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Effects of digital economy and city size on green total factor productivity

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Utilizing the digital economy's contribution to green total factor productivity is a key strategy for accelerating China's green growth, although more research is still needed to understand the mechanism of this influence. This study uses panel data from 282 Chinese prefecture-level cities from 2011 to 2019 to empirically assess the impact of the digital economy and city size on GTFP. First, GTFP overall exhibits an upward trend with excellent spatial correlation and minimal regional variation. Second, the findings demonstrate that, while surrounding locations' GTFP is not affected by the digital economy, local productivity can be improved. Third, the heterogeneity study demonstrates that the digital economy contributes more to local GTFP in the eastern region compared to the central and western regions, with the central region making the largest contribution to GTFP in the surrounding regions; the first, second, and third tier cities have more contributions from the digital economy to local and neighboring GTFP than the fourth and fifth tier cities. Fourth, city size positively modifies the relationship between the green total factor productivity and the digital economy. The western region is where the positive moderating effect of city size expansion is greatest. Moreover, compared to first-, second-, and third-tier cities, the fourth- and fifth-tier cities have a stronger beneficial moderating effect of city size increase. In light of this, we should focus on the growth of the digital economy, optimize city scale, and fully exploit the scale effect produced by the concentration of the digital industries and the spillover effect produced by the spread of the digital technology.

KEYWORDS

digital economy, city size, GTFP, spatial measurement, spatial spillover effects

1 Introduction

The level of green economic development is directly reflected in GTFP, and increasing GTFP is in line with the practical requirements of China's new development philosophy. China has made significant progress in its economic and social development since the reform and opening up, but it also faces a number of challenges, including environmental pollution, an aging population, an energy crisis, and high carbon emissions. Chinese digital economy has advanced to a new stage of deeper application, standardized development, and sharing for the benefit of everyone thanks to the deep integration of the digital economy and many fields in recent years. Accelerating the development of the digital economy is a significant way to address the challenging issues in the current development pattern, support Chinese high-quality development, and increase total factor productivity in this context as it is a key driving force for development in the new era. Therefore, one of the crucial academic themes of the present is investigating whether the digital economy can encourage the improvement of GTFP and by what mechanism it will boost GTFP.

Cities serve as the foundation of the national economy and are crucial to the advancement of sustainable and high-quality development. A significant factor in the process of the digital economy producing social repercussions is the breadth and depth of urban scale transformation. The future green and high-quality growth of Chinese cities will focus on developing the new green engine of the digital economy and urban scale transformation as well as exploring the new path of these factors that enable green development. In light of this, this paper explains how the digital economy and city scale affect GTFP and empirically analyzes the connection between the digital economy, city scale, and GTFP using panel data from 282 prefecture-level cities from 2011 to 2019. The goal is to provide a theoretical foundation for relevant departments to develop targeted policy measures in the context of modernization. On the basis of this, the paper's minor contributions are as follows. In order to analyze the respective roles and synergistic effects of the digital economy, city size, and GTFP in fostering GTFP growth, this article first integrates these three variables into a single analytical framework. Second, using spatial econometric models, 282 prefecture-level Chinese cities are utilized as empirical samples to examine the effects of the digital economy and city size on the GTFP.

2 Literature review

GTFP research is currently divided into two main areas. One of the elements is the measurement approach, in which researchers mostly use the SBM model-GML index to measure GTFP from an input-output perspective (Feng et al., 2018). The other aspect entails the research on the identification and role of the influencing factors that affect GTFP. The identified influencing factors can be categorized as economic development, ecological environment, and government policies. The economic development mainly includes market mismatch, technological innovation, OFDI, etc. According to empirical findings by Zhang et al. (2019), market mismatch hampered the expansion of GTFP in 33 countries along the Belt and Road from 1995 to 2012. Using panel data for the OECCD countries from 1996 to 2017, Wang H. et al. (2021) demonstrate that technical innovation has a strong positive impact on GTFP. Data from 21 European countries that took part in the Belt and Road Initiative from 2009 to 2018 are used by Xie and Zhang (2021), and the empirical findings indicate that China's OFDI helps these nations' GTFP increase. The ecological environment aspects are mainly related to environmental pollution and its management. The findings of Li et al. (2022) demonstrated that severe air pollution does not raise GTFP in agriculture. According to Tong et al. (2022), China's GTFP is greatly increased by stringent environmental rules. Further, government policies become an important basis for enhancing GTFP, such as the construction of national e-commerce demonstration cities, fiscal decentralization, carbon emission trading pilot, and pilot free trade zones, all of which have significant impacts on GTFP (Song et al., 2020; Cao et al., 2021; Wang A. et al., 2022; Yu et al., 2022).

Academics have focused their attention on the difficult economic activity of how to harness the force and rules of the digital economy to improve GTFP. Most research on the subject of the digital economy and GTFP agree that it has a good impact on the latter, although there are some variations between their conclusions, which primarily come from two points of view. One is that the development of GTFP can be directly influenced by the digital economy. Based on panel data from 108 cities in the Yangtze River Economic Zone from 2011 to 2019, the study by Hu and Guo (2022) demonstrates that the digital economy significantly increases GTFP. Second, the relationship between the digital economy and GTFP is U-shaped or inverted U-shaped. Meng and Zhao (2022) demonstrate that there is a specific threshold value for the impact of the digital economy on GTFP using panel data from 17 manufacturing industries from 2000 to 2014. The positive impact of the digital economy on GTFP is negligible before to exceeding the threshold, but it can dramatically increase GTFP after exceeding the barrier. According to Li et al. (2020), the encouragement of green technology advancement by the digital economy is the key source of the digital economy's impact on GTFP, which has a substantial U-shaped characteristic.

Cities serve as the fundamental building block of the national economy and are crucial to the high-quality growth of the digital economy. In the process of creating social consequences in the digital economy, the change in city size is crucial. City size and digital economy are interconnected and influence each other. On the one hand, the growth of the digital economy is based on city size. According to Pradhan et al. (2021), urbanization is a crucial foundation for the advancement of information and communication technology, which supports the growth of the digital economy. On the other side, the transformation of city size will be accelerated by the digital economy. The findings of Zhu and Chen (2022) demonstrate that the digital economy has a greater influence on urban space than urbanization. Academics have not yet reached consensus on the research findings about the connection between city size and GTFP, and there are three basic points of view. One is the promotion theory, which holds that increasing city size contributes to an increase in GTFP. The growth of city size is advantageous to the enhancement of GTFP, according to empirical findings from Peng et al. (2020) measurement of the level of GTFP in the nations that make up the Silk Road economic belt. The second is the suppression theory, which holds that increasing city size is bad for increasing GTFP. According to Xie et al. (2022), the mismatch of land resources brought on by rapid urban development prevents the growth of GTFP. There is a threshold for the contribution of city size expansion to GTFP, according to the third theory, which is nonlinear. The research by Tan et al. (2022) demonstrates that when the economic agglomeration is relatively modest, the impact of urban transportation infrastructure on GTFP change is not considerable, but it becomes clear as the agglomeration rises.

Although the literature now available is adequate, there are a number of issues. First, the present literature is mostly concerned with the mechanism and impact of the digital economy on GTFP at the local level; however, not enough studies have been done to pinpoint the precise mechanisms through which the digital economy influences GTFP at the local level of cities. Second, the existing studies on the external effects of the digital economy and city size assume that the relationship between the two factors and GTFP is linear. Yet, the spatial implications of the digital economy and city size on GTFP need for greater consideration in light of the spatial externality hypothesis. In order to provide workable policy recommendations, this study first integrates the digital economy, city size, and GTFP into a single analytical system for theoretical analysis. Then, it uses a spatial econometric model to empirically analyze the effect of the digital economy on GTFP and the moderating role of city size in this process.

3 Theoretical mechanisms and research hypotheses

3.1 Digital economy and GTFP

The digital economy is a critical component that offers a new strategic fulcrum for China's economic transition since it is redefining global factor resources, the global economic structure, and the global competitive environment. Thus, China's economy can change from being a factor-driven economy to an efficiency-driven and innovation-driven one, and it can exhibit a modern economic development path; consequently, the changes that affect power, efficiency, and quality provide a new growth path for GTFP.

First, the digital economy creates power shifts that impact GTFP through influencing developments in technology, models, and institutions (Chen, 2022b). The digital economy has fundamentally changed the way traditional sectors produce goods by leveraging cutting-edge technology in fields like big data, artificial intelligence, cloud computing, and high-end equipment manufacture. Innovation in digital technology increases the organic momentum of green economic development in addition to providing the technical foundation for data to become a revolutionary production technique and a key production element. Secondly, the digital economy via "Internet +" for the innovation of traditional industrial development mode, and for the promotion of digital recording, storage, interaction, and sharing of fundamental high-quality data resources across various industries, which indirectly improves productivity, promotes the quality and efficiency of traditional industries, and creates momentum for the intelligent and green development of industries. Finally, for the digital economy to develop, the government should facilitate the development of an environmental supervision system that is based on digital technology, which will effectively promote institutional innovation, accelerate the construction of a robust network that will transform China's economy into a digital economy, provide environmental support and policy support that is compatible with the form of the digital economy that the country will develop, encourage the development of a novel green and low-carbon development pattern and enlist the aid of institutional innovation funds that prioritize the improvement of GTFP.

Second, the digital economy encourages efficiency change and increases GTFP through improving production efficiency and factor allocation efficiency (Zhang et al., 2022). On the one hand, the economies of scale, scope, and long-tail effect of the digital economy can help businesses get around several institutional and technological constraints that prevent the improvement of production efficiency. Additionally, businesses can use digital technology to streamline operations, improve operational effectiveness, reduce resource waste, and cut expenses associated with transactions. As a result, business vitality is boosted, competitiveness is increased, and enterprise green transformation and development are accomplished. On the other hand, the digital economy has opened up the channels for the production factors' circulation; continually led the supply, value, and industrial chains, which made it possible to allocate resources efficiently using the internet; facilitated coordination and innovation among various industrial sectors; and yielded novel industrial forms such as the platform economy, sharing economy, "virtual" industrial parks, and industrial clusters; thus, the digital economy can help to further advance GTFP.

Third, the digital economy fosters quality change by raising the quality of factors, goods, and services, leading to GTFP growth (Wang M. et al., 2021). The digital economy produces significant changes in production relations and lifestyles through data factorization and factor datafication; reshapes the factor input structure that characterizes the original economic system, which in turn enhances factor quality, facilitates the development of a novel model for developing the digital economy, which exhibits a multi-level structure, wide coverage, differentiation, and the rational division of labor among large, medium, and small enterprises; and promotes the development of China's green economy. Furthermore, the quality and mode of supply of goods and services have undergone significant changes as a result of the digital economy, which enables enterprises to transform their products and services using digitalization and to promote the mode of supply from single to multiple, the motive from management to service, the content from rough to fine, the mode from decentralized to collaborative, and the performance evaluation from closed to open; thus, enterprises provide consumers with more digital products and with personalized and customized services. Therefore, the digital economy responds to the growing desire for a better living and raises total green factor productivity.

Based on the aforementioned study, we put up the following hypothesis (Hypothesis 1): the digital economy helps to positively boost GTFP.

3.2 City size and GTFP

The major ways that city size influences GTFP are through the agglomeration economic effect caused by the concentration of production factors, the technology spillover effect caused by technological advancement, and the structure-driven effect caused by the modernization of industrial structures.

First, when a city's population changes, agglomeration-based economic effects frequently follow, having a significant impact on GTFP (Cheng et al., 2022). In the early stages of urbanization, factors of production such as industries, talents, capital, and innovation activities are heavily invested in urban construction, which generates agglomeration effects, and the city scale becomes rapidly widened, which offers strong support for the modernization of the urban industrial structure, technological advancement, and economic growth; hence, city size aids in the ongoing improvement of urban GTFP. However, as the scale of cities continues to expand, the congestion effect that modifies the urban scale inhibits the growth of GTFP, the population and industries over-concentrate in cities, and the disorderly expansion of the urban space occurs.

Second, variations in city size offer an essential conduit for the information diffusion that impacts technological innovation, which affects the expansion of GTFP (Wang KL. et al., 2022). In terms of cities and towns, as economic and population scales increase, people, businesses, and industries are more likely to share resources, information, and markets. The diversified and specialized clustering of industries also changes how factor inputs are shared, which supports the growth of the green economy. The expansion of cities on a suitable scale can improve the quality of the labor force, the quality of the innovation factors, and provide enough capital to support technical innovation and knowledge spillover, thereby promoting GTFP. The information spillover effect that influences technological innovation will be lessened by the chaotic growth of city size; as a result, the improvement of GTFP will not be assisted.

Third, changes in city size result in sophisticated industrial structures, and the rationalization and advancement of these structures have an impact on GTFP (Cheng and Jin, 2022). During scale expansion, cities can guide and adjust the general layout of industries based on their own factor endowments and competitive advantages. The concentration of production factors encourages the emergence and growth of numerous industrial parks, which encourages the transformation of the industrial structure from agriculture to industry and services, low-level to high-level, and quantitative to qualitative. It also encourages the development of the urban industrial structure, which encourages GTFP. The spatial planning and element resetting that characterize the process of urban scale change can assist industry complementarity and mutual support, modify and optimize the industrial distribution pattern, and promote the ongoing extension and expansion of the industrial chain. Additionally, it can support the efficient use of resources, ease the change of the city's old-new dynamics, allocate resources and spatial components in the best way possible, and assist the orderly transformation of the economic development mode. Consequently, element resetting and spatial planning support the rationalization of the change in urban scale. Hence, improving GTFP is facilitated by rationalizing the industrial structure.

Based on the aforementioned study, we put up the following hypothesis (Hypothesis 2): the improvement of GTFP is facilitated by a proper city scale.

3.3 Digital economy, city size, and GTFP

In general, as development levels rise, which have an impact on the digital economy, cities will get larger, which in turn will fuel the expansion of the digital economy; thus, the digital economy and city size are correlated. Four theories are primarily used to explain how digitalization and city size interact to affect GTFP.

According to the first theory, the digital infrastructure's characteristic leapfrogging promotes GTFP growth (Pan et al., 2022). Cities support the simultaneous development of urbanization and informatization, which widens and deepens the application scenarios of digital infrastructure, by creating digital infrastructure, scaling up communication network construction, and boosting the capacity of communication services; hence, the master plan for the optimization of city scale is affected. As a result, the foundation for the growth of the digital economy, which guarantees that people's lives are improved, is digital infrastructure. As a result, numerous fields will see an acceleration of the digital revolution, which will continuously improve digital governance, support the upgrading and transformation of the regional economy, and provide a strategic, ground-breaking, and essential foundation for increasing GTFP.

According to the second theory, GTFP is promoted by the accelerated improvement of digital industries' potential for innovation (Qiu et al., 2021). Regarding the digital economy, the expansion of city scale creates opportunities for innovation, and the improvement of digital industry innovation capacity accelerates the application of digital technology to traditional industries. This motivates real businesses to increase their investment in information technology, get past technical hurdles, improve their information analysis skills, and address industrial bottlenecks. The gradual maturity of businesses results in increased security and stability when it comes to the use of digital technology in the industrial and supply chains, whereas the city's innovation-driven development strategy, which supports the growth of the digital economy and its radiation-driven capability, adds additional vitality and momentum that can boost GTFP.

Third, increasing GTFP is facilitated by the acceleration of digital industrialization and industrial digitization (Zhang and Zhou, 2022). Industrial digitization is the use of digital technology by established industries to innovate and transform, whereas digital industrialization refers to the creation of new industries and economic sectors based on digital technology. The rapid growth of digital industrialization and industrial digitization encourages the fusion and expansion of traditional industries and digital technologies as well as the exact balancing of supply and demand, blurs the boundary between traditional industrial sectors, transforms the mode of coupling digital information and production factors, facilitates the release of the agglomeration economic effect and the urban growth potential that is occasioned by urban scale expansion, promotes the rational layout of traditional industries and digital industries in urban space, and assists cities in promoting GTFP through a thorough, high-quality development process.

According to the fourth theory, the digitalization of public services encourages urban growth. The digital transformation of public services promotes the enhancement of GTFP (Thanh, 2022). Public services are an essential building block for the development of green cities; however, the separation of administrative responsibilities across cities, competing interests, and high transaction costs impede their integration, which in turn has a detrimental effect on the improvement of GTFP. By taking the initiative to direct the diffusion and application of digital technology in public services, the government can support the digital transformation of urban public services, eliminate "fragmented governance" and administrative hurdles between cities, support the integration of public services between central and local governments, improve its capacity to transform the scale of cities, and reshape the administration and quality of public services, thus contributing to promote GTFP.

Based on the aforementioned study, we put up the following hypothesis (Hypothesis 3): the connection between digitalization and city size is beneficial to improving GTFP.

4 Model setting and indicator construction

4.1 Measurement model setting

By constructing a spatial econometric model that takes into account the digital economy, city size, and GTFP, this study experimentally analyzes the relationship between the three. In order to decrease the potential endogenous influence of the dynamic change process of the variables on the estimation results, the dynamic spatial Durbin model is used in this research to conduct the empirical analysis. The specific model parameters are as follows:

$$gtfp_{i,t} = \alpha + \rho W \times gtfp_{i,t} + \beta_1 gtfp_{i,t-1} + \beta_2 digital_{i,t} + \beta_3 X_{i,t} + \theta_1 W \times \mathrm{digital}_{i,t} + \theta_2 W \times X_{i,t} + \mu_i + \eta_t + \varepsilon_{\mathrm{i,t}} \quad (1)$$

Considering Eq. 1, the explanatory variable $gtfp_{i,t}$ denotes GTFP; the core explanatory variables $digital_{i,t}$ denote the digital economy; α、β、θ denotes the coefficient that should be estimated; $X_{i,t}$ denotes the control variables; and μ_i、η_t and ε_{it} represent individual fixed effects, time fixed effects, and error terms, respectively.

This research introduces the interaction term of the digital economy ($digital_{i,t}$) and city size ($scale_{i,t}$) based on Eq. 1 to investigate the interaction effect of the digital economy and city size on green total factor productivity.

$$\begin{aligned} gtfp_{i,t} = {} & \alpha + \rho W \times gtfp_{i,t} + \beta_1 gtfp_{i,t-1} + \beta_2 digital_{i,t} + \beta_3 scale_{i,t} \\ & + \beta_4 X_{i,t} + \beta_5 digital_{i,t} \times scale_{i,t} + \theta_1 W \times \mathrm{digital}_{i,t} \\ & + \theta_2 W \times scale_{i,t} + \theta_3 W \times X_{i,t} + \theta_3 W \times digital_{i,t} \times scale_{i,t} \\ & + \mu_i + \eta_t + \varepsilon_{\mathrm{i,t}} \end{aligned} \quad (2)$$

4.2 Variable selection and measurement

4.2.1 Explained variable

We construct an SBM-Malmquist productivity index model ($gtfp_{i,t}$) to calculate GTFP, using variables for the labor force, the volume of capital inputs, and energy consumption (Fukuyama and Weber, 2010). First, the labor force is calculated by counting the number of employed people in each prefecture-level city during a given calendar year; second, capital input is calculated using the perpetual inventory method; and third, energy consumption is calculated by adding up all of the energy used by all prefecture-level cities during that same calendar year. The actual GDP of each prefecture-level city in a calendar year represents the expected output, and the emissions of industrial wastewater, industrial sulfur dioxide, and industrial smoke and dust in each prefecture-level city in calendar year represent the non-expected output. We determine the ratio of each city's total industrial output value to the total industrial output value of the province in which the city is located in order to account for missing data on energy or non-expected output indicators. After that, we multiply the total energy or non-expected output indicators of each provincial level by the number of cities that fall under its purview in order to obtain the data regarding energy or non-expected output indicators specific to each city.

4.2.2 Explanatory variable

Digital economy ($digital_{i,t}$) is the explanatory factors. First, we use four variables that are relevant to the growth of the internet: mobile phone penetration, related practitioners, related output, and internet penetration rate. Then, using data from Peking University's Digital Financial Inclusion Index, we incorporate the indicators of digital financial inclusion. Finally, we use the entropy weight approach to combine the five variables to create the digital economy development index.

4.2.3 Adjustment variable

City size ($scale_{i,t}$) is the adjustment variable. Nighttime lighting data is chosen as a proxy variable to estimate the size of the city. Furthermore, to increase the credibility of the results, the corrected DMSP-like OLS data are obtained by integrating DMSP–OLS and NPP–VIIRS data based on the administrative divisions that characterize China in a fixed year (2011), and nighttime lighting data are obtained based on the DMSP-like OLS data (Wu et al., 2021).

4.2.4 Control variables

1) Technological progress (tec) is expressed as the ratio of regional S&T expenditures to local GDP (unit: %). 2) Advanced industrial structure ($indgaoji$): the ratio of the tertiary industry output value to the secondary industry output value (unit: %) is utilized to express $indgaoji = \frac{P_3}{P_2}$, where P_2、P_3 denotes the output value of secondary and tertiary industries, and a high ratio indicates a highly advanced industrial structure. 3) Rationalization of industrial structure ($indheli$): the construction of $indheli = \sum_{I=1}^{n} \left(\frac{P_I}{P}\right) \ln\left(\frac{P_I}{L_I} / \frac{P}{L}\right)$ is based on the Thayer index, where P denotes the output value, I denotes the industry, L denotes the employment, and n denotes the number of industrial sectors, and a small value indicates a highly rational industrial structure. 4) Government intervention (gov) is expressed as the ratio of local fiscal expenditure to local GDP. 5) Regional openness ($open$) is expressed as the ratio of FDI to local GDP. 6) Environmental regulation (env): First, we standardize the index values of industrial wastewater, industrial sulfur dioxide, and industrial smoke; subsequently, we utilize the entropy weight method to determine the index weights; and, finally, we determine the comprehensive index of environmental regulation (unit: %) based on the reciprocal pertaining to the product of the weights and the standardized values, where a high comprehensive index score indicates strict environmental regulation.

4.3 Data sources

The China City Statistical Yearbook and the Digital Finance Research Center of Peking University provided the majority of the data that we used to measure the digital economy. We used the evening lighting data (DMSP/OLS and NPP/VIIRS) that the National Oceanic and Atmospheric Administration (NOAA) supplied from 2011 to 2019 to estimate the size of cities. The descriptive statistics for the variables are shown in Table 1.

TABLE 1 Descriptive statistics results.

Variable name	Symbols	Observations	Average value	Maximum value	Minimum value	Standard deviation
GTFP	*gtfp*	2,538	1.081	8.911	0.041	0.245
Digital Economy	*digital*	2,538	0.341	1.000	0.053	0.119
City Size	*scale*	2,538	7.909	58.518	0.130	9.423
Technological Advances	*tec*	2,538	0.003	0.063	0.000	0.004
Advanced Industrial Structure	*indgaoji*	2,538	0.923	13.477	0.094	0.548
Rationalization of Industrial Structure	*indheli*	2,538	0.271	3.839	0.000	0.221
Government Intervention	*gov*	2,538	0.157	1.936	0.003	0.118
Government Intervention	*open*	2,538	0.022	0.776	0.000	0.030
Environmental Regulation	*env*	2,538	0.108	0.328	0.082	0.015

TABLE 2 Annual average values of urban GTFP in China and regions, 2011 to 2019.

Year	National	East	Central	West	First, second and third tier cities	Fourth and fifth tier cities
2011	1.040	1.040	1.050	1.029	1.042	1.073
2012	1.032	1.021	1.038	1.042	1.022	1.039
2013	1.065	1.062	1.136	0.999	1.104	1.036
2014	1.031	1.020	1.093	1.051	1.021	1.039
2015	1.134	1.077	1.057	1.290	1.115	1.147
2016	1.093	1.156	1.100	0.994	1.159	1.045
2017	1.119	1.141	1.102	1.068	1.146	1.099
2018	1.128	1.127	1.150	1.108	1.147	1.114
2019	1.112	1.130	1.131	1.068	1.135	1.96

5 Regression results

5.1 Temporal characterization of GTFP

Table 2 displays the annual average GTFP values for the nation and individual cities from 2011 to 2019. Table 2 shows that there is a varying upward tendency in the annual average values of GTFP as a whole. By regions, the annual mean values of GTFP in eastern and central regions are higher than those in western regions, and the annual mean values of GTFP in first-, second- and third-tier cities are higher than those in fourth- and fifth-tier cities, demonstrating that areas with greater economic development are better able to increase GTFP than areas with lesser levels of economic development.

5.2 Spatial correlation analysis

Table 3 shows the Moran indices we developed to investigate the regional autocorrelation of the digital economy, city size, and GTFP. Table 3 shows that the global Moran index is significantly positive, with the exception of a few years. Consequently, there is a significant spatial relationship between the size of the city, the GTFP, and the digital economy, which emphasizes the requirement and sense of using a spatial econometric model to research this problem.

5.3 Trend analysis

We create 3D perspective views of the digital economy, city size, and GTFP using a "trend analysis" tool that was created using ArcGIS software; the corresponding images are shown in Figures 1–3. The *Z*-axis points to the properties, the *Y*-axis points to the north, and the *X*-axis points east. Figure 1's fitted curve for GTFP shows a decreasing East-West trend, and a "U"-shaped north-south curve shows that regional variations in GTFP are not significant. Figure 2's fitted curve for the digital economy shows a west-to-east growing tendency as well as a North-to-South increasing trend, both of which point to high levels of development in China's east and south. Figure 3 shows that the fitted curve for city size rises and

TABLE 3 Test results of the global Moran index.

Year	*gtfp*	*digital*	*scale*	Year	*gtfp*	*digital*	*scale*
2011	0.000	0.195***	0.469***	2016	0.044***	0.152***	0.453***
2012	0.041***	0.180***	0.451***	2017	0.051***	0.147***	0.463***
2013	0.008	0.180***	0.459***	2018	0.058***	0.152***	0.463***
2014	0.013	0.148***	0.453***	2019	0.009***	0.141***	0.468***
2015	0.234***	0.156***	0.453***				

Note: Robustness standard errors are placed within parentheses, where * indicates $p < 0.1$, ** indicates $p < 0.05$, and *** indicates $p < 0.01$. The same below.

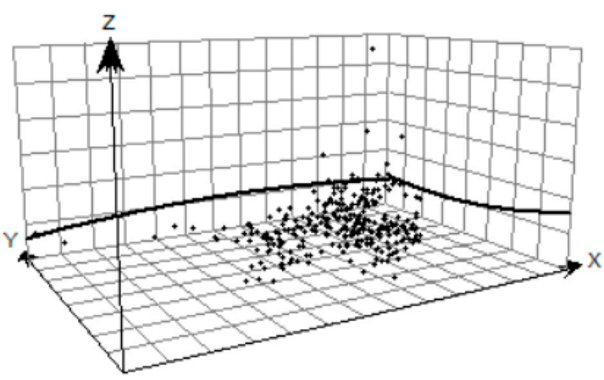

FIGURE 1
Trend analysis of GTFP.

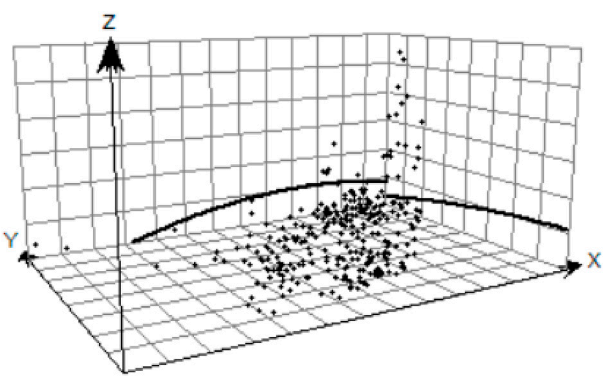

FIGURE 3
Trend analysis of city size.

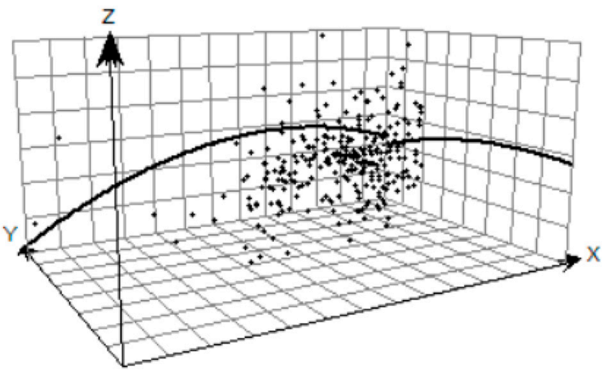

FIGURE 2
Trend analysis of the digital economy.

follows an East-West and North-South axis, indicating that the West and South of China have large cities.

5.4 Analysis of spatial measurement results

The geographic econometric correlation test is used in this paper to evaluate the appropriateness of applying the dynamic spatial Durbin model, and the specific outcomes are displayed in Table 4.

TABLE 4 Estimation results of spatial measurement correlation test.

Inspection	Value	Inspection	Value
VIF	1.35	Hausman	3.04*
$LR-lag$	10.08***	$LR-error$	10.85***
$Wald-lag$	10.09***	$Wald-error$	10.77***

There is no multicollinearity among the variables used for this paper, as shown by the VIF test findings in Table 4. The dynamic spatial Durbin model used in this work is known to be plausible based on the findings of the LR test and Wald test.

The findings of the spatial effect decomposition appear in columns 2 through 7, while the results of the dynamic spatial Durbin model based on the geographic distance matrix appear in the first column of Table 5. The results of Table 5's first column show that the estimated coefficient of GTFP ($L.gtfp$) in the lag period is significantly negative, showing that the GTFP in the prior period is not conducive to improving the GTFP in the subsequent period. The reason could be that issues with the city's construction process related to industrial development, ecological protection, technological advancement, and changes in spatial structure not only have an impact on the GTFP now but also pose a threat to it in the future, making it challenging to create a growth inertia for GTFP improvement. The estimated digital economy coefficient ($digital$) is significantly positive, showing that the growth of the local GTFP is

TABLE 5 Dynamic spatial Durbin model estimation results.

Variables	Estimated value	Short-term			Long-term		
		Direct effect	Indirect effects	Total effect	Direct effect	Indirect effects	Total effect
L.gtfp	−0.166*** (−8.43)						
digital	0.031* (1.73)	0.028 (1.58)	−0.125 (−0.78)	−0.098 (−0.59)	0.024 (1.62)	−0.096 (−0.82)	−0.072 (−0.59)
tec	0.214 (0.09)	0.487 (0.22)	2.171 (0.14)	2.658 (0.17)	0.410 (0.22)	1.538 (0.14)	1.948 (0.17)
indgaoji	0.019 (0.89)	0.015 (0.76)	−0.188 (−1.27)	−0.172 (−1.15)	0.013 (0.79)	−0.141 (−1.30)	−0.127 (−1.16)
indheli	0.074 (1.24)	0.069 (1.21)	−0.289 (−0.67)	−0.220 (−0.51)	0.060 (1.23)	−0.223 (−0.70)	−0.163 (−0.51)
gov	−0.126 (−1.49)	−0.117 (−1.40)	0.274 (0.48)	0.157 (0.27)	−0.101 (−1.41)	0.216 (0.51)	0.115 (0.27)
open	−0.005 (−0.02)	0.023 (0.08)	2.070 (0.82)	2.094 (0.82)	0.014 (0.05)	1.538 (0.82)	1.552 (0.82)
env	7.951*** (6.90)	7.975*** (7.16)	3.887 (0.35)	11.862 (1.05)	6.816 (7.18)	1.972 (0.24)	8.788 (1.06)
$W \times digital$	−0.083 (0.09)						
ρ	0.519 (9.85)						
$sigma^2$	0.084*** (37.47)						
R^2	0.0631						
N	2,256						

facilitated by the expansion of the digital economy, supporting hypothesis 1. The reason could be that by integrating the Internet with other industries, the digital economy can develop new business models and patterns for urban industrial development and structural upgrading, encourage the use of clean energy in cities, hasten the transition between old and new dynamics within cities, direct the clustering of high-tech businesses and high value-added services in cities, and encourage cities to optimize the form and scale of urban development. To support GTFP, cities should grow in size and scope (Chen, 2022a).

Among the control variables, the positive estimated coefficient of technological progress (*tec*) indicates that technological progress is conducive to GTFP, primarily because environmentally friendly technological advancement can greatly lessen the effects of using fossil fuels on the environment, increasing the output of green total factors (Wang H. et al., 2021; Wang M. et al., 2021). A positive coefficient of industrial structure advanced (*indgaoji*) indicates that industrial structure advanced is conducive to the improvement of GTFP, and a positive coefficient of industrial structure rationalization (*indheli*) indicates that industrial structure rationalization is conducive to the improvement of GTFP, the major justification for this is that modernizing the industrial structure encourages high-quality economic growth, which in turn encourages GTFP (Gu et al., 2022). The negative coefficient of government intervention (*gov*) indicates that government intervention inhibits the improvement of GTFP, the market's ability to allocate resources is constrained by excessive government intervention, which is harmful to increasing GTFP (Wu et al., 2021). The negative estimated coefficient of regional openness (*open*) indicates that the level of regional openness is not conducive to enhancing GTFP, primarily because improving regional openness by local governments may result in the introduction of polluting FDI, which is counterproductive to increasing the productivity of green total factors (Lin and Chen, 2018). The estimated coefficient of environmental regulation (*env*) is positive indicating that environmental regulation is conducive to increasing GTFP, primarily because implementing sensible and effective environmental regulation policies is a key strategy for boosting the productivity of green total factors (Cheng and Li, 2022).

Based on Table 5's direct, indirect, and total effects in the short and long terms, as well as the predicted spatial spillover effects of the main explanatory factors. The estimated coefficients of the spatial lag of the digital economy ($W \times digital$) are negative, and the short- and long-term direct effects of the digital economy (*digital*) are positive, but the indirect and total effects are negative, showing that the short-term and long-term effects of the digital economy are positive for improving local GTFP but negative for improving neighboring areas' GTFP. This suggests that, both immediately and over time, the digital economy helps to raise local GTFP but not surrounding GTFP. The development of the digital economy may be the cause because it encourages the deepening of data factors, removing barriers between industries, erasing geographic distinctions between cities, promoting the deep integration of the real and digital economies, igniting the interest of various market participants, and opening up the domestic integrated market, thus promoting the local. However, the growth of the local digital economy will take a significant quantity of production elements from nearby locations due to the siphon effect, which will restrict the improvement of GTFP in nearby locations.

5.5 Heterogeneity analysis

Based on the geography of their provinces, the 282 cities in this study were split into eastern, western, and central areas. The results are displayed in Table 6. Table 6 shows that the eastern region has

TABLE 6 Heterogeneity analysis of East, Central and West regions.

Variables	East	Central	West
L.gtfp	−0.172***	−0.154***	−0.274***
	(−5.73)	(−3.97)	(−7.48)
digital	0.120***	0.029	−0.019
	(4.15)	(0.67)	(-0.74)
$W \times digital$	0.271	0.798**	0.242
	(1.50)	(2.20)	(1.48)
ρ	0.080	0.302	0.361***
	(0.43)	(1.27)	(3.32)
$sigma^2$	0.086***	0.105***	0.064***
	(24.65)	(20.10)	(20.36)
Control variables	Control	Control	Control
R^2	0.118	0.115	0.169
N	960	640	656

TABLE 7 Heterogeneity analysis of city classification.

Variables	First, second and third tier cities	Fourth and fifth tier cities
L.gtfp	−0.172***	−0.242***
	(−5.61)	(−8.69)
digital	0.162***	0.0002
	(3.09)	(0.02)
$W \times digital$	0.301**	0.034
	(1.76)	(0.88)
ρ	0.010	0.054***
	(0.13)	(0.85)
$sigma^2$	0.162***	0.034***
	(24.54)	(28.72)
Control variables	Control	Control
R^2	0.101	0.146
N	952	1,304

the biggest positive digital economy (*digital*) coefficient, followed by the central region with the second largest, and the western region with the smallest and negative coefficient, additionally, the digital economy's favorable contribution the central region experiences the largest geographic spillover term ($W \times digital$), followed by the eastern region and the western region, demonstrating that the digital economy in the center region is more advantageous than that in the eastern and western regions to increase the GTFP of the surrounding regions. This may be due to the fact that eastern cities are better positioned than central and western cities to benefit from the "digital dividend" brought about by the growth of the digital economy. This will enable industrial upgrading, increase production efficiency, lessen resource mismatch, and reduce production costs, all of which will increase local GTFP. As the central region transitions from "central collapse" to "central rise," the growth of the digital economy can support that region's development potential and vitality. As a result, neighboring regions' GTFP will be increased more than in the eastern and western regions.

Table 7 displays the findings of the classification of 282 cities into Tier 1, 2, 3, 4 and 5 cities. According to Table 7, Tier 1, 2, and 3 cities have larger positive coefficients for digital economy (*scale*) and the spatial spillover term ($W \times scale$) than Tier 4 and 5 cities, indicating that Tier 1, 2, and 3 cities' development of the digital economy is more likely to increase GTFP locally and in nearby areas. This may be due to the fact that Tier 1, 2, and 3 cities have better economic development levels, population densities, technological innovation capacities, infrastructure, and transportation convenience than Tier 4 and 5 cities, making it simpler for Tier 1, 2, and 3 cities to create an environment in which the digital economy encourages urban GTFP improvement.

TABLE 8 Robustness tests.

Variables	(1)	(2)	(3)	(4)
L.gtfp		−0.161***		−0.173***
		(−5.89)		(−8.58)
digital	0.030	0.0331	0.030*	0.034*
	(1.36)	(1.54)	(1.77)	(1.86)
$W \times digital$			0.021	0.011
			(0.38)	(0.26)
Control variables	Control	Control	Control	Control
N	2,538	2,538	2,538	2,538

5.6 Robustness test

This paper conducts robustness tests using least squares estimation OLS, systematic GMM, static spatial Durbin model, and the use of economic distance matrix in four different ways. The specific results are displayed in columns (1)–(4) of Table 8 in the order in which they were obtained. Table 8 demonstrates that the estimated results of the primary explanatory variables are less different from the previous article in terms of coefficient values and significance, further demonstrating that the regression results of this paper are more reliable.

5.7 Test and analysis of interaction effects

Based on the previous work, this paper adds an interaction term between the two to investigate if the digital economy and city size

TABLE 9 Results of adjustment effects.

Variables	National	National	East	Central	West	First, second and third tier cities	Fourth and fifth tier cities
L.gtfp	−0.167***	−0.168***	−0.172***	−0.158***	−0.296***	−0.176***	−0.249***
	(−8.50)	(−8.57)	(−5.74)	(−4.07)	(−7.88)	(−5.76)	(−8.90)
digital	0.039**	0.013	0.108***	0.014	−0.033	0.148**	−0.007
	(2.19)	(0.61)	(2.91)	(0.23)	(−1.10)	(1.98)	(−0.40)
scale	0.014**	−0.032	−0.002	−0.013	−0.062	0.002	−0.016
	(2.38)	(−1.57)	(−0.08)	(−0.22)	(−0.73)	(0.05)	(−0.56)
digital × *scale*		0.004**	0.001	0.002	0.006	0.001	0.003
		(2.34)	(0.62)	(0.41)	(0.85)	(0.28)	(0.93)
W × *digital*	0.006	−0.00008	0.289	0.651	0.098	0.127	0.128**
	(0.09)	(−0.00)	(0.97)	(1.16)	(0.42)	(0.49)	(2.43)
W × *scale*	−0.007	−0.024	−0.140	−0.257	−1.068	−0.219	0.263**
	(−0.80)	(−0.40)	(−0.74)	(−0.44)	(−1.54)	(−1.37)	(2.55)
W × *digital* × *scale*		0.002	0.008	0.023	0.090	0.015	−0.025***
		(0.29)	(0.50)	(0.44)	(1.42)	(1.17)	(−2.57)
ρ	0.537	0.535***	0.206	0.307	0.345	0.004	0.035
	(10.52)	(10.47)	(1.02)	(1.28)	(3.16)	(0.06)	(0.56)
$sigma^2$	0.084***	0.084***	0.085***	0.105	0.064***	0.160***	0.034
	(37.48)	(37.48)	(24.63)	(20.10)	(20.36)	(24.54)	(28.73)
Control variables	Control	Control	Control	Control	Control	Control	Control
R^2	0.095	0.098	0.128	0.118	0.102	0.109	0.156
N	2,256	2,256	960	640	656	952	1,304

have a synergistic impact on green total factor production. The precise findings are displayed in Table 9.

When the interaction term is removed from the results in column 1 of Table 9, the positive correlations for the city size (*scale*) and its spatial lag term (*W* × *scale*) show that increasing city size is advantageous to enhancing GTFP, supporting Hypothesis 2. When we add the interaction term to the results in columns 2–7 of Table 9, we can see that the estimated coefficients of the interaction term between city scale and digital economy (*digital* × *scale*) are all positive. This means that city scale has a positive moderating effect on the process of local GTFP improvement, and Hypothesis 3 is true. The positive coefficient is bigger in the fourth and fifth tier cities than in the first, second, and third tier cities, and it is biggest in the western region, second largest in the central region, and smallest in the eastern region. This might be because there are more fourth- and fifth-tier cities in the western region than in the eastern and central regions. The foundation and starting point for the digitization of the urban economy and urban scale optimization is the western region's expanding new urbanization. Additionally, the urban economy's digitalization lays the groundwork for the knowledge, technology, and other intensive industries to congregate in cities in terms of time, place, technology, and economy. In order to actualize the logical architecture of the digital industries and to activate the multiplier, competitiveness, and spillover effects of digital technology, city scale optimization is a key factor. A digital economy development environment with the qualities of universality, inclusiveness, high permeability, reproducibility, and convenience is made possible by the deepening integration between the digitalization of the urban economy and urban scale optimization. This environment is very helpful in promoting the green development of the urban economy and the enhancement of GTFP.

6 Conclusion and recommendations

This research experimentally examined the relationship between digital economy, city size, and GTFP using a spatial econometric model, based on the panel data of 282 prefecture-level cities in China from 2011 to 2019, and came to the following conclusion. First, GTFP exhibits a yearly rising trend generally, with excellent spatial correlation and minimal regional variation. Second, the digital economy is advantageous for improving local GTFP, but not for improving GTFP in nearby locations. Third, the eastern region's digital economy is more suited to boosting regional GTFP than the central and western regions' are, and the central region's digital economy is more suited than the eastern and western regions to boosting GTFP in the surrounding areas. Comparatively to fourth- and fifth-tier cities, the digital economy in first-, second-, and third-tier cities is more suited to boosting GTFP in the region and its surrounding areas. Fourth, additional research reveals that the city size of the digital economy can increase GTFP, with the western area moderating the influence of city size more positively than the eastern and central regions. Additionally, in terms of city size, the fourth and fifth tier cities moderated the effects more favorably than the first, second, and third tier cities.

Based on the findings discussed above, this study proposes the following suggestions. First, it is underlined how important it is for the growth of the digital economy and city scale optimization to support the promotion of GTFP enhancement. The development of digital economy can provide effective support for the green and low-carbon transformation of urban economy through scale effect, spillover effect, and universal sharing, and thus promote the growth of GTFP. Second, it is important to address the local conditions when addressing the effects of the city size and the digital economy on GTFP. To advance the GTFP, individual cities should execute distinct digital economy development strategies based on their level of economic growth and orderly encourage the fusion of the digital economy with new urbanization. Third, it is important to properly acknowledge the beneficial effects of optimizing city size in the process of the digital economy's influence on GTFP. It is essential to actively encourage the use of digital technology during the process of new urbanization construction because this gives cities a digital technology foundation to improve their capacity for green development, optimizing the scale of cities and encouraging the improvement of GTFP.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

ZL contributed to conception and design of the study. JL and YY conducted the data analysis, wrote the original draft. XZ edited the paper. All authors contributed to the article and approved the submitted version.

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