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Has the development of the digital economy improved green total factor productivity in China?—A study based on data at the provincial level in China

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China's economic development has entered a new historical stage, and it is crucial to coordinate the linkage between economic development, resource allocation and environmental protection in this new stage. In view of this, this paper selects the panel data of 30 provinces (municipalities and autonomous regions) in China from 2011 to 2020, and firstly measures the Green Total Factor Productivity (GTFP) by using Slack Based Measure -Malmquist Luenberger method (SBM-ML); Then, the relationship between the development of digital economy and regional GTFP is analyzed by using the two-way fixed effect model and threshold effect; Finally, relevant policy suggestions are put forward. This paper found that: firstly, the development of digital economy significantly improves China's GTFP, and the conclusion still valid after considering a series of robustness tests; Secondly, there are obvious disparities in the development level of digital economy among provinces, and the development level of coastal areas is generally higher than that of inland areas, and according to the sub-regional regression results, the positive effect of digital economy on GTFP has regional heterogeneity, and the development of digital economy in coastal areas has a more significant effect on the enhancement of GTFP, while this effect in inland areas does not pass the significance test; Thirdly, according to the threshold effect test results, there is also a single threshold effect with institutional environment and technological innovation as the threshold variables for the impact of digital economy on GTFP in China.

KEYWORDS

digital economy, green total factor productivity, fixed effects, differential GMM, threshold effect

1 Introduction

In recent years, with the rapid development of the Internet, big data and other modern information and communication technologies, the digital economy is an emerging economic development model that uses data as a key factor of production and digital technology as an important carrier, which is regarded as a "new engine" for economic development (Carlsson, 2004). According to the data from the "White Paper on China's Digital Economy" published by China Academy of Information and Communication Technology (CAICT), from 2012 to 2021, the scale of China's digital economy increased from 11 trillion yuan to 45.5 trillion yuan, and the proportion of GDP increased from 21.6% to 39.8%, indicating that the digital economy is increasingly becoming one of the important engines of China's national economic development (Lyu et al., 2023). However, while the digital economy is developing rapidly, China's economic development is now facing multiple sustainable development pressures such as declining labor force and increasing labor costs due to the aging population, waste of resources, mismatch between supply and demand, and environmental pollution. Meanwhile, according to the Global Environmental Performance Index 2022 report released by Yale University and Columbia University, China's environmental performance score in 2022 is 28.4, ranking 160th out of 180 economies (Denmark scores 77.9, ranking first; the United States scores 51.1, ranking 43rd). This shows that the idea of relying on inherent labor, capital, and resource inputs to promote development is no longer sustainable, and there is an urgent need to crack the double problem of economic and environmental synergy, transform the economic development mode, accelerate the green transformation of the development mode, and find new economic development momentum has become an important issue for China's economy to achieve sustainable development.

Faced with the dual tasks of sustainable economic growth and coordinated development of resources and environment, the 14th Five-Year Plan clearly proposes to enhance the quality and quantity of economic development and promote green economic development. The emphasis on the development of green economy is an inevitable requirement from the emphasis on the "quantity" of economic development to the "quality" of economic development, and GTFP is an important indicator of high-quality economic development, and its overall improvement is the key to green economy (Young, 1996; Feng and Serletis, 2014). Liu et al. (2021) mention that the digital economy has become a major trend in global economic development, and its vigorous development will have an important impact on accelerating the transformation of old and new dynamics and improving GTFP. Many scholars have studied the impact of ICT technologies[6], digital finance[7] and other important components of the digital economy on GTFP. Specifically on how the digital economy enhances GTFP, Zhou et al. (2021) finds that the development of the digital economy enhances GTFP in our cities by optimizing the allocation of capital factors (Zhu et al., 2022); studies the development of the digital economy to enhance GTFP in our textile industry by optimizing the industrial structure. In terms of its spatial spillover effects, the digital economy not only has a positive effect on local GTFP, but also has a significant enhancement effect on other regions (Deng et al., 2022).

The marginal contribution of this paper is mainly reflected in the following three aspects: firstly, considering that the indicators for measuring digital economy and GTFP have not yet been unified, a system of measurement indicators is constructed to scientifically measure the level of development of digital economy and GTFP in each province; Secondly, from the perspective of regional heterogeneity, we divide coastal and inland regions for in-depth theoretical analysis and empirical research; Third, from the perspectives of market environment and technological innovation, a panel threshold model is used to verify whether there is a "threshold effect" of digital economy on GTFP.

The rest of the paper is framed as follows: The second chapter is literature review, compares the literature on the digital economy and GTFP. The third chapter analyses the transmission mechanism of digital economy to GTFP. The fourth chapter presents the variable setting and data selection. The fifth chapter is empirical analysis. The sixth chapter draws conclusions, policy recommendations and limitations.

2 Literature review

2.1 Digital economy

A great deal of research has been conducted in academia on the digital economy. Early foreign studies focused on the specific connotation of the digital economy from a theoretical level, considering it as a production activity directly related to digital technology (Kling and Lamb, 1999), while with the development and increasingly widespread application of modern communication technology, Quah (2003) extends the concept of digital economy to the sum of all economic activities transacted using the Internet. In contrast, domestic research on the digital economy started late and gradually enriched in recent years. Zhang and Ma, (2022) define the digital economy as an emerging way of economic development that uses data as a key production factor, ICT technology as a means of information transfer, and the Internet as a platform for information exchange. In addition, although research on the digital economy has been increasing in popularity, most studies have focused on exploring the economic effects of the digital economy, including the impact of digital economy development on optimizing and upgrading the industrial structure (Qin et al., 2022; Zhao et al., 2022), on improving the efficiency of regional green innovation (Dai et al., 2022), and thus on promoting high-quality economic development (Ding et al., 2022). Some scholars pay attention to the application of information technology in environmental governance (Ren et al., 2022a), and the impact of green investment on environmental pollution (Ren et al., 2022b). While few scholars pay attention to the environmental effects brought by digital economy. Some scholars have found that the digital economy can significantly reduce regional carbon emissions based on China's "3,060" vision (i.e., achieving carbon peaking by around 2030 and carbon neutrality by around 2060) (Xie, 2022). And some scholars have analyzed the impact of China's Internet development on environmental quality based on the spatial Durbin model, found that environmental pollution can be reduced through technological innovation, industrial upgrading, human capital and financial development (Ren et al., 2022c). From city-level data, the digital economy can optimize industrial structure, reduce emissions, thus improving urban environmental quality (Sun and Hu, 2021).

2.2 Green total factor productivity

Green Total Factor Productivity (GTFP) is a comprehensive indicator that builds on the traditional Total Factor Productivity (TFP) and organically combines economic efficiency, resource efficiency and environmental efficiency. Many useful discussions have been conducted by academics on GTFP. On the one hand, some scholars have measured GTFP in different industries and regions based on the super-efficient SBM model (Cheng and Jin, 2020; Chen et al., 2021; Li et al., 2021). On the other hand, some scholars have explored the factors influencing GTFP, which can be divided into two main categories of factors: policy and market. At the policy level, Liu Q. et al. (2022) examines the impact of China's innovative city pilot policies on green development, and finds that innovative city pilot policies can significantly improve GTFP through green innovation, energy saving and consumption reduction, and environmental rules. At the market level, Hou and Wang (2022) shows that the business environment effect has become a new driver of GTFP improvement.

2.3 The effect of digital economy on GTFP

Based on the existing literature, on the one hand, more scholars focus on TFP considering only the desired output. For example, Tian and Liu (2021) found that the digital economy has a significant positive impact on TFP based on the micro perspective of enterprises. Hu et al. (2022) found that the development of digital economy has a significant positive direct effect and spatial spillover effect on TFP growth. On the other hand, the mechanism of the impact of China's digital economy development on GTFP is more complex and may be influenced by a variety of factors. Cheng and Qian (2021) shows that there is a single threshold effect of China's digital economy development on GTFP in the industrial sector with regional industry size and institutional environment as thresholds, and shows a non-linear characteristic of marginal increment and U-shaped relationship respectively; Liu S. et al. (2022) finds that under the constraints of industrial structure, technological innovation and marketization degree, the impact of digital economy on GTFP exhibits a non-linear relationship.

In summary, the existing literature has conducted richer studies and discussions on the digital economy and GTFP. Distinguishing the existing literature, this paper 1) combines the existing literature and methods to construct a framework for measuring the digital economy and GTFP. 2) Explore whether the impact of the digital economy on GTFP is heterogeneous based on the variability of regional development. 3) To investigate whether there is a "non-linear" relationship between the impact of the digital economy and GTFP using threshold effects. This study is of great importance in bringing into play the value of the digital economy in enhancing economic efficiency and improving resource allocation efficiency, and in achieving green and high-quality development in China's economy.

3 The transmission mechanism of digital economy to GTFP

3.1 Direct transmission mechanism of digital economy affects GTFP

With the popularity and development of information and communication technologies such as the Internet, big data and artificial intelligence, the digital economy not only affects the production and operation activities of enterprises, but also has a profound impact on the lives of Chinese residents. An and Liu (2022) points out that the development of the digital economy is not only manifested in the increase in the proportion of the digital economy to GDP, but also in the role of the digital economy in "improving quality and efficiency" of the economy. The GTFP is a combination of economic efficiency, resource utilization efficiency and environmental efficiency, taking into account both the "quality" and "quantity" of economic development (Li and Liao, 2022). Therefore, this paper will analyse the direct transmission mechanism of the digital economy on GTFP based on above, and propose a research hypothesis.

On the one hand, the development of the digital economy, led by digital technologies such as the Internet and big data, can facilitate easier information transfer, effectively reduce the cost of information search, break down "information silos," promote the rational distribution of resources and energy, improve the efficiency of resource and energy use (Li et al., 2021). When digital technology is combined with government administration, it can reduce government corruption (Sadik-Zada et al., 2022) and improve the efficiency of government administration (Niftiyev, 2022a). Yang (2020) mentions that the digital economy is growing at a faster rate, accounting for an increasing share of China's GDP and has a significant effect on economic efficiency. In summary, the digital economy promotes the improvement of China's GTFP by unblocking information transmission channels and improving the efficiency of resource utilization.

On the other hand, from the perspective of digitalization and digital industrialization, digital industrialization, as an important part of the digital economy, is usually dominated by information technology service industries such as Internet enterprises and information service industries, which tend to pay more attention to the environment benefits of the enterprises due to their strong economic power (Jardim-Goncalves et al., 2012). However, Lin and Zhang (2011) found that the location choice of such IT service companies tends to be in areas with better accessibility, while the eastern coastal region of China is a gathering place for various digital industries due to its historical conditions and geographical location, and therefore has a good foundation for the development of the digital economy. The digitalization of industries, as the focus of the development of the digital economy, is the integration of digital technology with traditional industries, and the use of digital technology for real-time monitoring of various types of production links in traditional manufacturing industries, which not only improves their production efficiency (Niftiyev, 2022b), but also reduces the emission of pollutants in various links and promotes the improvement of GTFP.

Based on the above analysis, this paper proposes the relevant Hypothesis 1, Hypothesis 2:

Hypothesis 1: The development of the digital economy can improve the GTFP.

Hypothesis 2: There is regional heterogeneity in the role of the digital economy on GTFP.

3.2 Non-linear relationship of the digital economy affecting GTFP

3.2.1 Market environment

The development of the digital economy is constantly changing our market environment, blurring the boundaries between market players in space and time, breaking the disadvantages of poor factor mobility in traditional markets, and reducing transaction costs (Goldfarb and Tucker, 2019). When the market environment is poor, the barriers to factor mobility are high and the high efficiency of the digital economy is not fully exploited, which is not conducive to enterprises using the digital economy to integrate traditional supply chains and has a negative impact on enterprises using the digital economy to reshape production processes (Iqbal et al., 2018). In recent years, the word "digital" has appeared more and more frequently in the Communist Party of China (CPC) and state policy documents. In 2017, the digital China was written into the programmatic document of the CPC and the state for the first time, and the report of the 19th National Congress clearly pointed out the construction of "a strong network country, a digital China and a smart society;" In 2020, the "14th Five-Year Plan" explicitly mentioned the need to speed up digital development and build a digital China; in 2022, the State Council issued the Digital Economy Development Plan for the 14th Five-Year Plan, which proposed to promote the deep integration of the real economy and digital technology, develop the digital economy comprehensively, and strive for the core industries of the digital economy to account for 10% of GDP by 2025. To sum up, Chinese government has issued various documents to stimulate market subject to use digital technology for innovation, which provides a good business environment for the smooth operation of the digital economy, thus realizing the improvement of GTFP.

3.2.2 Technological innovation

The digital economy itself has certain technological attributes, and with the continuous development of the digital economy in the region will promote the continuous improvement of the innovation capacity in the region, while the learning effect and scale effect brought by the agglomeration of digital industries also drive the improvement of the scientific and technological innovation capacity, promote the innovation of green technology and improve GTFP (Li, 2019). Boer and During (2001) mentions that innovation is essentially a process of information collection and processing, and the digital economy represented by the Internet acts as a medium in the process of information exchange, which makes information transfer more convenient. To sum up, the application of digital technology shortens the time of information collection, improves economic efficiency, thus increasing the overall GTFP of China.

Based on the above analysis, this paper proposes the relevant Hypothesis 3, Hypothesis 4:

Hypothesis 3: There is a threshold effect of the impact of digital economy development on GTFP with the market environment as the threshold.

Hypothesis 4: There is a threshold effect of the impact of digital economy development on GTFP with technological innovation as the threshold.

4 Variable setting and typical facts

4.1 Model construction

To test Hypothesis 1 above, the following model is constructed the following model:

$$GTFP_{it} = a_0 + a_1 DIG_{it} + a_j \sum X_{jit} + \mu_i + \delta_t + \varepsilon_{it}$$

Where, $GTFP_{it}$ denotes the explanatory variable green total factor productivity, DIG_{it} denotes the core explanatory variable the development level of digital economy, and X_{jit} denotes a series of control variables of the model, mainly containing: regional economic development level, foreign direct investment, industrial structure, etc. μ_i are individual fixed effects, δ_t is the year fixed effect, and ε_{it} is the random disturbance term.

In addition, in order to verify Hypothesis 3 and Hypothesis 4, and examine whether there is a threshold effect of the development of digital economy on GTFP in terms of market environment and technological innovation, the panel threshold model is set as follows:

$$GTFP_{it} = \omega_1 DIG_{it} {}^* I(Tv_{it} \le r) + \omega_2 DIG_{it} {}^* I(Tv_{it} > r) + \omega X_{it} + \varepsilon_{it}$$

Where, $I(\cdot)$ is the demonstrative function, Tv_{it} represents the threshold variable, and r is the threshold value. If the inequality inside the parentheses holds, $I(\cdot) = 1$; and *vice versa*, $I(\cdot) = 0$.

4.2 Variable selection

4.2.1 Explanatory variable: Green total factor productivity (*GTFP*)

Green total factor productivity (GTFP) is developed on the basis of TFP, which is a comprehensive indicator considering economic efficiency, resource utilization efficiency and environmental efficiency. In the calculation of GTFP, the measurement methods adopted by domestic and foreign scholars mainly include parametric and non-parametric methods. The SBM model based on non-expected output incorporates slack variables into the objective function and uses a non-radial and non-angular measure to effectively solve the problem of slackness of input-output variables and the problem of efficiency measurement when considering non-expected output. Drawing on Chung et al. (1997) research, this paper uses the super-efficient SBM model with the Malmquist-Luenberger index to measure the GTFP of each province in China, in order to enhance the comparability between effective decision-making units. The specific measurement formula is as follows.

$$GTFP = \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{S_i^-}{x_{io}}}{\frac{1}{s_1+s_2}\left[\sum_{q=1}^{s_1}\frac{S_q^g}{y_{q0}^g} + \sum_{q=1}^{S_2}\frac{S_q^b}{u_{q0}^b}\right]}$$

Satisfy $x_{io} = \sum_{i=1,j\neq k}^{n} x_{ij}\lambda_j + S_i^-$, $y_{io}^g = \sum_{i=1,j\neq k}^{n} y_{ij}^g\lambda_j - S_i^g$, $u_{io}^b = \sum_{i=1,j\neq k}^{n} u_{ij}^b\lambda_j + S_i^b$ at the same time.

Where, $GTFP$ are the values of GTFP for each province, the $S-$, S^g, S^b are input slack, desired output slack and non-desired output slack, respectively; and are all greater than or equal to zero.

Further the ML productivity index from period t to period t+1 can be expressed as

$$ML_t^{t+1} = \left|\frac{1 + D_0^t(x^{t+1}, y^{t+1}, c^{t+1}, g^{t+1})}{1 + D_0^t(x^t, y^t, c^t, g^t)} * \frac{1 + D_0^{t+1}(x^{t+1}, y^{t+1}, c^{t+1}, g^{t+1})}{1 + D_0^{t+1}(x^t, y^t, c^t, g^t)}\right|^{\frac{1}{2}}$$

In addition, the corresponding input and output indicators were selected by drawing on the method of selecting relevant indicators from Qifeng et al. (2022), specifically from three aspects: input variables, desired output variables and non-desired output variables, which mainly include labor input, measured by the number of employees at the end of the year in each province; capital input, as the capital stock is difficult to measure, this paper uses the method of replacing capital stock with fixed assets, which is expressed as total investment in fixed assets of the whole society; energy input, which is measured by the electricity consumption of each province. Expected output is measured by the real GDP of each province, which is based on the GDP index to eliminate the effect of inflation. Non-desired output indicators are measured by the "three wastes" of industry, mainly including sulfur dioxide emissions, smoke (powder) dust emissions and wastewater emissions. The specific evaluation indicators are shown in the Table 1.

4.2.2 The core explanatory variables: Digital economy (*DIG*)

At present, there is no unified index for measure the development level of digital economy. In this paper, according to the definition of digital economy in "China Digital Economy White Paper" published by China Institute of Information and Communication Technology, the digital economy development index is constructed at the provincial level from two dimensions: digital industrialization and industrial digitalization. Referring to the research of Liu Y. et al. (2022), digital industrialization is measured from three aspects: Internet and telecommunication industry, electronic information manufacturing industry and software and information technology service industries, etc., and industrial digitalization is measured from three aspects: Digital talents, digital infrastructure and digital transactions. The specific evaluation indicators are shown in the Table 2.

On the basis of the above digital economy development level evaluation index system, the comprehensive index of digital economy development level is measured. The commonly adopted methods are subjective assignment method and objective assignment method. The subjective assignment method includes principal component analysis, AHP, etc., and the objective assignment method includes cluster analysis, entropy value method, etc. In order to avoid artificial subjective influence, this paper uses the entropy method to assign the weights of each index by referring to the research of Wang and Zhu, (2021).

Since there are significant differences in both the magnitude and order of magnitude of the above index values, they are first standardized and the specific formula is as follows: $x_{ij} = \frac{x_{ij} - min\left\{x_j\right\}}{max\left\{x_j\right\} - min\left\{x_j\right\}}$

Where, $max\left\{x_j\right\}$ is the maximum value of the indicator in all years, and $min\left\{x_j\right\}$ is the minimum value of the indicator for all years, and x_{ij} is the normalized value.

Calculate the proportion of the j index in the year i, using w_{ij} indicates that $w_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}$.

Calculate the information entropy and redundancy of the metrics. The information entropy is $e_j = -\frac{1}{ln\, m}\sum_{i=1}^{m}(w_{ij}{}^{*}\, ln\, w_{ij})$ and the redundancy degree is $d_j = 1 - e_j$.

Where, m is the evaluation year, and the index weights are calculated based on the information entropy redundancy $\varphi_j = \frac{d_j}{\sum_{j=1}^{m} d_j}$.

Based on standardized indicators x_{ij} and measured indicator weights φ_j, the index level of digital economy development level is derived using the weighting of multiple linear functions: $DIG_i = \sum_{j=1}^{m}(\varphi_j{}^{*} x_{ij})$.

Finally, the combined value can be calculated DIG_i between 0 and 1, indicating the level of digital economy development in each province. The development of digital economy in each province in 2020 is shown in Figure 1.

4.2.3 Control variables

Referring to the research of Wu et al. (2021) and Cao et al. (2021), the following three variables are selected as the main control variables in this paper: 1) the level of economic development (*PERGDP*), the gross regional product *per capita* was selected to measure. On the one hand, the improvement of economic development level requires not only the expansion of the overall scale of economic development, but also the improvement of energy utilization efficiency and environmental efficiency, which may have a positive impact on GTFP. On the other hand, the GDP-only growth theory, which sacrifices the environment for GDP growth, may have a negative effect on GTFP; 2) Industrial structure (*IS*), the secondary industry is the main source of all kinds of pollutants and the development of tertiary industry promotes the transformation and upgrading of industrial structure, so this paper selects the ratio of the added value of tertiary industry to GDP to indicate the industrial structure; 3) Foreign direct investment (*FDI*). According to the pollution halo hypothesis, the learning effect, scale effect and technology spillover effect brought by the entry FDI may have a positive effect on the improvement of GTFP in the host country (Hao et al., 2020). This paper selects the actual amount of FDI utilized in the current year as a proportion of the regional GDP in the current year after being converted by annual average exchange rate to measure.

4.2.4 Threshold variables

The market environment (*ME*) can be regarded as a new type of production factor, and a good market environment can have an important impact on both supply and demand. Therefore, this paper uses the inverse of the marketability index as a threshold variable to explore the possible impact on GTFP when the regional marketability index exceeds the threshold value. Technological innovation (*TEC*) can affect both the development of the digital economy and China's GTFP. This paper uses the number of domestic patents granted as measure of regional technological innovation and explores the possible impact on GTFP when regional innovation capacity exceeds the threshold.

4.3 Data sources and descriptive statistical results

This paper selects panel data of 30 provinces (autonomous regions and municipalities) in China except Tibet Autonomous Region, Hong Kong, Macao and Taiwan from 2011 to 2020 for empirical analysis. The data used in this paper are mainly come from China Statistical Yearbook, EPS database, CSMAR database and statistical yearbooks of various provinces (autonomous regions and municipalities), among which some missing data are filled by interpolation method, and the non-ratio data in this paper are logarithmically processed to reduce the heteroscedasticity. The descriptive statistics of the data are shown in Table 3, and the correlation analysis of the core variables is shown in Figure 2.

5 Empirical analysis

5.1 Regression results of benchmark model

In order to examine the influence of digital economy development on GTFP in China, a model with time and region double fixation was selected for the benchmark regression. Table 4 reports the regression results of the benchmark model. Model (1) analyzes the impact of the digital economy on GTFP without considering control variables, and it can be found that the influence coefficient of the digital economy is 3.8723, which is significantly positive at the 1% confidence level, indicating that the development of the digital economy can significantly increase GTFP. Model (2) is shown the results of adding control

TABLE 1 Evaluation index system of provincial green total factor productivity in China.

	Level 1 indicators	Secondary indicators	Variable selection
Green total factor productivity	Input Indicators	Labor input	Number of employees at the end of the year/10,000 people
		Capital input	Total social fixed asset investment/billion yuan
		Energy input	Electricity consumption/billion kWh
	Expected output	Economic output	Real GDP/billion yuan
	Non-expected outputs	Industrial waste	sulfur dioxide emissions/million tons
			smoke (powder) dust emissions/million tons
			wastewater emissions/million tons

TABLE 2 Index system of digital economy development level among provinces in China.

	Level 1 indicators	Secondary indicators	Variable selection
Digital economy development level	Digital Industrialization	Internet and Telecommunications	Internet broadband access ports/million
			Cell phone penetration rate/units per 100 people
			Total telecom business/added value of tertiary industry/%
		Electronic Information Manufacturing	Computer, communication and other electronic equipment manufacturing employment/10,000 people
		Software and Information Technology Services	Software business income/tertiary industry added value/%
			Information transmission, software and information technology services employment/10,000 people
			Number of software and information technology services enterprises/ea
	Industry Digitization	Digital Talent	Number of degrees awarded by higher education institutions/person
			Full-time teachers in higher education institutions/person
		Digital Infrastructure	Number of pages/billion
			Long distance fiber optic cable line length/km
		Digital Trading	Above-standard industrial enterprises new product sales revenue/above-standard industrial enterprises main business income/%
			Courier volume/million pieces
			Original insurance premium income/added value of tertiary industry/%
			Technology market turnover/billion yuan

variables, the influence coefficient of the digital economy is 3.5589, which is still significantly positive at least at 1% confidence level. It can be seen that the digital economy can significantly improve GTFP whether adding control variables or not, that is, assuming H1 holds. The reason for this can be mainly analyzed from the input side and the output side to analyze the positive effect of the digital economy on GTFP. From the input side, the digital economy relies on information technology and the Internet as a platform to improve the efficiency of information transmission and reduce the waste of resource caused by information asymmetry; it also promotes the optimization of production factor inputs through digital technology innovation and promotes the improvement of GTFP (Ishida, 2015). From the output side, the integration of digital technology with the traditional manufacturing industry not only enables real-time monitoring of its production process, but also unifies the supervision of pollutant emissions from relevant enterprises and reduces the difficulty of government environmental supervision, thus achieving the purpose of reducing pollutant emissions.

In terms of control variables, all the selected control variables in this paper are significant positive at 1%, 5% and 10% level of significance respectively. The positive relationship between the level of economic development and GTFP indicates that the more developed the regional economy is, the higher the requirements for environmental protection in the region, and the coordinated positive development of economic development and environmental protection

TABLE 3 Descriptive statistics of data.

	Variables	Sample size	Average value	Standard deviation	Minimum	Maximum
Explained variables	Green Total Factor Productivity (*GTFP*)	270	1.5034	0.4412	0.8920	2.6135
Core explanatory variables	Digital Economy (*DIG*)	270	0.2302	0.1122	0.0573	0.6750
Threshold variables	Market Environment (*ME*)	270	0.1585	0.0547	0.8333	0.3953
	Technological innovation (*TEC*)	270	10.1962	1.4023	6.2186	13.4726
Control variables	Level of economic development (*PERGDP*)	270	10.8779	0.4215	9.8889	12.0130
	Industrial structure (*IS*)	270	0.4793	0.0951	0.3094	0.8387
	Foreign direct investment (*FDI*)	270	0.5303	2.0932	0.0477	34.2064

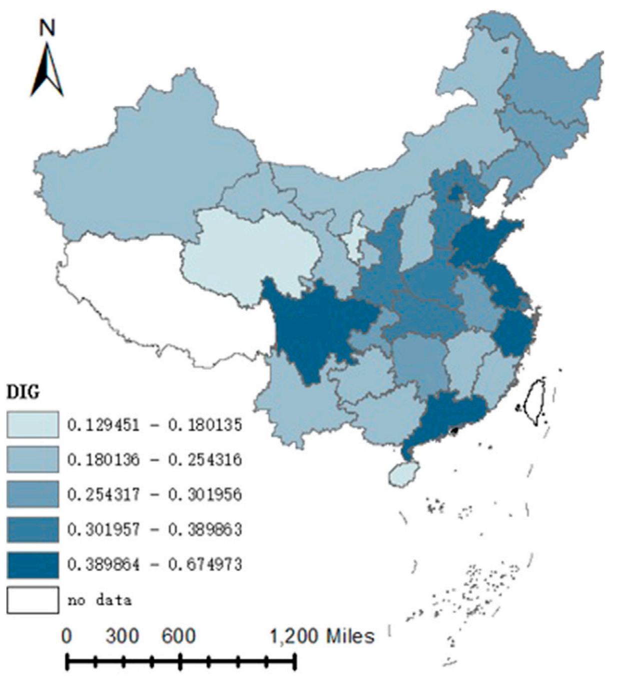

FIGURE 1
Development level of digital economy in China provinces in 2020.

leads to the higher GTFP. Foreign direct investment promotes the improvement of GTFP in China through the technology spillover effect and learning effect (Yoon and Nadvi, 2018); the secondary industry is one of the main sources of pollutants. The measurement index of industrial structure selected in this paper is the ratio of tertiary industry to GDP. There is an obvious positive correlation between industrial structure and GTFP, indicating that the more advanced the industrial structure is, the higher its GTFP.

5.2 Robustness analysis

In order to verify the reliability of the above regression results, the following two approaches are used to perform robustness tests in this paper.

5.2.1 Adding control variables

To examine the possible omitted variables in the model, three control variables, education support (GOV), human capital (HC) and fiscal decentralization (FDE), are added by drawing on the method of Wei Junying et al. (2022), which were respectively expressed by the ratio of education to general budget expenditure, the number of graduates to undergraduate students and the ratio of general budget revenue to general budget expenditure. The results are shown in Table 5 (1). It can be found that the regression results after adding the control variables are consistent with the baseline regression, indicating that the baseline regression results are somewhat robust.

5.2.2 Dynamic panel regression

To ensure the robustness of the above findings, this paper uses a dynamic panel model that lags the variables by one order, and chooses

TABLE 4 Baseline regression results.

Variables	Explained variable:GTFP	
	(1)	(2)
DIG	3.8723***	3.5589***
	(2.8305)	(2.9283)
PERGDP		1.0728***
		(5.7931)
IS		2.3187**
		(2.7184)
FDI		0.0053*
		(1.9744)
Constant	0.3992*	−11.8793***
	(1.7403)	(−6.6570)
Observations	270	270
R-squared	0.6774	0.7413
Regional fixed effects	Yes	Yes
Time fixed effects	Yes	Yes

Note: 1) *, **, *** represent significant at the 10%, 5% and 1% levels respectively; The *t*-value are in parentheses. 2) The following table is the same as.

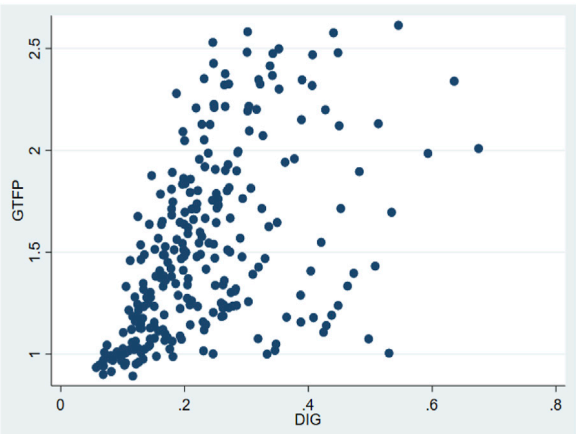

FIGURE 2
Correlation analysis of core variables.

a differential GMM approach for regression. The results are shown in Table 5 (2) and (3). It can be found that the *p*-values of AR(1) test are all less than 0.1, and the *p*-values of AR(2) test are all greater than 0.1, which indicates that there is no second-order autocorrelation. Meanwhile, the *p*-values of Hansen test are 0.2579 and 0.2598 are greater than 0.1, indicating that the instrumental variables are valid, and the regression results of differential GMM again confirm the robustness of the benchmark regression results.

5.2.3 Endogenous treatment and instrumental variables

In order to avoid the problem of endogeneity caused by factors such as two-way causality and possible omitted variables, this paper will adopt the instrumental variable method for endogeneity testing. Referring to the study by Huang et al. (2019), the number of landline telephones by region in 1984 is selected as the instrumental variable for the digital economy. The reason for this is that the development of Internet technology should have started with the popularization of landline telephones, so that regions with historically high landline penetration are also most likely to be regions with high Internet penetration. In addition, as the research sample in this paper is panel data and the original data for the instrumental variables selected are cross-sectional, the interaction term between the number of landline telephones per 10,000 people in 1984 and national IT service revenues in the previous year was constructed for each region as an instrumental variable for the 2SLS regression, drawing on the setup of Nunn and Qian (2014). The results are shown in Table 5 (4) and (5). It can be seen that after accounting for endogeneity, the coefficient on the impact of the digital economy on GTFP is still significantly positive and the benchmark regression results remain robust. Meanwhile, the Kleibergen-Paap rk LM statistic is 40.013, corresponding to a *p*-value of 0, indicating that there is no under-identification problem; the value of the Cragg-Donald Wald F is 46.626, which is greater than the critical value of the Stock-Yogo test of 16.38, indicating that there is no weak instrumental variable problem.

TABLE 5 Results of robustness analysis.

Variables	Explained variable: GTFP				
	(1)	(2)	(3)	(4)	(5)
L.TFPCRS		0.7916***	0.6690***		
		(7.0650)	(4.2873)		
DIG	3.4896***			29.5328*	27.9986*
	(2.9098)			(1.7361)	(1.9553)
L.DIG		0.5547*	0.7423*		
		(1.6591)	(1.8696)		
PERGDP	1.1397***			0.5342	0.4982
	(6.0663)			(1.0072)	(0.9119)
L.PERGDP		0.2722	0.3638**		
		(1.0346)	(2.0582)		
IS	2.3943**			4.6229**	4.6327**
	(2.7011)			(1.9755)	(2.1473)
L.IS		0.0491	0.0910		
		(0.0837)	(0.1550)		
FDI	0.0061**			0.0420	0.0406
	(2.4164)			(1.4159)	(1.5547)
L.FDI		−0.4678	−0.1497		
		(−1.1565)	(−0.4421)		
GOV	2.6960				3.7674
	(1.5982)				(0.9617)
L.GOV			3.6639		
			(1.5467)		
HC	0.1176				1.6464
	(0.0739)				(0.4843)
L.HC			−0.7026		
			(−0.3779)		
FDE	−1.2213*				−0.0923
	(−1.7846)				(−0.0618)
L.FDE			−0.7179		
			(−1.0724)		
Constant	−12.4849***	−2.5072	−3.5927*	−19.5528***	−19.5265***
	(−7.2438)	(−0.9273)	(−1.8266)	(−3.2057)	(−3.4484)
Observations	270	270	270	270	270
R-squared	0.7498			0.3270	0.3470
Regional fixed effects	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes
AR(1) test *p*-value		0.0218	0.0226		
AR(2) test *p*-value		0.5600	0.5642		
Hansen		0.2579	0.2598		

TABLE 6 Results of heterogeneity analysis.

Variables	Coastal region			Inland region		
	(1)	(2)	(3)	(4)	(5)	(6)
DIG	4.0540**	3.7724*	3.3553*	3.4262	2.9267	2.7412
	(2.3113)	(1.9606)	(1.9585)	(1.0597)	(1.6913)	(1.4385)
PERGDP		0.5072	0.8934		1.3392***	1.3915***
		(0.9791)	(1.8081)		(6.8669)	(6.6392)
IS		−0.5478	0.8418		2.2483**	2.1307**
		(−0.1579)	(0.3337)		(2.8383)	(2.5239)
FDI		0.0029	0.0041		−0.4522**	−0.4943*
		(0.5103)	(0.9134)		(−2.1501)	(−2.0966)
GOV			6.7291**			−1.3062
			(3.1035)			(−0.5781)
HC			−1.4521			−0.4097
			(−0.4226)			(−0.2471)
FDE			−2.0956**			−0.3189
			(−2.4685)			(−0.3390)
Constant	0.2449	−4.9811	−9.2368	0.5319	−14.2080***	−14.2191***
	(0.7217)	(−0.7631)	(−1.5869)	(1.0846)	(−6.3813)	(−6.2318)
Observations	99	99	99	171	171	171
R-squared	0.7547	0.7747	0.8074	0.6401	0.7684	0.7700
Regional fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

TABLE 7 Threshold effect test.

Threshold variables	Number of thresholds	*p*-value	F-value	Number of BS	Threshold value		
					1%	5%	10%
Market Environment	Single Threshold	0.0300	23.78	300	29.3054	21.6791	17.8236
	Double Threshold	0.5833	6.87	300	24.6924	16.8118	14.4540
Technology Innovation	Single Threshold	0.0567	24.60	300	33.4531	25.7120	20.3840
	Double Threshold	0.2500	11.30	300	32.3484	22.4991	17.3227

5.3 Heterogeneity analysis

Influenced by historical conditions, geographical location and other factors, there are large disparities in the level of economic development among different regions in China, and there are also large disparities in the level of development of digital economy and GTFP in different regions, which generally show that the development of digital economy in coastal areas is better than that in inland areas. Therefore, in order to study whether there is regional heterogeneity in the influence of digital economy on GTFP, this paper divides the 30 provinces into two sub-samples of coastal areas and inland areas according to their geographical location, and the regression results are shown in Table 6 again. It can be seen that there is significant regional heterogeneity in the influence of digital economy development on GTFP, that is, Hypothesis 2 holds. The development of digital economy in the eastern coastal region has a obviously promoted the regional GTFP. The reason is that the coastal region is more conveniently located, and generally speaking, the level of regional economic development is higher, the digital infrastructure is relatively complete, and the overall development of the digital economy is better. By promoting regional innovation, the digital economy in the region can improve the utilization efficiency of capital and resources, improve the economic development efficiency, and at the same time achieve the goal of reducing pollutant emissions. In contrast, in China's inland areas, the digital economy foundation is weaker, and the role of digital economy in promoting regional GTFP is not significant.

TABLE 8 Threshold estimates.

Threshold variables	Number of thresholds	Estimated value	Confidence interval
Market Environment	Single Threshold	0.1054	[0.1030 0.1062]
Technology Innovation	Single Threshold	7.2612	[7.0504 7.5310]

TABLE 9 Threshold model estimation results.

Threshold variables	Market environment	Technology innovation
DIG_1	1.5148*	7.6433***
	(1.9205)	(6.6285)
DIG_2	2.2271***	1.9805**
	(3.4682)	(2.6241)
PERGDP	0.9294***	0.9142***
	(5.6458)	(4.7558)
IS	0.9724	1.6063***
	(1.2970)	(2.7865)
FDI	0.0025	0.0037**
	(1.3386)	(2.3035)
GOV	1.9411	2.1769*
	(1.3200)	(1.7759)
HC	−0.3338	0.6312
	(−0.2921)	(0.5192)
FDE	−0.4396	0.0849
	(−0.7539)	(0.1630)
Constant	−9.5837***	−10.2207***
	(−5.3662)	(−5.5155)

5.4 Threshold effect of digital economy on GTFP

The empirical analysis conducted above implicitly assumes the prerequisite that the factor endowment characteristics of all regions in China are non-differentiated. However, in fact, the influence of the digital economy on GTFP will also be constrained and influenced by various objective factors. To study whether there is a non-linear relationship between the digital economy and GTFP, this paper will introduce threshold variables, market environment and technological innovation, to analyze the threshold effect.

5.4.1 Threshold test

Firstly, the threshold variables market environment and technological innovation are verified to determine whether there is a threshold effect, and the test results are shown in the following Tables 7, 8. It can be seen from Table 7 that the threshold variables market environment and technological innovation both passed the single threshold effect test, and from Table 8, the threshold values of market environment and technological innovation are 0.1054 and 7.2612 respectively.

5.4.2 Threshold regression results

As shown from the results of the threshold effect in Table 9, when the market environment is lower than the threshold value of 0.1054, the impact of digital economy on GTFP is significant at the 10% confidence level with a coefficient of 1.5148; When the market environment is higher than the threshold value of 0.1054, the impact of digital economy on GTFP is significant at the confidence level of 1%, with a coefficient of 2.2271. It indicates that in regions with better market environment, the influence of digital economy on GTFP is more significant. In regions with good external market environment, these regions tend to have a higher level of economic development and a better development of digital economy. In these areas, digital economy has a great direct impact on GTFP, that is, H3 is assumed to be true. However, when the technological innovation is lower than the threshold value of 7.2612, the impact of digital economy on GTFP is significant at the 1% confidence level, and the impact coefficient is 7.6433; When the technological innovation is higher than the threshold value of 7.2612, the influence coefficient of digital economy on GTFP is 1.9805, which passes the significant level test of 5%. It indicates that the effect of digital economy on GTFP is more significant where the level of technological innovation is lower, that is, Hypothesis 3 holds.

6 Conclusion, policy recommendations and limitations

6.1 Conclusion

In the context of digital economy becoming an important driving force for green and high-quality economic development, this paper focuses on the dynamic interaction among economic efficiency, resource utilization efficiency and environmental efficiency. Based on provincial panel data from 2011 to 2020, using the super-efficient SBM-ML model measure the GTFP of each province. And a digital economy measurement system is constructed to measure the development level of digital economy in each province from two dimensions: digital industrialization and industrial digitalization. On this basis, we empirically tested whether the development of digital economy can improve GTFP in China. The results of the study show that: firstly, from an overall perspective, the development of digital economy can significantly improve GTFP in China; Secondly, the analysis of regional heterogeneity shows that the positive impact of digital economy development on regional GTFP is more significant in coastal areas than inland areas with a lower level of digital economy development; Thirdly, the results of threshold effect analysis show that in regions with better market environments and poor technological innovation level, the promotion of digital economy to GTFP is more significantly influenced by external market environment and a lower level of regional technological innovation.

6.2 Policy recommendations

Based on the above analysis and conclusions, this paper puts forward the following policy recommendations:

First, the findings of this paper find that the development of the digital economy can significantly enhance China's GTFP, therefore strengthening the development of the digital industry should accelerate the integration of digital technology with traditional industries when developing the economy, improve the efficiency of energy and resource conversion, and bring into play the role of the digital economy in enhancing GTFP.

Second, in terms of regional heterogeneity, the eastern coastal regions of China should continue to actively and steadily promote the development of the digital economy and foster new competitive advantages, while the central and western inland regions should actively undertake the technological spillover from the eastern coastal regions, strengthen the application of modern digital technology to traditional industries, encourage enterprises to carry out digital technology innovation and digital reform, and continuously explore new dynamics of economic growth while trying to avoid the loss of factors.

Third, at the market environment level, the impact of the digital economy on GTFP is more significant in regions with a better market environment, so the government should formulate corresponding policies, laws and regulations to create a good market environment and development space for the development of the digital economy (Gao et al., 2022). In terms of technological innovation, the impact of the digital economy on GTFP is more significant in regions with less technological innovation, so the government should play the role of a "guide," and such regions should invest more in digital technology, accelerate the construction of digital infrastructure, and provide the foundation for the development of the digital economy. Actively promote the development of the digital economy (Jia et al., 2022).

6.3 Limitations

First of all, affected by the objective factors of different statistical indicators and incomplete statistical data, this paper only collected the relevant data of 30 provinces (municipalities and autonomous regions) in China from 2011 to 2020, and the data collection year span was short. Secondly, the digital economy is in a high-speed development stage, with the development of economy, it may show new development characteristics, which need to be included in the index system of digital economy development for measurement.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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