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Original Research

A Research on the Development of Digital Economy on Green Total Factor Productivity Changes

Reyihan Aihemaiti[1], Li Honghan[2*], Mu Yanru[1]

[1]Urumqi Vocational University, China
[2] Hua Xia Bank Co., Limited, China

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Abstract

The transformation of China's economic development mode depends on the high-quality development of the digital economy industry, and the proposal of the concept of green development provides a new direction for promoting the digital economy to promote the upgrading of China's industrial structure. Based on the data of 290 prefecture-level cities in China from 2011 to 2018, this paper analyzes the impact of digital economy development on green total factor productivity (GTFP) through the fixed effect model. The results show that the development of the digital economy significantly promotes GTFP, and the results are still valid after a series of robustness tests. The development of the digital economy has heterogeneous effects on GTFP, especially in the central and western regions, regions with a low productivity index, and regions with a low industrial structure level. This study provides a useful reference for cities to use the digital economy to promote the development of green economies.

Keywords: digital economy, green total factor productivity change, innovative efficiency, optimal allocation

Introduction

Since the reform and opening up, China's economy has achieved world-renowned results, with an average annual GDP growth rate of 6.6% from 2010 to 2022, accompanied by the impact of the epidemic and China's GDP growth rate of 3% between 2022-2023. Despite the complexity, severity, and uncertainty of China's economic development environment, under the efforts of all parties, China's economy still maintains a stable and rising trend. However, the rising rate of economic development has also brought about a series of environmental problems, such as massive energy consumption in industrial production and environmental pollution caused by excessive carbon dioxide emissions. Therefore, economic development is not only the pursuit of GDP growth, but also requires more consideration of reasonable energy consumption as well as industrial emissions. To ensure stable economic growth, it relies not on high energy consumption and high pollution industry sustained output, but on the need to establish the concept of green development and promote a green economy and green society synergy. For the rigid constraints that limit the quality of economic development - environment as well as resources - we need to incorporate green sustainability into total factor productivity and improve green total factor productivity.

*e-mail: 4918016@qq.com

Green Total Factor Productivity (GTFP) refers to the consideration of resource consumption and environmental pollution as one of the indicators in the total factor productivity measurement system to evaluate China's industrial development and economic growth, and the "Green Total Factor Productivity" oriented economic development model takes into account the reasonable consumption of energy and resources and the reduction of environmental pollution while guiding economic development. The development of the green concept and the GTFP-oriented development model suppress the impulse of local governments to pursue GDP and increase the endogenous motivation to reduce energy and resource consumption, energy conservation, and reduce emissions, as well as promote healthy competition among local governments. Oriented toward "green total factor productivity", it is important to promote the high-quality development of our economy.

With the rapid rise and growth of new technologies, industries, formats, and models, the influence of the digital economy has expanded from a single enterprise or industry to a comprehensive change in the whole economy. At the micro level, the traditional governance mode of enterprises is facing the challenge of the digital economy, which brings not only technological innovation to enterprises but, more importantly, the optimization of enterprise operation and management through digital technology and the improvement of management efficiency and performance [1]. From a macro perspective, the promotion of the digital economy has narrowed the urban-rural gap and the income difference between the eastern and western regions, created a good employment environment, and improved the number and quality of employment [2]. GTFP plays a positive role in the development of the digital economy. However, how to improve GTFP through the digital economy and the differences in GTFP in different regions driven by the digital economy still need further research. In this regard, this paper uses the SBM model to measure the GTFP of 290 prefecture-level cities in China and the fixed effect model to analyze the impact of digital economy development on GTFP.

The main contributions of this paper are as follows: First, based on the perspective of industrial digitalization and digital industrialization, this paper selects 24 indicators to systematically measure the development level of the digital economy, which is more accurate and reasonable than the previous literature. Second, this paper analyzes the development of GTFP from the perspective of the digital economy and studies its influencing factors, which enriches the relevant theories of the digital economy and green development. Thirdly, this paper evaluates the impact of the development level of the digital economy on the change of GTFP from the perspective of regional development characteristics and the heterogeneity of industrial structure, which provides a policy basis for local governments to formulate a digital economy and promote green development.

The remaining chapters of this paper are arranged as follows: The second chapter is a literature review. Chapter three is the research hypothesis; the fourth chapter is the research design; the fifth chapter is the empirical results and analysis; and the sixth chapter is the conclusion and policy recommendations.

Literature Review

Research and calculation of GTFP have always been hot topics for scholars at home and abroad. However, most scholars' research focuses on the action mechanism of GTFP on the transformation of industrial development modes and the impact of environmental institutions on GTFP. In terms of industrial production, based on the analysis of production data for 36 industrial sectors in China from 2001 to 2010, the literature applied the SBM efficiency measurement model and the Malmquist-Luenberger productivity index and found that the decline of total factors of green production had a negative impact on industrial economic growth [3]. Literature used the SBM directional distance function and Luenberger productivity index to analyze the industrial GTFP of 30 provinces in China from 2000 to 2012. It is concluded that environmental institutional planning has a significantly positive effect on GTFP [4]. For the manufacturing industry, the literature conducted an empirical test on the GTFP of 27 manufacturing industries in China from 2002 to 2010 by using the SBM model [5]. This empirical finding provides evidence of a significant positive relationship between environmental institutions and the realization of GTFP in the manufacturing sector.

In terms of agriculture, the literature used the global GML index to measure the growth rate of agricultural GTFP [6]. On the other hand, the literature explored the regional differences in China's agricultural green production and the influencing factors on production development by analyzing the production function technology, GIS, and Theil index [7]. The literature used SBM directional distance function analysis and Malmquist-Luenberger index theory to study the influence mechanism of the digital inclusive finance index on agricultural GTFP and believed that the development of digital inclusive finance plays an important role in promoting the development of rural areas. Total factor productivity gains can be achieved [8].

In terms of spatial structure, the literature used the SBM directional distance function and the Malmquist-Luenberger index method to calculate the panel data for 30 provinces in China for 13 consecutive years [9]. Through the construction of different spatial structures in the middle, west, and east, it has been found that the local spatial correlation of agricultural GTFP has gradually increased over time. Literature conducted in-depth research on the provinces with high efficiency by comparing and analyzing the differences in production efficiency of various spatial green production, and the provinces with high efficiency are mainly distributed in the southeast coastal and western regions, while the provinces with the lowest efficiency are concentrated in North China [7]. Based on the EBM function and Malmquist-Luenberger index, the literature decomposed the differences in GTFP in central and western China, indicating that the speed of green innovation in the eastern region is significantly higher than that in the central and western regions, and agricultural green efficiency plays a restricting role [6].

In terms of the digital economy's promotion of GTFP, by studying the role of the digital economy in TFP, the literature found that the development of the digital economy in the eastern region is much higher than that in the central and western regions, and there are obvious differences in the transmission paths of the three regions [10]. Literature calculated the industrial GTFP of all provinces in China by using the SBM-ML model and then studied the influence mechanism of the digital economy on industrial green production efficiency by constructing the digital economy indicators [11]. There is an obvious positive effect between the two. In terms of regional total factor productivity, the development of the digital economy has a stronger and more significant effect on industrial productivity and enterprise intelligence transformation in the central and western regions. On the whole, the construction of national comprehensive experimental areas for big data has significantly improved regional TFP [12].

Therefore, many scholars in academia have conducted in-depth research on GTFP and its influencing factors. However, due to the limitations of the measurement of GTFP and the measurement of the development level of the digital economy, there are still problems such as unreasonable index construction, incomplete index construction, and inaccurate results, and there are relatively few studies on the impact of the digital economy on GTFP. This paper will analyze the following three aspects: First, GTFP is measured based on the SBM model. Second, this paper measures the development level of the digital economy in Chinese cities based on digital industrialization and industrial digitalization. Thirdly, the logical relationship between the two is studied from the perspective of the digital economy in relation to the development of GTFP. Fourthly, this paper evaluates the heterogeneous impact of the digital economy development level on GTFP from the perspective of regional development characteristics and the heterogeneity of industrial structure.

Theoretical Analyses

The green development of cities needs to rely on the improvement of GTFP, which depends on the resource allocation effect, network effect, and innovation spillover effect of the digital economy.

From the perspective of the "resource allocation" effect of the digital economy, the development of the digital economy optimizes the overall resource allocation of the region and then improves green factor productivity. The improvement of urban construction level depends on the effective allocation of resources, while the development of the digital economy enables the government to efficiently allocate and accurately connect relevant assets and effectively supervise the matching, transaction, investment, and circulation of tangible assets, and intangible assets so as to activate all kinds of resources in the industrial development of the region and release the core value of resources. The search cost and transaction cost of factors can be reduced to improve allocation efficiency and promote resources in all fields of the industry and all links between enterprises [13]. With the improvement of resource allocation efficiency and the transformation of allocation mode, the direction of economic development has gradually changed from being driven by factors such as land and labor to being driven by scientific and technological innovation and by low-carbon and green secondary and tertiary industries [14]. In addition, digital allocation can provide a regulated, managed, market-oriented, and independent platform for regional resources, improve the market-oriented circulation level of resources, reduce the negative externalities of public resources and public goods, and effectively improve the relationship between supply and demand, which is conducive to the formation of economies of scale, thus promoting GTFP.

According the "network effect theory" of the digital economy, the development of the digital economy is conducive to improving regional production efficiency. Different from the development mode of traditional economies, digital economies can effectively serve enterprises in a region and promote information exchange and business cooperation among enterprises by taking advantage of the rapid transfer of information technology and the shortening of geographical distance. The development of the digital economy can promote the reorganization of enterprise resources, technological progress, and further industrial upgrading and transformation. Through the data of the enterprise questionnaire survey, it was found that companies or enterprises with information technology can enhance their innovation abilities to a greater extent and release more potential value [15]. In addition, the digital economy promotes economies of scale in industries within a region by improving the allocation efficiency of physical and human resources, thus significantly improving regional production efficiency. The development of digital technology not only promotes the improvement of the innovation ability of the environment, resources, and personnel among regions, but also realizes the synergistic effect. At the same time, creating a good digital economy atmosphere and enhancing innovation capacity can promote the agglomeration of innovation resources [16], thus improving urban GTFP.

From the perspective of the innovation spillover effect of the digital economy, the development of the digital economy promotes urban R&D innovation and then improves GTFP. The changes in economic forms brought about by the development of the digital economy have promoted the transformation of enterprises, industries, and regional innovation ecosystems and further promoted the improvement of urban R&D innovation capabilities [16]. At the level of enterprise innovation, the application of digital technology strengthens the innovation chain of enterprises and extends the industrial chain, enabling enterprises to break through technological bottlenecks and use new technological means such as artificial intelligence, privacy computing, digital twin, human-computer interaction, and quantum computing, so as to improve the green production efficiency of enterprises [17]. In terms of industrial innovation, the development of the digital economy has promoted the upgrading of manufacturing technology, the development of emerging industries, and improved industrial production efficiency and management efficiency [18]. The development of the digital economy makes knowledge accumulation and information dissemination no longer limited by time and space; it promotes the integration and processing of information, and different degrees of information accumulation exist in the process of different individuals sharing and disseminating information, thus promoting social and technological progress and improving GTFP.

Based on the above analysis, this paper puts forward the following hypothesis:

H1: The development of the digital economy is conducive to improving urban GTFP.

Research Methodology

Research Methodology

In order to analyze the relationship between the digital development level and GTFP, this paper constructs the following model:

$$GTFP_{it} = \alpha + \beta digital_{it} + \gamma CVs_{it} + \sum regionfe + \sum yearfe + \varepsilon_{it}$$

The explained variable $GTFP_{it}$ denotes the change in green total factor productivity in year t in prefecture-level city i, and the explanatory variable $digital_{it}$ denotes the level of digital economy development in year t in prefecture-level city i. CVs are the control quantities in this paper, which include: urbanization level $urban_{it}$, fiscal expenditure $fiscal_{it}$, foreign investment fdi_{it}, road area per capita $road_{it}$, financial development level fin_{it}, science and technology development level $tech_{it}$, education level edu_{it}. To prevent the emergence of economic fluctuations or the implementation of corresponding policies and the emergence of unexpected events that lead to changes in the factors and thus have an impact on the experimental results, this study strictly controls for time and region, incorporating time fixed effects $\sum yearfe$ and region fixed effects $\sum regionfe$. The random disturbance term is represented by ε_{it}.

Explained Variables: Measurement of Green Total Factor Productivity Change

In this study, the indices of all-green factors of production are calculated by combining the DEA-Malmquist-Luenberger index (ML index) with the SBM efficiency measurement model. The traditional ML index model tends to cause discontinuity in technological progress, and the index is in the form of a geometric mean, which has the problem of linear programming infeasibility in measuring the distance function (DDF) across the period direction, so this paper uses the SBM index model to measure GTFP. The traditional ML exponent is defined as:

$$ML^{t,t+1} = \left[\frac{1+D^t(x^t,y^t,b^t;g)}{1+D^t(x^{t+1},y^{t+1},b^{t+1};g)} \times \frac{1+D^{t+1}(x^t,y^t,b^t;g)}{1+D^{t+1}(x^{t+1},y^{t+1},b^{t+1};g)}\right]^{\frac{1}{2}}$$

$ML^{t,t-1}$ Denotes the change in GTFP under the set of production technologies for a single period cross-sectional decision unit. D^t denotes the SBM directional distance function based on the set of contemporaneous production possibilities, x^t and x^{t+1} denote the input vectors for each prefecture-level city in periods t and t+1, respectively. y^t and y^{t+1} denote the expected output vectors of each prefecture-level city, respectively. b^t and b^{t+1} denote the non-desired output vector of each prefecture-level city, respectively.

Literature defines the application of the SBM efficiency measurement model for non-desired outputs to analyze the relationship between inputs and outputs and pollution and to achieve the evaluation of efficiency in order to solve related problems [19]. The setting of the SBM model considering the undesired output, based on specific values is as follows:

$$MIN\rho^* = \frac{1-\frac{1}{n}\sum_{i=1}^{n} s_i^- / x_{i0}}{1+\frac{1}{u+v}\left(\sum_{j=1}^{u} s_j^g / y_{j0}^g + \sum_{j=1}^{v} s_j^b / y_{j0}^b\right)}$$

$$s.t.x_0 = X\lambda + s^-, y_0^g = Y^g\lambda + s^b, \lambda, s^g, s^b, s^- \geq 0$$

where $s^-\in R^n$ and $s^b\in R^v$ denote the value of the input and the value of the output, respectively, when the value is higher, while for $s^g\in R^u$ denotes a shortfall compared to the non-desired output. The expected output is not sufficient. The numerator and denominator of ρ* then represent the inputs and outputs in the items decided in the production process, respectively, versus the average proportion that can be scaled down or expanded under

Table 1. Descriptive statistics for measuring each of the GTFP indicators.

	Classification of indicators	Specific indicators	Unit	Indicator Description	Data sources
Inputs	Labor input	Number of employees at the end of the year	million people	Number of employees at the end of the year by city	(China Environment Statistical Yearbook) (China Urban Statistical Yearbook) and various local statistical yearbooks
	Capital Investment	Capital stocks	Billion	Using the perpetual inventory method to calculate the city's actual capital stock with a discount rate of 9.6%, the initial capital stock is measured by dividing the city's total actual fixed asset investment in 2011 by 10%	
	Electricity consumption	Electricity consumption	Wattage	Energy input (E) is selected as the total inter-provincial energy consumption as the base data of energy input, and the proportion of the city's total social electricity consumption to the province it belongs to is converted to the city's energy input data.	
Outputs	Expected output	Real Gross Regional Product	Billion	Real urban GDP (obtained by deflating the GDP deflator of the corresponding province using 2011 as the base period)	
	Non-desired outputs	Sulfur dioxide Total Emissions	ton	Sulfur dioxide emissions by prefecture-level city	

the current technological development, so that the values can be compared and analyzed.

According to the existing literature on GTFP measurement and the actual production process, the values of inputs are set as labor, capital stock, and energy production. The desired output is set as the gross product as well as the pollution emissions made. All indicators in terms of prices were set in 2011 as the base period to ensure the comparability of the data. The selection of specific indicators and descriptive statistics is shown in Table 1.

Definition of Key Variables and Data Sources

Core Explanatory Variables: The Digital Economy Development Index

In this paper, the level of digital economy development is analyzed through indicators, and the main indicators are divided into two dimensions: digital industry development and industrial digital development indicators. The following 24 measurement indicators are selected, and the basic data sources of the indicators are listed in Table 2.

The index measures the development level of digital industrialization from an input-output perspective, referring to the Digital Economy Index (DEI) constructed by the China Academy of Information and Communication Research (CAICR) and a literature study on the development level of informatization, and the mobile telephone exchange capacity and the length of long-distance fiber optic cable lines are selected to measure the level of basic telecommunication construction [20]. Based on the output perspective, this study selects the level of electronic information manufacturing and the scale of software and services as being closely related to the development of the digital economy, which directly reflects the efficiency brought about by the information industry. Thus, this study measures the level of Internet development from the perspective of Internet technology development as well as application. Based on the consideration of data availability, this study selects the number of web pages, domain names, and Internet penetration rate to measure the breadth of regional Internet development and selects Internet broadband access ports and access users to measure the level of Internet broadband construction. The higher the Internet development indicators, the better the construction of the Internet development platform in the region, the more extensive the Internet community, and the more flourishing the digital economy.

Compared with the analytic hierarchy process and other methods used in previous literature, the entropy weight method can avoid the influence of subjective factors on the weight and objectively measure the importance of indicators. The core idea of this study is to use the entropy method based on the standardization of indicators, and to assign weights according to the amount of information reflected in the degree of change of the measured indicators, which reduces the influence of subjective human factors on the weights of indicators, the traditional entropy method can only assign weights to cross-sectional data, in order to facilitate the comparison of the digital economy in time and space, the panel data study method is selected so as to achieve the evaluation

Table 2. Digital Economy Development Level Indicator System.

Objective	Tier 1 Indicator	Secondary Indicator	Measurement Metrics	Unit	Data source
Level of digital economy development	Digital Industrialization	Basic telecommunications construction level	Mobile telephone exchange capacity	million households	National Statistics Bureau
			Long-haul fiber optic cable line length	Kilometers	
		Electronic Information Manufacturing Levels	Integrated Circuit Production	Billion pieces	
			Mobile communication handheld production	Million units	
			Microcomputer equipment production	Million units	
		Software & Services Scale	Text message service volume	Billion bars	China Urban Statistical Yearbook
			Number of employees in the information transmission, computer services, and software industry	Million people	
			Software business revenue	Billions of dollars	eps database
			Number of information technology and e-commerce enterprises	Individuals	
		Internet Development	Number of web pages	Million	National Statistics Bureau
			Number of domain names	Million	
			Internet broadband access port	Million	
			Internet broadband access subscribers	Million households	
			Internet penetration rate	%	
	Industry Digitization	Digitalization of Agriculture	Value added of agriculture, forestry, animal husbandry, and fishery	Billions of dollars	
			Electricity consumption in rural areas	Billion kWh	
		Industrial Digitalization	Industrial value added	Billions of dollars	
			The proportion of new product sales revenue to the main business revenue of industrial enterprises above the scale	%	
			Expenditure on technical transformation of industrial enterprises above the scale	Million yuan	China Science and Technology Statistical Yearbook
			Expenditure on the introduction of technology in industrial enterprises above the scale	Million yuan	
		Digitization of the service industry	Number of people with Internet access	Million people	National Bureau of Statistics
			Tertiary industry value added	Billions of yuan	
			Express delivery	Million pieces	
			The telecommunications industry's main business income	Billions of yuan	China Tertiary Industry Database

of efficiency, and the overall measurement results of the digital economy development are horizontally and vertically comparable, the main processing of the data is as follows.

In the initial step, each measure x_{tij} of the level of digital economy development is standardized using the extreme difference method:

$$y_{tij} = \frac{x_{tij} - \min\left(x_{tij}\right)}{\max\left(x_{tij}\right) - \min\left(x_{tij}\right)}$$

t denotes the year, i denotes the province, and j denotes the measure, x_{tij} and y_{tij} denote the original and standardized digital economy development level measures, respectively, and max(x_{tij}) and min(x_{tij}) denote the maximum and minimum values of x_{tij}, respectively.

In the second step, the information entropy of each indicator y_{tij} of the level of development of the digital economy e_j:

$$e_j = -\frac{1}{\ln(m \times n)} \sum_{t=1}^{k} \sum_{i=1}^{n} \left[\frac{y_{tij}}{\sum_{t=1}^{m} \sum_{i=1}^{n} x_{tij}} \ln \left(\frac{y_{tij}}{\sum_{t=1}^{m} \sum_{i=1}^{n} x_{tij}} \right) \right]$$

In the third step, the weights w_j of the test data y_{tij} in the digital economic development model are calculated from the data:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{k} (1 - e_j)}$$

In the fourth step, the numerical development levels of different regions are calculated:

$$digital_{ti} = \sum_{j=1}^{k} w_j \times \frac{y_{tij}}{\sum_{t=1}^{m} \sum_{i=1}^{n} x_{tij}}$$

Control Variables

The control variables are selected to measure the level of urbanization, fiscal expenditure, road area per capita, foreign investment, level of financial development, level of scientific and technological development, and level of education. Of these, the level of urbanization $urban_{it}$ is measured by the share of the urban population at the end of the year, and as urbanization continues, the continuous development of technology drives the increase in total factor productivity [21]. Fiscal expenditure $fiscal_{it}$ is expressed as per capita local fiscal general budget expenditure, and scientific and effective fiscal policy is an important prerequisite and basic requirement for promoting high-quality economic development [22]. Effective implementation of fiscal policy can have an impact on economic growth from the perspectives of monetary policy, employment environment, macroeconomic operating conditions, and environmental regulation [23], so effective fiscal policy can have an impact on the green total factor productivity index to a certain extent. Road area per capita $road_{it}$ is defined by the urban road area per capita, which to a certain extent reflects the size of the city and the degree of infrastructure development, while the better the regional infrastructure development, the more it can promote the growth of green total factor productivity. Outward investment fdi_{it} is expressed as the total investment of foreign invested enterprises. In addition to introducing cutting-edge production technologies and better management concepts, foreign investment also brings higher pollution emissions, both of which may affect green total factor productivity changes from opposite directions, while outward investment can promote China's economic growth in terms of boosting employment and consumption, and therefore the control variable of foreign investment is added [24].

The level of science and technology development is expressed in terms of local expenditure on science and technology, which can reflect the strength of regional investment in local science and technology development. The increase in the level of science and technology development will lead to the improvement of production technology, and the increase in the level of technology has a greater promotion effect on the total factor productivity, which will lead to the further improvement of green productivity and the growth of the level of change. The level of education is represented by regional spending on investment in education, and the higher the level of regional education, the stronger the ability to learn and explore advanced technology in the economy, and the same human input can generate greater utility, which in turn promotes the growth rate of green total factor productivity [23].

To prevent heteroskedasticity due to inconsistency in the order of magnitude of variables from bringing estimation bias to the model and to clarify the elasticity coefficients of change in the variables, the aggregate indicators are treated as logarithms in the empirical regressions. Descriptive statistics for the variables are presented in Table 3.

Data Sources

In order to achieve the scientificity and continuity of the sample data and ensure the authenticity of the experimental results, through the division and adjustment of regions and the absence of relevant data, the research data selected in this paper are the panel data of a total of 290 prefecture-level city-level data from 30 provinces in China from 2011 to 2022 (except Tibet, Hong Kong, Macao, and Taiwan), whose data sources are authentic and reliable, and the data are The data were obtained from the China City Statistical Yearbook, the China Science and Technology Statistical Yearbook, and the EPS database. For the missing data, the linear difference method is used to make up for the missing data to ensure the reliability of the experimental results.

Empirical Results

Reference Regression

Table 4 shows the regression results of the impact of digital economy development on GTFP. For the study of the relationship between the level of development of the digital economy and total factor productivity, the chosen

Table 3. Descriptive statistics of the main variables.

Variable	Sample size	Average value	Standard deviation	Minimum value	Maximum value
GTFP	2304	1.014	0.029	0.961	1.060
digital	2304	0.094	0.052	0.017	0.819
urban	2304	3.997	0.224	3.371	4.495
fiscal	2304	9.137	0.550	7.791	10.450
road	2304	14.780	4.653	4.040	26.200
fdi	2304	6.390	1.404	3.136	9.880
fin	2304	1.609	0.739	0.644	5.313
tech	2304	13.520	1.809	8.623	17.860
edu	2304	13.390	0.813	10.650	14.660

method is the Ordinary Least Squares (OLS) method for calculation. Column (1) of Table 4 strictly controls for time variables, and the results of the experimental study indicate that the level of digital economy development has some positive impact on green total factor productivity with an estimated coefficient of 0.2353. Preventing regional differences from influencing the experimental results by controlling for region, the regression coefficient was also significantly positive at the 1% significance level (t=5.69). In addition to controls for time and province fixed effects, this study also controls for the aforementioned urbanization level, fiscal expenditure, road area per capita, foreign investment, financial development level, science and technology development level, and education level variables to avoid other factors interfering with the results. The results are shown in column (3); the regression coefficient of digital economy development is 0.2527, and the regression coefficient decreases after adding the control variables, indicating that the control variables have influenced the model to some extent, but the regression coefficient is still significantly positive, which indicates that there is a positive promoting relationship between the level of digital economy development and green total factor productivity, and this relationship is positive; an increase in the level of the digital economy, and factor productivity increases accordingly. All of the above results support the expected hypothesis that the increased level of digital economy development can, to some extent, promote green economic growth and improve the green total factor productivity index. This is contrary to the result of the literature that the digital economy has no impact on GTFP [25]. The reasons may be as follows: first, compared with previous literature, this paper often uses 4-5 indicators to measure the development level of the digital economy, which is more abundant and accurate; Secondly, the GTFP in this paper takes more into account the undesirable

Table 4. OLS Regression of Digital Economy Development and Green Total Factor Productivity Index.

	(1)	(2)	(3)
	GTFP	*GTFP*	*GTFP*
digital	0.2353***	0.3317***	0.2527***
	(5.5393)	(5.6888)	(4.4451)
_cons	1.0008***	0.9525***	1.6473***
	(49.8743)	(41.5450)	(3.0129)
CVs	False	False	True
region	False	True	True
year	True	True	True
N	360	360	360
adj. R^2	0.105	0.770	0.821
F	4.5232	30.3217	35.3931

Note: p indicates significance level, * p<0.1, ** p<0.05, *** p<0.01 (same below), t-statistic in parentheses.

output of pollution emissions. The reasons why the digital economy promotes China's urban green total productivity are as follows: The digital economy optimizes the efficiency of resource allocation and improves the efficiency of resource allocation between cities; The digital economy promotes the spillover of knowledge [26], making green technology innovation applied to industrial transformation [27]; The digital economy promotes economies of scale of industries in a region [16, 28], thus significantly improving urban GTFP.

Robustness Test

Based on the analysis of the above results, the increase in the level of digital economy development has a positive contribution to green total factor productivity, and the results are still significant after adding the fixed effects of time and region. However, the internal problems of the model are still very obvious. First of all, in terms of measurement error, the relationship between digital economy development and green total factor productivity is calculated by the data in this study, and the results of the data analysis between the two are basically consistent in the academic literature. In the second place, there are omissions in the control of explanatory variables. In the process of experimental research, it is often impossible to find all explanatory variables, and while the model is constructed, a full comparative study is conducted for all explanatory variables to reduce the omitted variables. Finally, in the model, the explanatory variables can affect the other variables to focus on the situation. Regions with better digital level development also require relatively less manpower; physical capital inputs can achieve the same output as high inputs; and the application of advanced technologies such as big data and artificial intelligence reduces pollutant emissions and non-essential energy inputs to some extent, thus increasing green productivity. However, the relatively high level of green total factor productivity is related to the level of innovation in the region, and the level of advanced technology is also more widely applied. The concentration of digital industries can achieve an increase in the level of digital economic development, and the higher the level of digital development, the reverse causality phenomenon mentioned above will occur. In order to avoid the above problems from affecting the accuracy of the empirical test, this paper achieves the stability of the experiment by using the following method for simulation.

Lagged Variable

The above analysis of the level of digital economy development explores the factors influencing green total factor productivity. Although there is a causal relationship between the two, there is also the possibility that regions with higher levels of green total factor productivity pay more attention to the development of the digital economy, which leads to digital economy development, i.e., there may be an endogeneity problem of reverse causality in the model.

According to the analysis of the data results in column (1) of Table 5, the relatively lagging level of digital economy development with a technology level above 1% shows a positive correlation of impact. This also justifies the level of development of the digital economy, which plays a positive role in promoting green total factor productivity, and therefore, in the study of the intrinsic problems present in the model, the resulting, results still show a positive correlation. A one-period lag is also done for the control variables in the paper to optimize the spurious regression of the model due to the control variables, as shown in column (2) of Table 5. According to the experimental results, the regression coefficient is determined at 1% when the level of digital economy development shows an upward trend, at which time the model has stability.

Instrumental Variable

This paper uses the instrumental variable method to obtain the optimization strategy for the internal problems and analyzes the changes in green TFP from the perspective of the development of the digital economy [29]. The development of Internet technology has also gone through a certain process. The primary stage starts with telephone line dial-up access (PSTN), so this document argues that provinces with relatively high penetration of fixed-line telephones also have relatively high Internet technology, a relatively good level of development, and a better degree of digital economy development. So the number of fixed telephones can be used as the data for the study to analyze the requirements of the relevance of the level of development of the digital economy, but with the continuous progress of the level of economic development, the total factor productivity is also affected, and the impact factors are also very complex. The current requirements for green development, through the fixed telephone statistics, make it difficult to study the impact factors of total factor productivity. Based on this background, this study selects the number of fixed-line telephones in each province in 1984 as a statistical tool to realize the study of the numerical level. In the course of the experiment, the model would have been difficult to build if the landline telephone was simply chosen as the instrumental variable, so drawing on the findings of the literature [30], the number of telephones in 1984 was compared with the cost of Internet investment in the previous year to achieve an interaction as the instrumental variable in the experimental study. The two-stage least squares (2SLS) method was used to test the endogeneity of the model, and the regression results are shown in Table 6.

Column (1) of Table 6 indicates the regression results without adding control variables and without controlling for time and area effects; column (2) indicates the

Table 5. Lagged explanatory variables, control variables, and test results.

	(1)	(2)
	GTFP	*GTF* reverse causation *P*
digital1	0.2451***	0.2927***
	(3.8058)	(4.9307)
urban	0.0858	
	(0.8201)	
fiscal	0.1084**	
	(2.4400)	
road	-0.0086***	
	(-3.7648)	
fdi	-0.0813***	
	(-6.2617)	
fin	-0.0309**	
	(-2.0506)	
tech	0.0079	
	(1.2131)	
edu	-0.0982**	
	(-2.0128)	
urban1		0.0809
		(0.8436)
fiscal1		0.1139***
		(2.9546)
road1		-0.0096***
		(-4.2080)
fdi1		-0.0918***
		(-7.7030)
fin1		-0.0477***
		(-2.6631)
tech1		0.0144**
		(2.2524)
edu1		-0.1219***
		(-2.6553)
_cons	1.5264**	1.8446***
	(2.5292)	(3.4040)
region	True	True
year	True	True
N	330	330
adj. R^2	0.853	0.866
F	41.6170	46.3993

regression results without adding control variables but controlling for time and area; and column (3) indicates the regression results with adding control variables and controlling for time and area. The Kleibergen-Paap rk LM statistic approach yields experimental results with a significant level of correlation between the two at 1% of the data results, and the variables are correlated with the endogenous explanatory variable in the model, the level of digital economic development, and the instrumental variables are set reasonably. The results of the Kleibergen-Paap rk Wald F-statistic test showed that the instrumental variable passed the test of weak identification in the experiment, that is, its performance was highly significant, and according to the analysis of the regression results, the level of digital development, among the endogenous problems present, still has a relatively important and positive effect on green total factor productivity.

Heterogeneity Analysis

First, exploring the influence of different regions on green total factor productivity changes can compare the development advantages among different regions and provide a theoretical basis for the government to formulate development policies related to the digital economy and private capital to invest in related digital technologies. Second, the level of GTFP changes varies widely across the country, and what is the difference in the impact of the level of digital economy development on GTFP at different levels? Is the positive effect of the level of the digital economy on the change in green total factor productivity more pronounced in the more developed regions or in the less developed regions? Further analysis is needed. Finally, the specific impact of the level of development of the digital economy on green total factor productivity is studied by analyzing the differences in the industrial structure.

Heterogeneity in Regional Development

From Table 7, regional grouping results can be obtained. The central and western regions for the level of digital economy development in the data level performance are obvious; in the digital economy and green total factor productivity related data, a comparative analysis can be found that the level is a growing trend; the eastern region is not obvious. This phenomenon is influenced by many factors, such as the layout of the region and the planning of the development stage. Compared with the western region, the economic development in the eastern region is relatively good, and the speed of digital economy development is also fast, so the marginal benefit in the process of digital economy development is relatively low, which is consistent with the results of the literature [31]. With the development of the region and the continuous implementation of policies, the state has vigorously supported the development of the western region and favored policies and resources

Table 6. Regression results for instrumental variables.

	(1)	(2)	(3)
	GTFP	*GTFP*	*GTFP*
digital	0.2663***	0.6723***	0.6565***
	(3.4103)	(4.3090)	(2.8910)
_cons	0.9993***	0.8751***	1.3929**
	(50.0344)	(21.8697)	(2.4647)
CVs	False	False	True
region	False	True	True
year	True	True	True
Kleibergen-Paap rk LM	37.545***	20.030***	17.229***
Kleibergen-Paap rk Wald F	59.117	59.085	20.883
	[16.38]	[16.38]	[16.38]
N	360	360	360
adj. R^2	0.104	0.745	0.792

Table 7. Heterogeneity analysis results.

	Regional groupings		GTFP groupings		Industry Structure Grouping	
	East Division	Central and Western	High	Bottom	High	Bottom
	GTFP	*GTFP*	*GTFP*	*GTFP*	*GTFP*	*GTFP*
digital	0.0584	0.3836**	0.0627	0.7257***	0.1232*	0.6267***
	(1.3378)	(2.1311)	(1.3715)	(4.5294)	(1.7142)	(5.4962)
_cons	-0.1996	0.3137	-0.7304	2.0367***	0.7992	1.4522*
	(-0.2664)	(0.4478)	(-1.0413)	(3.1983)	(1.0489)	(1.9061)
CVs	True	True	True	True	True	True
region	True	True	True	True	True	True
year	True	True	True	True	True	True
N	132	228	180	180	180	180
adj. R^2	0.894	0.792	0.829	0.726	0.840	0.891
F	38.9730	24.3259	23.8010	13.8436	22.9353	35.9321

to support less developed regions [32]. At the same time, because the development of the digital economy in the eastern region has reached saturation, its role in promoting it is not obvious. In addition, the current situation of China's digital economy development also shows this point; that is, China's big data platform has been gradually built and improved in the southwest region (such as Guizhou), and the eastern region has also actively helped the western region promote the development of the digital economy, realize the planning layout, and expand the development scale, which has significantly improved the GTFP in the western region.

There is Heterogeneity in the Level of Green Total Factor Productivity Changes

There is a high and low classification of green total factor productivity level, and this document refers to the literature to use the median of the index for measurement [33]. That is, if the region GTFP value is greater than the medium level of the year, it is determined to be a highly productive region, and if the value is less than the medium level, it is a low-productivity region. The results of the relevant studies show that the development of the digital economy has a positive impact on the level of the green total factor productivity index, but this impact is not evident in regions with relatively high productivity, and this promotion is more evident in regions with relatively low productivity again. The results obtained from the test are consistent with the regional level grouping, which means that the eastern region is relatively higher in the total factor productivity statistics, than the western region. The positive effect is more pronounced in regions with more room for development.

Heterogeneity of Industrial Structure Exists

In this study, we start from the perspective of differences in industrial structure, and grouping is also based on the median according to the weight of value added of different industries. If the industrial structure of a region is greater than the median level of its year, it is a region with a higher share of tertiary industry; otherwise, it is a region with a lower share of tertiary industry. Generally speaking, the rapid economic development is accompanied by an increase in the proportion of tertiary industries in the region, while driving the development of other industries. Table 7 The analysis of the industrial structure results shows that the development of the digital economy has a positive impact on green total factor productivity, especially in regions with a relatively high share of tertiary industries. However, there are differences in the coefficient data derived, which means that there is an exercise between the development of the digital economy and industrial structure. The effect of total factor productivity enhancement is more obvious in regions with relatively low industrial structures. This difference is due to the relatively low share of service industries in regions with a relatively low industrial structure, the relatively large share of industry, the low impact of the digital economy in traditional industries, and the improvement of traditional industries, which can reflect the cure effect that the digital economy is said to bring to achieve economic growth [34, 35]. At the same time, the economic structure of the expanding share of the service sector is an important manifestation of the change in the de-industrial structure. The higher the proportion of tertiary industry, the better the economic development. The digital economy development is also relatively good, and its application and popularity are also relatively simple, so the positive effect on green economic growth is not obvious compared to the lower industrial structure of the region.

Conclusions and Policy Recommendations

Conclusions

In recent years, with people's attention to climate and environmental risks, the pursuit of urban economic growth has become increasingly green, and improving GTFP is at the core of urban green development. How to use the development of the digital economy to promote urban GTFP is not only related to the development of the urban green economy, but also an important demand for the government to promote the integration of the digital economy and the green economy. This paper uses the double fixed effect model to test the impact of digital economy development on urban GTFP. The main conclusions are as follows:

First, the development of the digital economy has played a positive role in improving GTFP, and this positive effect of economic growth is sustainable. After a series of robustness tests, such as the instrumental variable method, the results are still valid.

Second, there is heterogeneity in the impact of digital economy development on GTFP. The development level of China's digital economy is unbalanced, and the impact of the digital economy on GTFP in the eastern region is significantly higher than that in the central and western regions.

Third, the impact of the development of the digital economy on the level of GTFP is positive, but this impact is not obvious in the regions with relatively high productivity, and the promotion effect is more obvious in the regions with relatively low productivity.

Fourthly, the development of the digital economy has a positive impact on GTFP, especially in regions with a high proportion of tertiary industry. In regions with a low proportion of industrial structures, the role of the digital economy in improving TFP is more obvious.

Policy Implications

Based on the findings of this study, the following recommendations are made:

First, cities should vigorously develop the digital economy. This paper shows through experimental research that the development of the digital economy can play a positive role in green total factor productivity improvement, and this role is in line with the concept of green development, and this positive effect of economic growth has a certain degree of sustainability. The digital economy is currently in a high growth stage, and the progress of science and technology industry digitalization has laid the foundation. In recent years, the country has also focused its development on 5G, artificial intelligence, blockchain, high-end chips, and other industries. The transformation of these industries is dependent on the development of the digital economy. The current development stage of China's digital economy has reached a leading level, while digital technology is still relatively limited in its scope of application. If the digital economy can continue to promote green total factor productivity growth, we must focus on the real economy.

The second is to build a regional cyberspace and improve the level of the digital economy. This paper shows through research that there are still many problems with the development level of China's digital economy, and there is an imbalance in internal development, with the development level in the eastern region being significantly higher than that in the central and western regions. Therefore, a regional cyberspace should be established as soon as possible to realize the common development level of the digital economy, to play the driving role of high level regions to low level regions, to realize the effective improvement of the regional digital economy development, and to promote the common development of the central and western regions and the east.

The third is to improve innovation ability. Innovation ability drives the development of digital technology, and to further improve the level of digital technology, we need to improve innovation ability. To achieve innovation-driven technology development, the "14th Five-Year Plan" clearly puts forward the development of digital technology to focus on the chip manufacturing industry, the renewal of operating systems, artificial intelligence, and other key areas. The 14th Five-Year Plan clearly states that the development of digital technology should focus on the chip manufacturing industry, the renewal of operating systems, artificial intelligence, and other key areas, insist on the improvement of innovation ability, expand the application of digital technology, cultivate professional and comprehensive talents, improve the overall innovation ability of the team, and expand the radiation range of the digital field.

The fourth is to conduct sound market data elements and improve the market rules. According to the experimental research results, the improvement of the digital economy development level can realize the optimal allocation of resources, thus leading to the improvement of green total factor productivity. At this time, we should carry out market regulation, sound data elements, and promote the standardization of the factor market, and each local government should reduce unreasonable interventions to prevent hindering the free flow of digital elements among regions.

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Conflict of Interest

The authors declare no conflict of interest.

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