finance Index published by Peking University. With the continuous development of big data and artificial technology techniques, scholars in the future can explore more ways to measure digital finance through technologies such as web crawlers.

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Conflict of interest

Authors state no conflict of interest.

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