



How financial development scale and R&D influence regional innovation efficiency: empirical evidence from the financial industry

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Received: 10 September 2021 / Accepted: 29 September 2021 / Published online: 10 November 2021
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Abstract

Financial elements and R&D elements are significant drivers for enhancing regional innovation efficiency. This paper measures financial elements by financial development scale and the marketization level of the financial industry and R&D elements by the inputs and flow of R&D personnel and R&D capital and specifically considers R&D element flow to quantify the consequential spatial spillover effects. Based on provincial panel data from 2008 to 2018, the paper firstly estimates the regional innovation efficiency of China's 30 provincial-level administrative regions using super-efficiency DEA and then conducts an empirical analysis of the influence of financial elements and R&D elements on regional innovation efficiency by the use of the Tobit model and three spatial econometric models. It is found that, by and large, the financial development scale, the marketization level of the financial industry, the inputs of R&D personnel and R&D capital, and R&D capital flow all have significant effects on regional innovation efficiency. Nonetheless, by region, R&D personnel flow in central China can significantly boost regional innovation efficiency while fails in eastern and western China. From the spatial perspective, both financial elements and R&D elements have significant positive spatial spillover effects. Therefore, in order to bolster regional innovation efficiency, it is crucial to improve the allocation of financial elements and R&D elements and build a tight regional collaborative innovation network.

Keywords Financial element · Financial industry · Innovation efficiency · DEA model · Spatial econometric model · Financial development · Responsible Editor: Nicholas Apergis

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Introduction

Sustainable economic development is characterized by resource conservation and environmental friendliness, aiming at low consumption, low emissions, low pollution, as well as high efficiency, high effectiveness, and high circulation. Apparently, sci-tech innovation serves as a major driver for sustainable regional economic development. As per China's economic development history, the main impetus for economic development has changed from exogenous natural resources to endogenous science and technology innovation, which indicates that economic development is no longer driven by investment but by technological progress. Regrettably, there are still many problems hindering sustainable regional economic development in China (Ullah et al. 2021). For instance, regional capacity for sci-tech innovation is still unbalanced, led by eastern China, followed by central and western China; the sci-tech innovation system provides insufficient support for the economic system (Kreso

et al. 2021). The fundamental solution to these problems is to boost the operational efficiency of the sci-tech innovation system. And therein lies the significance of the research on regional innovation efficiency and its influencing factors (Hu and Chang 2021). For one thing, the process of sci-tech innovation is very risky because of large capital demand, long periodicity, and high uncertainty (Cheng et al. 2019), (Chen et al. 2018), and (Gao et al. 2020).

It is a capital-intensive investment, whose demand is often difficult to meet only by free capital or government finance, and must rely on a robust financial market. However, some enduring problems of China's financial market, like the imperfect financial system, inadequate development, and the imbalance between supply and demand, have severely impeded the efficiency of sci-tech innovation (Ren and Yu 2021; Zhao et al. 2021; Banerjee et al. 2021). In recent years, China has largely improved the domestic financial environment and facilitated the cooperation between financial institutions, professional service providers, and technology companies, via promoting market-oriented financial reform and the market-based allocation of production factors. Precisely, professional service providers (Zhao et al. 2021) (incubators, technological, and financial service platforms) create a suitable environment for corporate sci-tech innovation, while financial institutions provide financial support. Enhancing the three financing channels for science and technology, namely the investment by the capital market, venture capital, and financial institutions, is influential in fostering regional innovation efficiency for it can alleviate the financing difficulties facing many science and technology enterprises (Ritchie and Roser 2019). For another, increasing the inputs of R&D elements can effectively fuel regional innovation efficiency for R&D elements provide the material basis and guarantee for innovative activities and thus spur them (Min et al. 2020).

In recent years, China has attached great importance to the role of R&D elements in enhancing regional innovation efficiency. In the *Outline of National Medium- and Long-term Program for Science and Technology Development (2006–2020)*, China emphasized that increasing R&D element inputs would offer important support for fuelling China's comprehensive national strength and international competitiveness (Ling et al. 2020; Hong et al. 2019; Banerjee et al. 2021). Under the guidance of relevant policies, China's R&D element inputs have been mounting but still insufficient compared with developed countries. In this case, the issue of efficiency becomes more substantial. Moreover, R&D element flow will promote the dissemination of knowledge and technology, thus affecting innovation efficiency, and it is particularly obvious in China due to the different locations and development levels of each region and the wide regional gap of the stock and increment of R&D elements. (Emrouznejad and Yang, 2018) Therefore,

it is noteworthy how to utilize the inputs and flow of R&D elements to bolster regional innovation efficiency. As mentioned above, under the background of innovation-driven development strategy and the new normal of economic development, improving regional innovation efficiency is an essential prerequisite for high-quality development of regional economy, which are conditioned by two pillars of sci-tech innovation, namely financial elements and R&D elements.

Regrettably, in China, uneven distribution of these two and other relevant problems still linger on, which to some extent hinders the enhancement of regional innovation efficiency. What is the status quo of financial elements, R&D elements, and innovation efficiency in each provincial-level administrative region at this stage? What is the influence of financial elements, R&D elements, and their flow on regional innovation efficiency? How to maximize regional innovation efficiency? It is of great practical significance to investigate these questions. Thereby, this paper centers on the influence of financial elements and R&D elements on regional innovation efficiency delves into the basic conditions of these three in each region of China, and establishes models to explore the effects of the allocation of the two elements on regional innovation efficiency at the present stage, with the aim of offering advice for the institution and implementation of relevant policies in China.

Literature review

The financial sector has always been at the core of socio-economic development, vital to the healthy functioning of the social economy. And innovation entails large amounts of capital investment. American economist Schumpeter was the first to argue that technological innovation and economic development could not be achieved without the support of the financial system, such as money and credit, which undoubtedly affirms the positive role of the financial system in regional innovation. Besides, financial development can drive capital to industries with high allocation efficiency by market signals, thus reducing transaction costs and spurring the independent innovation of enterprises (Zhu et al. 2021). Tadesse found that the improvement of the financial system promoted capital mobilization and risk sharing, which fuelled technological innovation, a major stimulus for productivity. Whereupon, increased productivity could promote the restructuring and upgrading of regional industries, thus fostering regional economic development (Guan et al. 2021). The difficulty of financing has always been the primary obstacle to the enhancement of the innovation capacity of innovative enterprises in China. Given this, the construction of a diversified and sound financial support system plays

an important part in the deep development and upgrading of innovation of high-tech enterprises (Ling et al. 2020).

By decomposing total factor productivity, Jeong and Townsend found that the enhancement of technological innovation efficiency relied heavily on regional financial deepening. (Ren and Ren 2018) empirically explored the impact of financial structure, financial development, and financial activities on innovation efficiency in China's regions and found that the development of financial elements in each provincial-level administrative region significantly backs the enhancement of regional innovation efficiency (Mohsin et al. 2019, 2020a, 2021). Hsu et al. studied how the development of the financial market affected industrial innovation level and found that the more developed the stock market is, the higher the innovation level of the high-tech industry. With the in-depth study of innovative activities by a multitude of scholars, the academic community has gradually paid more attention to the resources required for the R&D process, which have become a hot topic of studies. (Audretsch and Feldman 1996) suggested that R&D-element-driven technological development was a key impetus to promote regional industrial restructuring and economic development, as evidenced by the fact that technological innovation inputs could enhance enterprise production efficiency, product quality, and ultimately regional economic development.

Accordingly, technological development fostered by R&D inputs is a critical step in enhancing regional innovation efficiency and economic development. Ljungvall and Tingvall found that the greater the R&D element inputs, the more significantly they can spur regional economic growth (Kijek and Kijek 2019). The R&D element inputs can significantly foster the regional production of new knowledge and have a spatial spillover effect to a certain extent, positively contributing to the output of new knowledge in neighboring provincial-level administrative regions. R&D elements, basic to the function of the innovation system, can exist independently from the original innovation system. And on the one hand, similar to traditional production elements, they are also characterized by scarcity and profit-seeking, spontaneously flowing to regions with a higher marginal return. On the other hand, R&D elements also have spatial spillover effects of different degrees. According to Hansen and Birkinshaw's concept of innovation value chain, scientific and technological innovation activities can be divided into two stages: knowledge innovation and product innovation, while the input and flow of R&D elements and the consequential spatial spillover effects influence the whole process. Moreover, in the process of innovation, R&D personnel, R&D capital and the spatial flow of them have spillover effects on any stage of the innovation value chain, thus fostering regional innovation efficiency (Hansen and Birkinshaw 2007). Li et al. (2021), Chien et al. (2021), and Iqbal et al. (2021) established multiple spatial econometric models, and

from a spatial perspective, they found that the flow of R&D personnel and R&D capital has a significant spatial spillover effect on economic growth (Mohsin et al. 2018a, 2018b; Ikram et al. 2019a).

Fritsch and Slavtchev defined efficient regional innovation as "maximizing the innovation output with a given amount of innovation inputs." As early as 2002, Niosi first studied the innovation efficiency of the national innovation system at the national level and explained that the current national innovation activities are inefficient from a qualitative point of view (Yang et al. 2021; He et al. 2020; Mohsin et al. 2020b). Afterward, an increasing number of scholars began to carry out research from a quantitative point of view. Wang and Huang explored the efficiency and influencing factors of R&D activities in 30 countries based on the DEA-Tobit mode. Tiep et al. (2021) had used the DEA approach to study regional innovation efficiency. Ikram et al. (2019a) and Shah et al. (2019) first used SFA to evaluate regional innovation efficiency, whose study unveiled China's low innovation efficiency and a large gap in regional development (Zhang et al. 2006). Later, SFA was widely accepted as an evaluation method of regional innovation efficiency. As the research progressed, the research methods were improved, and the three-stage DEA model was applied to the measurement of innovation efficiency. For example, Bai and Jiang used it to explore the influence of environmental factors on regional technological innovation efficiency, which made the research results more consistent with the regional objective reality (Bai and Jiang 2011). Fu and Jiang used fuzzy-set qualitative comparative analysis (Fs/QCA) to evaluate the innovation performance and regional cooperation in China's 31 provincial-level administrative regions and found that multiple participants had a significant positive impact on regional innovation.

Meanwhile, scores of scholars have also conducted research on the influencing factors of regional innovation efficiency. Guo et al. found that innovation funds can improve the innovation performance of enterprises via the panel data of Chinese manufacturing companies. Ikram et al. (2019a), Sun et al. (2019), and Ikram et al. 2019b dissected the influence of academic and industrial cooperation (AIC) on regional innovation performance and found that AIC can narrow the gap of innovation efficiency amid different regions (Hong et al. 2019).

The above literature review suggests that at present, the academic community has yielded quite fruitful results of the research on financial elements, R&D elements, and regional innovation efficiency and has basically established a research system. Notwithstanding, the existing research still has the following shortcomings: as regards financial elements, many scholars have explored the influence of financial elements on regional innovation efficiency and economic development but without a system and unified standard for the selection

of indicators of financial elements. As for R&D elements, most of the relevant research focuses on R&D personnel and R&D capital per se, examining the influence of R&D element inputs on regional innovation efficiency from a static perspective. There are relatively few studies on inter-regional dynamic R&D element flow.

As to regional innovation efficiency, in the past, there were fewer choices of evaluation indicators for it, and the influence of spatial connections and element flow on regional innovation efficiency was not considered (Baloch et al. 2020). Based on the provincial panel data of China from 2008 to 2018, this paper puts financial elements, R&D elements, and regional innovation efficiency in the same framework, takes account of R&D element flow and establishes a Tobit regression model and three spatial econometric models to explore the interaction mechanism among variables; as per empirical research, the paper aims to bolster the allocation of regional financial elements, R&D elements, thus enhancing regional innovation efficiency, spurring regional economic development, and offering policy advice for the implementation of regional innovation-driven development strategies.

Methodological mechanism of financial elements and R&D elements on regional innovation efficiency

Analysis of the influence mechanism of financial elements on regional innovation efficiency

In the context of economic transformation, every country has issued a series of financial-related policies to stimulate enterprises, universities, and other subjects to conduct innovative activities and promote R&D inputs and innovation outputs, thus fostering regional innovation via the innovation of each subject. There are four main ways for financial elements to affect regional innovation, which are as follows. (1) Credit; the establishment and improvement of the financial system provide strong financial support for regional innovative activities, thus realizing the transformation of innovative brainstorming to outputs with social value. With the continuous refinement of the financial system, its ability to absorb idle social funds increases, which in turn reduces credit costs and enhances local innovation efficiency. (2) Spreading risk; generally speaking, a more mature financial system offers more abundant financing channels for innovative institutions such as enterprises for the existence of financial institutions with different risk preferences.

Thereupon, innovative enterprises can achieve horizontal risk diversification, namely transferring the risk of innovative activities to financial institutions with a higher risk appetite, which reduces the potential loss caused by

innovative activities while ensuring control over outputs. (3) Motivating corporate management and supervision; technological innovation is faced with serious adverse selection and moral risks. If investors allow management to conduct scientific experiments blindly, it will increase the risk of innovative activities and harvest grave losses to the company. By introducing external financial agents, investors can effectively foster the initiative of management and reduce losses due to moral hazards (Amore et al. 2013).

(4) Reducing information asymmetry and transaction costs; high-tech projects entail extremely high expertise and rich information resources, whereas general investors find it difficult to have both, thus erecting the research barrier. By introducing financial institutions and increasing the efficiency of information collection, it can often yield twice the result with half the effort, greatly reducing the information asymmetry in the R&D process and lowering the transaction costs (Zhang et al. 2021; Hsu et al. 2021; Ehsanullah et al. 2021).

Analysis of the influence mechanism of R&D elements on regional innovation efficiency

R&D elements mainly affect regional innovation efficiency via R&D element inputs and R&D element flow, and there are four ways hereunder.

(1) Promoting the agglomeration effects of R&D talents: R&D talents are the subjects of innovative activities, and talent flow promotes the aggregation effects of talents, so the high-quality talent inputs assist enterprises in carrying out innovative activities, thus enhancing regional innovation efficiency.

(2) Strengthening the spillover effects of technological innovation between neighboring regions: the R&D element flow enables the transfer of knowledge amid regions, and this process tends to achieve the rapid dissemination of innovative technologies and ideas, which improves the technological level and production capacity of the inflow region and evokes the regional innovation atmosphere, a great impetus to the enhancement of regional innovation efficiency (Kwon and Kwon 2019).

(3) Optimizing regional resource allocation: the R&D element flow, on the one hand, encourages the abundant idle resources of R&D elements in Beijing, Shanghai, Guangzhou, and Shenzhen flow to other regions, which optimizes the spatial distribution of R&D elements to a certain degree and enhances the overall innovation efficiency. On the other hand, R&D element flow among provincial-level administrative regions summons the enthusiasm of internal competition, placing appropriate pressure on regions to thrive (Cozza et al. 2018).

(4) Realizing the division of labor effects: in essence, the division of labor of innovative activities is the division of knowledge (Hu and Chang 2021), and R&D element flow motivates each region to concentrate on innovative production with comparative advantages, which facilitates the formation of a staggered development pattern among city clusters. Therefore, R&D element flow can enhance innovation efficiency through the division of labor effects.

Model establishment and variable design

This paper aims to conduct a qualitative and quantitative analysis of the influence of financial elements and R&D elements on regional innovation efficiency and then propose relevant policy advice to enhance regional innovation efficiency based on the empirical results. In order to evaluate the regional innovation efficiency of China’s provincial-level administrative regions, the paper adopts the super-efficiency data envelopment analysis, with efficiency as the response variable and financial elements and R&D elements as the core explanatory variables. It firstly uses the Tobit model to explore the comprehensive influence mechanism of financial elements and R&D elements on regional innovation efficiency; secondly, it takes account of the spatial connections between R&D activities and economic activities of each provincial-level administrative region and constructs three spatial econometric models to analyze the spatial effects of each factor. The empirical research design of this paper is shown in Fig. 1.

Super-efficiency DEA model

The traditional DEA model can only determine whether a decision-making unit (DMU) is efficient. That is, the measured efficiency score always lies in the interval (0–1). The model cannot determine efficiency scores when those of multiple DMUs are 1, which can be achieved by the

super-efficiency DEA model (Yin et al. 2020). Assuming that there are n mutually independent DMUs, each of them has m inputs and p outputs. x_{kr} is denoted the k th input of the r th DMU and y_{sr} is denoted the s th output of the r th DMU, then the super-efficiency DEA model of the i th DMU is presented below:

$$\begin{cases} \min[\theta - \varepsilon(\sum_{k=1}^m S_k^- + \sum_{s=1}^p S_s^+)] \\ \text{s.t. } \sum_{r=1}^n x_{kr}\lambda_r - S_k^- = \theta x_{ki}, k = 1, 2, \dots, m \\ \quad r \neq i \\ \sum_{r=1}^n y_{sr}\lambda_r + S_s^- = y_{si}, s = 1, 2, \dots, p \\ \quad r \neq i \\ \lambda_r \geq 0, S_k^- \geq 0, S_s^+ \geq 0, r = 1, 2 \dots, n \end{cases} \quad (1)$$

where θ is denoted the super-efficiency score of DMU, namely the regional innovation efficiency of each provincial-level administrative region; ε is the Archimedean infinitesimal, λ_r is the efficient weight of DMU, and S_s^+, S_k^- are slack variables.

Tobit model

This paper constructs a panel Tobit model to analyze the internal influence mechanism of financial elements and R&D elements on regional innovation efficiency, and to examine the regression of limited dependent variables. Because the efficiency score derived from the super-efficiency DEA model is non-negative, it is a limited dependent variable (Amirteimoori et al. 2020). Ordinary least squares (OLS) cannot be used directly, otherwise, it will bring bias and inconsistency to the parameter estimation, thus necessitating the Tobit model. The mathematical expression of the Tobit model is shown in (2):

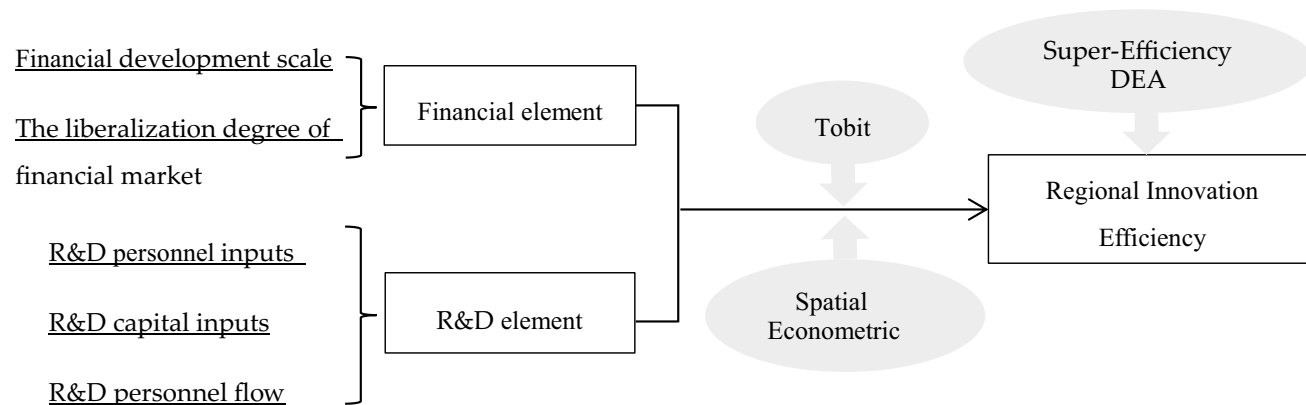


Fig. 1 Empirical research design

$$\begin{cases} y_i^* = \beta X_i + \mu_i & i = 1, 2, \dots, n \\ y_i = y_i^* & \text{if } y_i^* > 0 \\ y_i = 0 & \text{if } y_i^* \leq 0 \end{cases} \quad (2)$$

where y_i is denoted the regional innovation efficiency of each provincial-level administrative region, X_i is denoted the influencing factor of all aspects of regional innovation efficiency, μ_i is independently and identically distributed following the normal distribution $N(0, \delta^2)$ (Zha et al. 2020).

Spatial econometric models

Based on the influence of financial elements and R&D elements on regional innovation efficiency, the benchmark model (3) is constructed. Considering that the R&D element flow will enhance interregional knowledge spillover, the paper introduces the spatial weight matrix W and constructs three spatial panel models—spatial error model (SEM), spatial autoregressive model (SAR), and spatial Durbin Model (SDM)—to analyze the magnitude and mechanism of the impact of knowledge spillover effects on regional innovation efficiency.

Benchmark model:

$$\ln Inn_{it} = \alpha + \beta \ln M_{it} + \gamma \ln X_{\text{control}} + \varepsilon_{it} \quad (3)$$

SEM:

$$\begin{aligned} \ln Inn_{it} &= \alpha + \beta \ln M_{it} + \gamma \ln X_{\text{control}} + \mu_{it} \\ \mu_{it} &= \lambda W \mu_{it} + \varepsilon_{it} \end{aligned} \quad (4)$$

SAR:

$$\ln Inn_{it} = \alpha + \delta W \ln Inn_{it} + \beta \ln M_{it} + \gamma \ln X_{\text{control}} + \varepsilon_{it} \quad (5)$$

SDM:

$$\begin{aligned} \ln Inn_{it} &= \alpha + \delta W \ln Inn_{it} + \beta \ln M_{it} + \gamma \ln X_{\text{control}} + \theta W \ln M_{it} \\ &+ \mu W \ln X_{\text{control}} + \varepsilon_{it} \end{aligned} \quad (6)$$

where Inn_{it} is denoted the regional innovation efficiency of province i in year t , M_{it} is denoted the financial elements and R&D elements of province i in year t , X_{control} is denoted the control variables of the models, and ε_{it} is the stochastic disturbance. All variables in the models are in logarithmic form.

Variable descriptions and data sources

Response variable

The paper takes the regional innovation efficiency measured by the super-efficiency DEA model as the response variable, hence the need to determine the indicators of innovation inputs and innovation outputs in the DEA model.

1. Innovation input indicators

In general, capital and personnel are the two input factors often considered in innovative activities (Fernández-Macho et al. 2020). The paper chooses full-time equivalent (FTE) of R&D personnel to measure the R&D personnel element in the innovation system and R&D expenditure to measure the capital element. Drawing on Wang et al.'s study, the number of granted patents in the last 2 years is chosen as the third input indicator (Wang et al. 2016).

2. Innovation output indicators

Innovation output is characterized by “the number of granted patents,” “the number of papers in three major indexes (SCI, EI, and ISTP),” and “the sales revenue of new products.” The main reasons are as follows: the number of granted patents has been used extensively by previous studies due to its easy accessibility and consistency (Chandio et al. 2020; Sun et al. 2020). Nevertheless, although patents reveal information on technology and inventions, they are relatively one-sided in reflecting the development level of regional innovative activities. Since innovation output is also manifest in high-quality papers, the paper selects “the number of papers in three major indexes (SCI, EI, ISTP)” as another indicator of R&D output. Additionally, the sales

Table 1 The selection of regional innovation efficiency indicators

Goal	Indicator type	Indicator parameters	Indicator description
Regional innovation efficiency	Input indicators	R&D personnel full-time equivalent	Manpower input
		Sum of the number of patents granted in the previous 2 years	Knowledge input
		R&D expenditure	Capital input
	Output indicators	New product sales revenue	Real economy output
		Number of patents granted	Knowledge output
		Number of papers in the three major indexes	

revenue of new products is a good measure of the actual level of innovation output, thereby becoming the third output indicator. In summary, the input and output indicators of regional innovation efficiency are shown in Table 1.

The raw data of FTE of R&D personnel, R&D expenditure, the number of granted patents, and the sales revenue of new products of provincial-level administrative regions come from the China Statistical Yearbook on Science and Technology 2009–2019, and the number of papers in three major indexes (SCI, EI, and ISTP) is from the Wind Economic Database.

Explanatory variables and control variables

1. Financial elements

In order to more systematically reflect the financial gap between the different regions of China, the paper probes into two dimensions: one is financial development scale, which mirrors the general level of financial development; the other is the marketization level of the financial industry, showing the liberalization degree of the financial market (Alemzero et al. 2020b, 2020a; Sun et al. 2020). As per the existing measurement of the financial development scale, the paper uses “the deposits and loans of financial institutions/GDP” to measure the financial development scale, and “the marketization index of the financial industry” to measure the marketization level of the financial industry.

“The marketization index of financial industry” is obtained by compiling and fitting the first subindex of the factor market development in the NERI Index of Marketization of Chinas Provinces 2011 Report. In addition, the raw data of GDP of each provincial-level administrative region come from the China Statistical Yearbook 2008–2019, and the deposit and loan balance of financial institutions are from the Almanac of China’s Finance and Banking 2008–2019. The division of the three major regions of the country is based on the division method in China City Statistical Yearbook.

2. R&D elements

R&D elements are composed of two parts, namely R&D element inputs and R&D element flow. R&D personnel and R&D capital are variables and the indicators of R&D elements, whose interregional flow is also measured (Agyekum et al. 2021) and (Zhang et al. 2021).

(1) R&D element inputs.

The R&D element inputs consist of R&D personnel inputs and R&D capital inputs, which are respectively embodied by the annual number of R&D personnel P_{it} and the annual amount of R&D capital Ca_{it} in each provincial-level administrative region. The formulae of Ca_{it} and the R&D capital stock in the base period Ca_{i0} are as follows:

$$Ca_{it} = (1 - \epsilon) \times Ca_{i(t-1)} + E_{i(t-1)} \tag{7}$$

$$Ca_{i0} = E_{i0} / (f + \epsilon) \tag{8}$$

where $E_{i(t-1)}$ is the actual R&D expenditure of region i in period $t - 1$, E_{i0} is the actual R&D expenditure of region i in the base period, ϵ is the constant depreciation rate of 15%, and f is the geometric growth rate of the actual R&D expenditure during the examination period.

(2). R&D element flow.

R&D element flow includes R&D personnel flow and R&D capital flow. Drawing on the study of Bai and Jiang, the paper calculates the inter-regional flow of these two variables through the gravity model.

For R&D personnel flow, the interregional differences in average wages and average residential sales price are gravitational variables, as shown in Formula (9):

$$pfl_{ijt} = \ln P_{it} * \ln(\text{Wage}_{jt} - \text{Wage}_{it}) * \ln(\text{House}_{it} - \text{House}_{jt}) * R_{ij}^{-2} \tag{9}$$

where pfl_{ijt} is the R&D personnel flow from region i to region j in year t , P_{it} is the number of R&D personnel of region i in year t , Wage_{it} represents the average wage of urban on-duty employees of region i in year t , House_{it} represents the average residential sales price of region i in year t , and R_{ij} represents the distance between the capital cities of province i and province j . Thus, the total R&D personnel flow of region j in year t , pfl_{jt} , can be obtained, as shown below:

$$pfl_{jt} = \sum_{i=1}^n pfl_{ijt} \tag{10}$$

For R&D capital flow, the interregional differences of economic development and the marketization level of the financial industry are gravitational variables. The specific formula is (11):

$$cfl_{ijt} = \ln Ca_{it} * \ln(\text{Value}_{jt} - \text{Value}_{it}) * \ln(\text{Market}_{jt} - \text{Market}_{it}) * R_{ij}^{-2} \tag{11}$$

where cfl_{ijt} is the R&D capital flowing from region i to region j in year t , Ca_{it} is the R&D capital of region i in year t , Value_{it} represents the per capita GDP of region i in year t , and Market_{it} stands for the “marketization index of financial industry” of region i in year t . Thus, the total R&D capital flow of region j in year t , cfl_{jt} , can be obtained, as shown below:

$$cfl_{jt} = \sum_{i=1}^n cfl_{ijt} \tag{12}$$

The raw data of the number of R&D personnel and R&D capital of each provincial-level administrative region come from China Statistical Yearbook on Science and Technology 2009–2019, and the population with different education levels, the average wages, and the average

residential sales price are from China's National Bureau of Statistics and Wind Economic Database.

Control variables

Apart from financial elements and R&D elements, regional innovation efficiency is affected by many other factors. Based on extensive literature research, the paper selects foreign direct investment, industrial structure, and government intervention as the control variables of the models. The variables and measuring methods are shown in Table 2.

Results and discussion

Analysis of the measuring results of regional innovation efficiency

The measuring results are shown in Table 3, which indicates that: the regional innovation efficiency of 30 provincial-level administrative regions nationwide from 2008 to 2018 is on an upward trend; from a holistic perspective, most of the provincial-level administrative regions in eastern China have efficiency scores over 1, making the utmost of the input resources; all provincial-level administrative regions in central China, except Jilin and Hunan, have low regional innovation efficiency scores; western China, though a late starter, has enhanced efficiency by virtue of resource inputs and infrastructure construction, with Chongqing and Sichuan close to efficient, probably attributable to a large amount of capital attracted by the vigorous development of local tourism. The paper uses the CCR model in MaxDEA 8 to calculate the regional innovation efficiency of 30 provincial-level administrative regions across the country from 2008 to 2018.

Analysis of Tobit empirical results

Based on the theoretical exploration and model setting (Formula 2) above, the paper measures the influence of financial elements and R&D elements on regional innovation efficiency by Stata, and the final Tobit regression results of the whole country and each region are shown in Table 4. At the national level, the following factors exert a major influence on regional innovation efficiency—financial development scale, the marketization level of the financial industry, R&D personnel inputs, R&D capital inputs, R&D capital flow, and the amount of foreign direct investment; while R&D personnel flow, industrial structure, and government intervention have insignificant effects. Amid the financial elements, the financial development scale and the marketization level of the financial industry both significantly enhance regional innovation efficiency at the 0.01 significance level, implying that the development of the financial industry can provide a good financial environment for scientific research, which greatly bolsters regional research and development. Among the R&D elements, R&D personnel inputs, R&D capital inputs, and R&D capital flow all significantly contribute to the improvement of regional innovation efficiency at the 0.01 significance level. Specifically, R&D capital inputs have the largest coefficient, 2.0632, mirroring the pivotal role of R&D capital in the R&D process, R&D personnel inputs also play an important part in enhancing regional innovation efficiency, and R&D capital flow plays a significant though weaker role.

In contrast, the interregional flow of R&D personnel does not play a significant role in promoting regional innovation efficiency, perhaps due to the poor mobility of R&D positions in China, the lack of experimental equipment and infrastructure in the inflow regions, suggesting that the current interregional flow of R&D personnel in China does not bolster the overall innovation efficiency, interregional R&D

Table 2 The variables and measuring methods

Dimensions	Indicators	Metrics
Regional innovation level	Regional innovation efficiency: Inn_{it}	Measured by super-efficient DEA
Financial elements	Scale of financial development: F_{it}	Total deposits and loans of financial institutions/GDP
	The level of marketization of financial industry: M_{it}	Financial industry marketability index
R&D elements	R&D personnel input: Per_{it}	The number of R&D personnel input by provinces and cities in each year
	Amount of R&D capital input: Cap_{it}	Amount of R&D capital input by provinces and cities in each year
	R&D personnel flow: pfl_{it}	Calculated by the gravity model
	R&D capital flow: cfl_{it}	Calculated by the gravity model
Control variables	Foreign direct investment: Fdi_{it}	Amount of foreign direct investment
	Industrial structure: Ind_{it}	Value added of tertiary industry/value added of secondary industry
	Degree of government intervention: Gov_{it}	Local fiscal expenditure/local fiscal revenue of the year

Table 3 Innovation efficiency of China's provincial-level administrative regions

Province	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Mean	Rank
Beijing	1.82	2.35	2.22	2.22	1.93	1.01	2.18	2.29	2.74	2.44	1.54	2.07	1
Tianjin	0.75	0.70	0.74	1.07	0.82	0.98	0.85	0.75	0.85	0.84	0.68	0.82	11
Hebei	0.26	0.34	0.37	0.37	0.52	0.60	0.59	0.54	0.57	0.44	0.39	0.45	27
Shanxi	0.17	0.23	0.25	0.29	0.38	0.42	0.35	0.39	0.44	0.38	0.35	0.33	29
Inner Mongo	0.18	0.23	0.27	0.26	0.33	0.31	0.25	0.25	0.26	0.29	0.36	0.27	30
Liaoning	0.33	0.47	0.59	0.63	0.68	0.83	0.71	0.70	0.73	0.58	0.37	0.60	15
Jilin	0.87	0.66	1.17	1.14	1.22	0.47	0.97	0.93	1.03	1.00	1.52	1.00	6
Heilongjiang	0.23	0.32	0.30	0.54	0.71	0.71	0.50	0.56	0.52	0.56	0.72	0.52	22
Shanghai	1.84	1.93	1.84	1.98	1.14	1.67	1.90	1.81	1.82	1.85	1.60	1.76	2
Jiangsu	0.85	0.68	0.98	0.87	0.91	1.49	1.49	1.43	1.34	1.15	0.94	1.10	4
Zhejiang	0.82	0.90	0.87	1.01	1.15	1.20	1.07	1.09	1.08	1.10	1.17	1.04	5
Anhui	0.24	0.41	0.56	0.81	0.82	0.83	0.86	0.82	0.81	0.62	0.50	0.66	14
Fujian	0.32	0.43	0.47	0.53	0.55	0.57	0.52	0.55	0.54	0.45	0.46	0.49	24
Jiangxi	0.25	0.26	0.34	0.39	0.62	0.74	0.71	0.70	0.69	0.64	0.53	0.53	20
Shandong	0.31	0.49	0.56	0.57	0.70	0.75	0.70	0.61	0.64	0.55	0.35	0.57	17
Henan	0.24	0.34	0.34	0.41	0.43	0.75	0.71	0.69	0.70	0.48	0.44	0.50	23
Hubei	0.30	0.40	0.44	0.46	0.58	0.72	0.70	0.69	0.68	0.60	0.39	0.54	19
Hunan	0.37	3.09	0.54	0.57	0.78	1.07	0.97	0.92	0.96	0.69	0.37	0.94	7
Guangdong	0.93	1.03	0.96	1.20	1.58	1.38	1.29	1.28	1.31	0.93	0.81	1.15	3
Guangxi	0.50	0.44	0.50	0.52	0.67	0.96	0.74	0.93	1.02	1.08	0.71	0.73	12
Hainan	2.07	1.15	0.74	0.81	0.68	0.81	0.64	0.61	0.89	0.85	0.66	0.90	8
Chongqing	0.48	0.61	0.86	1.05	0.98	1.01	1.08	1.17	1.14	0.73	0.49	0.87	9
Sichuan	0.50	0.95	1.22	1.06	0.98	0.93	0.76	0.80	0.71	0.58	0.59	0.83	10
Guizhou	0.37	0.49	0.52	0.56	0.62	0.78	0.77	0.80	0.49	0.52	0.57	0.59	16
Yunnan	0.39	0.74	0.56	0.56	0.59	0.57	0.54	0.52	0.45	0.42	0.44	0.53	21
Shaanxi	0.26	0.42	0.46	0.47	0.45	0.50	0.44	0.50	0.67	0.44	0.44	0.46	26
Gansu	0.24	0.31	0.45	0.54	0.65	0.75	0.74	0.58	0.62	0.52	0.66	0.55	18
Qinghai	0.44	0.43	0.21	0.36	0.28	0.27	0.26	0.54	0.47	0.49	0.91	0.42	28
Ningxia	0.26	0.45	0.40	0.32	0.50	0.79	0.47	0.62	0.60	0.40	0.39	0.47	25
Xinjiang	0.42	0.62	0.55	0.50	0.64	0.78	0.88	0.84	0.78	0.81	0.66	0.68	13

personnel flow are mainly comprised of low- and mid-level talents, whereas high-level talents mostly agglomerate in the more economically developed regions such as Beijing, Shanghai, Guangzhou, and Shenzhen, hence the “crowding externalities” in some regions. In eastern China, the marketization level of the financial industry and R&D capital inputs significantly enhance regional innovation efficiency at the 0.01 significance level, while R&D personnel inputs significantly inhibit regional innovation efficiency at the 0.01 significance level.

These denote that eastern China has a higher level of economic development and more sufficient R&D capital, so the social deposit and loan balance has less influence on regional innovation efficiency. Moreover, eastern China has larger R&D personnel inputs and R&D capital inputs. With relatively high marketization level, innovation resources agglomerate spontaneously, but R&D personnel inputs are not coordinated with R&D capital inputs, and thereupon during the R&D process, the quantity of R&D equipment

and infrastructure cannot meet the demand of R&D personnel, hence the considerable redundancy of personnel and the waste of resources. Worse still, there are vicious competitions among the redundant R&D personnel, which inhibits the enhancement of innovation efficiency to a certain extent. In central China, the following factors can significantly enhance regional innovation efficiency—financial development scale, R&D personnel inputs, R&D capital inputs, R&D personnel flow, R&D capital flow, and the amount of foreign direct investment. Nevertheless, the marketization levels of the financial industry, industrial structure, and government intervention have insignificant effects on regional innovation efficiency.

Compared with eastern China, central China has a lower level of economic development and relatively insufficient R&D personnel inputs and R&D capital inputs. Therefore, R&D personnel inputs, R&D capital input, and their interregional flow can significantly boost regional innovation efficiency. In western China, the following factors can

Table 4 The Tobit regression of factors of regional innovation efficiency

Variables	National	Eastern	Central	Western
<i>lnFit</i>	0.3135*** (0.0552)	0.1250 (0.1063)	0.0546*** (0.1257)	0.0962 (0.0909)
<i>lnMit</i>	0.6533*** (0.0624)	1.0082*** (0.1334)	0.0452 (0.1128)	0.7786*** (0.1149)
<i>lnPerit</i>	0.3142*** (0.0636)	-0.5553*** (0.1844)	0.3748** (0.1465)	0.6742*** (0.0988)
<i>lnCapit</i>	2.0632*** (0.1681)	1.8066*** (0.3147)	3.4275*** (0.3230)	3.0026*** (0.2420)
<i>lnpfrit</i>	0.0057 (0.0103)	-0.0187 (0.0122)	0.0314** (0.0136)	0.0223 (0.0270)
<i>lncflit</i>	0.0634*** (0.0049)	0.0032 (0.0139)	0.0487*** (0.0067)	0.0491*** (0.0083)
<i>lnFdiit</i>	0.0759*** (0.0146)	0.0112 (0.0391)	0.2540*** (0.0289)	0.1004*** (0.0224)
<i>lnIndit</i>	0.0368 (0.0142)	-0.0181 (0.0755)	0.1100 (0.0792)	0.1072 (0.0862)
<i>lnGovit</i>	-0.0137 (0.0182)	-0.0044 (0.0292)	-0.0069 (0.0488)	-0.0373 (0.0369)
Constant	2.2464*** (0.4578)	5.5210*** (0.8392)	-2.0447** (0.9882)	-1.2758* (0.6980)
Log likelihood	80.90	44.91	61.70	51.70
<i>p</i> -values	0.0000	0.0000	0.0000	0.0000
Sample size	330	121	88	121

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; the values in parentheses under the coefficients are standard errors, the same as below.

significantly enhance regional innovation efficiency—the marketization level of the financial industry, R&D personnel inputs, R&D capital inputs, R&D capital flow, and the amount of foreign direct investment. Nonetheless, the financial development scale, R&D personnel flow, industrial structure, and government intervention have insignificant effects on regional innovation efficiency. With an underdeveloped economy and scarce R&D resources, increasing marketization will prompt resources to spontaneously flow to the regions with higher production efficiency, and thus the marketization level of the financial industry can significantly enhance regional innovation efficiency in Western China. The R&D personnel flow there generally comprises low- and mid-level talents, hence its insignificant effects of enhancing regional innovation efficiency.

Analysis of spatial econometric empirical results

On the basis of the empirical model setting, the paper utilizes the maximum likelihood estimation (MLE) for spatial panel model estimation. First, the paper selects either the fixed effect model or its random effect counterpart based

on the results of Hausman's test, and as per the results of MLE, chooses spatial econometric models with spatial fixed effects, temporal fixed effects, or spatiotemporal fixed effects. The paper conducts a comparative analysis of the estimation results of the benchmark panel model, SAR, SEM, and SDM models under the spatial weight matrix based on geographical distance, as shown in Table 5. Table 5 indicates that the estimation results of spatial econometric models are basically consistent with the models with traditional fixed effects except for some errors in coefficients. And the spatial efficiency values of SEM, SAR, and SDM models are all significant, indicating the existence of the spatial effects on regional innovation efficiency.

In terms of curve fitting effects, the SDM model obviously has the most regression coefficients and more results compared with the SAR and SEM models. To further study the curve-fitting effects of the SDM model, the paper conducts a likelihood ratio (LR) test, and the results show that it is significant at the 0.01 significance level, suggesting that the SDM model has the best curve-fitting effects. In light of this, the paper selects the estimation results of the spatial SDM model for analysis.

As to core explanatory variables, except for R&D personnel flow, both financial elements and R&D elements significantly enhance regional innovation efficiency. In particular, the development of the regional financial environment, R&D personnel inputs, and R&D capital inputs have a significant positive impact on the enhancement of regional innovation efficiency, and the interregional spontaneous R&D capital flow can fuel the industries with high marginal efficiency and foster regional sci-tech industrialization, thus enhancing regional innovation efficiency. In recent years, China has attached greater importance to the integration of science and technology and finance. It guides R&D capital flow through some R&D fund programs and has built banks specialized in providing financial support for research projects in Beijing, Shanghai, etc., thereby empowering regional innovation. R&D personnel flow has insignificant effects on regional innovation efficiency.

On the one hand, the majority of the high-level talents agglomerate in economically developed regions such as Beijing, Shanghai, Guangzhou, and Shenzhen, which is a trigger for vicious competition among R&D personnel and redundancy of human resources; on the other hand, most of the talents flowing to the central and western China are at low- and mid-levels, who can hardly boost the innovation efficiency of the whole region. Concerning the control variables of the models, the amount of foreign direct investment and industrial structure can significantly enhance regional innovation efficiency. More precisely, foreign direct investment can promote local economic development, thus creating a better financial environment for R&D; the development level of tertiary

Table 5 Spatial panel regression results of the spatial weight matrix

Variables	Baseline panel model	SEM model	SAR model	SDM model
<i>lnFit</i>	0.4188*** (0.0642)	0.6072** (0.1953)	0.3560** (0.1618)	0.3530** (0.1767)
<i>lnMit</i>	1.0589*** (0.0839)	0.0855 (0.0682)	0.2701*** (0.0657)	0.2089*** (0.0634)
<i>lnPerit</i>	0.1921*** (0.0335)	0.0406** (0.0164)	0.0240 (0.0162)	0.0430*** (0.0152)
<i>lnCapit</i>	1.7108*** (0.2271)	0.1609*** (0.0308)	0.2403*** (0.0274)	0.1984*** (0.0277)
<i>lnpflit</i>	0.0042 (0.0069)	0.0010 (0.0042)	−0.0009 (0.0044)	0.0040 (0.0039)
<i>lncflit</i>	0.0317*** (0.0056)	0.0263*** (0.0038)	0.0290*** (0.0040)	0.0215*** (0.0038)
<i>lnFdiit</i>	0.0629*** (0.0147)	0.0073 (0.0091)	0.0131 (0.0096)	0.0159* (0.0086)
<i>lnIndit</i>	0.2531*** (0.0511)	0.2333*** (0.0361)	0.1265*** (0.0304)	0.2417*** (0.0343)
<i>lnGovit</i>	−0.1144 (0.0928)	−0.2013** (0.0637)	−0.0957* (0.0578)	−0.2071*** (0.0584)
rho	/	/	−0.4918*** (0.0510)	−0.4267* (0.2457)
Constant	2.8764*** (0.5656)	8.7819*** (0.5957)	3.5036*** (0.5774)	/
lambda	/	0.9436*** (0.0125)	/	/
sigma2_e	/	0.0039*** (0.0003)	0.0040*** (0.0003)	0.0030*** (0.0002)
<i>Wx lnFit</i>	/	/	/	0.3715** (0.1847)
<i>Wx lnMit</i>	/	/	/	0.1820*** (0.0603)
<i>Wx lnPerit</i>	/	/	/	0.0433*** (0.0148)
<i>Wx lnCapit</i>	/	/	/	0.1975*** (0.0272)
<i>Wx lnpflit</i>	/	/	/	0.0034 (0.0038)
<i>Wx lncflit</i>	/	/	/	0.0217*** (0.0036)
Log-likelihood	/	347.2453	494.1147	488.8256
Hausman	85.10***	−283.08	0.48	81.63***
Sample size	330	330	330	330

industry is often related to the development level of the regional economy—the higher the development level of the regional economy, the greater the development speed and scale of the tertiary industry—so the booming tertiary industry can bring vitality to research and development. Government intervention significantly inhibits regional innovation efficiency because the government has to take a systemic view of regional sci-tech innovation and

economic development. In 2016, the Chinese government put forward the slogan “lucid waters and green mountains are invaluable assets,” striving to coordinate sci-tech innovation and economic development with environmental protection and pursuing high-quality regional economic development, which reflects China’s image as a responsible major power. From the spatial perspective, the following variables have significant positive coefficients, namely

financial development scale, the marketization level of the financial industry, R&D personnel inputs, R&D capital inputs, and R&D capital flow, indicating that they have positive spatial spillover effects.

① The financial development scale and the marketization level of the financial industry of the neighboring regions can significantly enhance regional innovation efficiency, possibly attributable to the regional innovation momentum built by the economic development of neighboring regions; ② R&D personnel inputs and R&D capital inputs of neighboring regions can significantly foster regional innovation efficiency. Perhaps because on the one hand, once a region starts focusing on research and development, the surrounding areas will follow suit. On the other hand, knowledge has spatial spillover effects and will be disseminated to neighboring regions through personnel exchanges; ③ the R&D capital flow of neighboring regions can significantly increase regional innovation efficiency, possibly because the proximity to neighboring regions leads to the spillover of the benefits of capital operation.

Conclusion and policy implication

The efficiency of the innovation system is vital for the sustainable development of the regional economy. The paper measures the efficiency of the innovation system via the super-efficiency DEA model and analyses the influencing factors of regional innovation efficiency from the perspectives of the input and flow of financial elements and R&D elements. This paper selects provincial panel data in China from 2008 to 2018 to empirically analyze the influence of financial elements and R&D elements on regional innovation efficiency. Most of the existing literature on regional innovation efficiency is from the R&D perspective, only considers input and output variables, and therein lies the innovativeness of this paper. From both financial and R&D perspectives, the paper focuses on how financial elements and R&D elements jointly affect regional innovation efficiency, takes into account the spatial correlation of provinces, and chooses three spatial panel models to empirically investigate the influence of financial elements and R&D elements on regional innovation efficiency, delving deeper into the magnitude and attribute of the influence.

The main conclusions are as follows. First, from an overall perspective, the following variables have a significant influence on regional innovation efficiency: financial development scale, the marketization level of the financial industry, R&D personnel inputs, R&D capital inputs, and R&D capital flow; while R&D personnel flow has insignificant effects, signifying a lagging information exchange of inter-regional R&D employment, insufficient

R&D equipment in inflow regions, and the crowding-out effects of R&D personnel flow. Second, by region, R&D personnel flow in central China can significantly enhance regional innovation efficiency, while it fails in eastern and western China, mainly because eastern China has a high level of economic development and abundant resources, so the inflow of abundant resources engenders redundancy and waste, while western China has a low level of economic development, and limited R&D personnel flow generally comprising low- and mid-level talents. Third, spatially, the following variables have significant positive spillover effects: financial development scale, the marketization level of the financial industry, R&D personnel inputs, R&D capital inputs, and R&D capital flow. Specifically, the marketization index of the financial industry has a significant indirect spillover effect, and the R&D capital flow has a significant direct spillover effect, suggesting that the marketization of the financial industry is beneficial to regional integration, and R&D capital flow can significantly improve the innovation performance of the region.

Based on the above findings, the paper proposes the following suggestions. First, the insignificant effects of R&D personnel flow on regional innovation efficiency imply the blind profit-seeking nature of factor flow, and the prevalence of information asymmetry between R&D resource supply and demand, and therein lies the importance of technology service intermediary. Thereupon, fostering multifarious and full life-cycle technology service intermediaries is a key vehicle for addressing the “disconnection” phenomenon of regional innovation efficiency in China. Second, the unreasonable allocation of financial elements and R&D elements results in an unhealthy competition of R&D resources during the innovative process in central China. Thereby, to realize regional coordinated development, it is necessary to build a tighter regional collaborative innovation network. A tight regional collaborative innovation network covers the whole process from R&D to the final product launch, which can more effectively integrate various innovation factors of manifold subjects and jointly establish an efficient cooperative innovation system, so as to balance production and research, complement each other's advantages and give full play to the positive spillover effects of innovation efficiency spatially and on value chains. Third, the marketization of the financial industry makes for regional integration, and the government should guide and promote interregional capital flow. For one thing, it is necessary to geographically expand cooperation networks on the basis of reinforced economic ties amid developed cities; for another, “let some parts develop first in order to stimulate the overall development” and then enhance regional innovation efficiency in all facets, via comprehensively deepening the market-oriented reform of the regional financial industry, improving the infrastructure for

the exchange of R&D factors, and amplifying the geographic spillover of production and innovation efficiency.

Acknowledgements The authors thank the reviewers for their careful reading and for providing some pertinent suggestions.

Author contribution The authors worked together in the process of planning and designing the paper. Meijuan Tang designed the research content, analyzed the data, and wrote the first draft of the paper. Xiaoxia Wang revised the final version of the paper. Wenyao Niu was involved in the data analysis. Jingmin Fu revised and directed the writing of the paper. Mengran Zhu participated in the writing of the English paper. All authors have read and agreed to the published version of the manuscript.

Funding This research was funded by the program of Shanghai Planning Office of Philosophy and Social Sciences of China (No. 2020BGL023).

Availability of data and materials The data that support the findings of this study are openly available on request.

Declarations

Ethics approval and consent to participate The authors declare that they have no known competing financial interests or personal relationships that seem to affect the work reported in this article. We declare that we have no human participants, human data, or human tissues.

Consent for publication We do not have any individual person's data in any form.

Competing interests The authors declare no competing interests.

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