Pol. J. Environ. Stud. Vol. 33, No. 2 (2024), 1251-1265
DOI: *10.15244/pjoes/172849* ONLINE PUBLICATION DATE: 2023-12-04

Original Research

Digital Technology and Green Total Factor Productivity

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Received: 15 July 2023
Accepted: 23 September 2023

Abstract

Along with the rapid development of digital economy and the urgency of green development, more studies focus on the relationship between digital economy and green development. However, the existing research focuses on the impact of digital economy on green total factor productivity, ignoring digital technology, which is a key technology for improving efficiency to achieve green development. Exploring the impact of digital technologies on green total factor productivity helps to understand the impact of digital economic development on green development from an internal perspective of the digital economy. This paper uses an SBM-GML index to measure regional green total factor productivity based on provincial level data and innovatively constructs digital technology indicators based on micro-level ICT patent data in China. Fixed-effects model is used to study the impact of digital technology on green total factor productivity and moderating model is used to examine the moderating effect of capital accumulation. The results indicate that: (1) At the national level, digital technology is conducive to the improvement of green total factor productivity, and the result passes the robustness test. From a dynamic long-term impact perspective, the effect of digital technology development on green total factor productivity is showing an increasing trend. (2) Digital technology's effect on green total factor productivity is heterogenous. The results of the subregional heterogeneity analysis indicate that the effect is greater in the coastal regions and southern regions. The results of the heterogeneity analysis of the external environment indicate that the effect is greater in regions with smaller economies, regions with lower external economic dependence, and regions with lower government fiscal intervention. (3) Capital accumulation has moderating effect in the process of digital technology affecting green total factor productivity which will inhibit the improvement of digital technology development on green total factor productivity. Based on the conclusions, to better utilize the role of digital technology in promoting green development, it is necessary for the government to build a digital technology exchange platform, promote the balanced development of digital technology, and expand domestic demand to reduce the dependence on capital accumulation.

Keywords: digital technology, green total factor productivity, ICT patents, capital accumulation

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Introduction

As a consequence of the ongoing industrial and scientific revolutions, developing nations now have unprecedented chances to "overtake" developed nations [1]. The Internet, cloud computing, and artificial intelligence in particular are integrating with industrial development in developing nations. For developing nations to get to the stage of high-quality development, a new development model has emerged: the digital economy [2]. Digital technologies have an enormous scope of influence and comprehensive coverage as standard general purpose technologies (GPTs), driving the digital reorganization of traditional technologies and physical components and continuously spawning new products, new processes, and new business models [3]. As a result, digital technologies have an expanding range of influence on economic development [4-5]. In the context of the rapid growth of the digital economy, environmental issues have become the focus of relevant studies [6-7], especially regarding the impact of the digital economy on green total factor productivity. As the world's second-largest economic development entity, China actively promotes the establishment of an economic system of green, low-carbon, and circular development, and attaches great importance to environmental benefits while pursuing economic benefits in economic development. At the same time, China's digital economy is developing rapidly, and the scale of the digital economy is the second largest in the world. All facets of China's economy are changing as a result of digital technology. Based on this, this paper empirically looks into the impact of digital technology on green total factor productivity using data from China's provinces, providing suggestions for developing nations to support green economic development.

Existing studies have examined the impact of the digital economy on green development from a variety of perspectives, however, there are also existing studies that need to be further improved. First of all, the digital economy, as a new mode of economic development, contains a lot of content, and thinking about its impact on green development from the perspective of the internal composition of the digital economy provides a more targeted viewpoint for the digital economy to empower green development. Secondly, enriching micro-level data processing provides more diversified data support for macro-level research. Existing research on the measurement of the digital economy is mainly from the macro-level data, with the continuous advancement of research, more and more micro databases can be constructed, if the micro-level data to measure the digital economy from the micro-level data to become an important support for future research. Finally, pay attention to the moderating effect brought about by the external environment. Along with the rapid development of the digital economy, it will not only have an impact on the external environment, but also be affected by the external environment, therefore, thinking about the impact of the digital economy on green development from the perspective of the external environment will help to put forward a more effective implementation program.The following aspects are the marginal contribution of this paper. (1) Although exiting studies have looked at the issue of green economic development from the digital economy perspective, this paper, for the first time, considers the issue of green economic development from the perspective of digital technology, grasps the core of the digital economy, and enhances the pertinence of the research. Digital technology accelerates the process of industrial digitization by empowering traditional industries, and then promotes the development of digital economy. This paper analyzes from the perspective of digital technology, expands the research content of digital economy affecting green development, and provides new ideas for subsequent related research. (2) Quantifying digital technology using ICT patent data at the micro level provides a novel insight into data processing for further related investigations. Studies on the digital economy that are

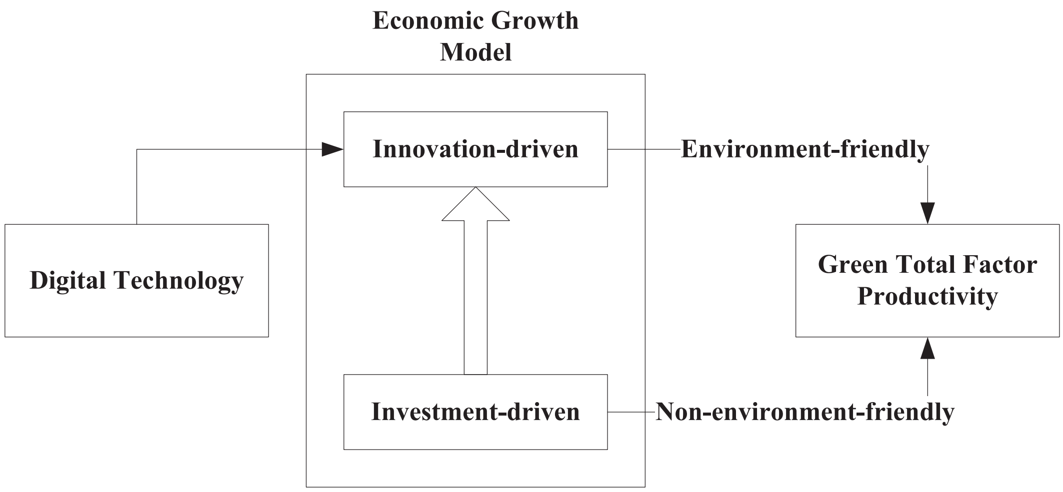

Fig. 1. Capital Accumulation Moderating Effect Analysis Framework.

now available typically use a macro-to-macro data processing strategy without accounting for the micro dimension. To compensate for the micro dimension of data processing, this paper ingeniously begins with the microdata at the enterprises and research institutions level, collects the ICT patent data at the enterprises and research institutions level, and aggregates them at the macro level. The digital technology indicators constructed in this paper can be applied not only to the macro-level analysis, but also to the micro-level analysis, such as the city or enterprise level, which provides data support for the future promotion of research on digital technology-related issues. (3) Both digital economic development and green development are closely related to the economic growth model, so the inclusion of the economic growth model in the analytical framework helps to deepen the understanding of the research problem. The moderating effect of capital accumulation is investigated, and the transformation of the economic growth model is integrated into the analysis framework. The move from the old investment-driven model to the innovation-driven model has become an increasingly major reality in many emerging countries. According to Fig.1, contemplating the moderating impact of capital accumulation can, on the one hand, evaluate the impact of the investment-driven model on the development of the green economy and, on the other hand, consider the impact of digital technology on green total factor productivity in the stage of economic transformation.

The remainder of this paper is structured as follows. In the second section, the relevant research literature is reviewed; in the third, an empirical test is conducted using the two-way fixed effect analysis method; in the fourth, the impact of digital technology development on green total factor productivity and its heterogeneity is examined; and in the fifth section, the research findings are summarized and development recommendations are made.

Literature Review

Digital Technology

Digital technologies are information and communication technology systems that can organize rapid encoding, storage, and other functions and standardize information [8-9]. The economic effects of digital technologies in the digital economy era have become the focus of relevant research. At the macro level, digital technologies embedded in production services and distribution processes act on economic development mainly through cost reduction, innovative factor allocation, and accelerated digitization of industries [10]. According to Jorgenson and Vu, the digital economy revolution has sped up the development of globalized infrastructure network facilities, enabling cross-border communication, significantly reducing the cost of information exchange for governments, raising tax revenues, and promoting global economic growth. Digital technology and enterprise innovation operate at the micro level [11]. Enterprises are undergoing a digital transformation as a result of the usage of digital technology, which is reflected in innovative changes to production and operation models and innovative changes to personnel organization models [12]. Qualitative research by Nylén and Holmström and Reuter discovered that businesses innovate their development models and concentrate on the actual needs of users to maximize profits as they integrate digital information technology into the industrial development process [13-14]. From a macro perspective, the process of industrial integration quickens in the age of the digital economy, and the strong industrial linkage effect propels digital innovation across the board.

Along with the rapid development of the digital economy, the scope of the impact of digital technology on economic development is also increasing, and existing research mainly focuses on the following economic effects of digital technology. (1) Economic development. Digital technology can be understood as a technological paradigm based on information and communication technology (ICT) [15]. Hwang and Shin argue that ICT contributed to past economic growth through intermediate inputs and embedded technology in investment products, in addition, ICT contributed to 40% of Korea's economic growth from 2000 to 2012. ICT will assist business and financial systems to ensure sustainable economic development [16]. Hussain et al. point that ICT will assist business and financial systems to ensure sustainable economic development [17]. (2) Labor market. Acemoglu and Restrepo point out that digital technologies such as artificial intelligence are in their early stages of development and do not have enough advantages to create new jobs, which in turn can lead to stagnant labor market demand and a decline in the share of labor income [18]. Akaev et al. find that in the driven by digital technologies, the share of employee compensation has declined by 5-16% [19]. (3) Green development. From the perspective of macro level, Zhang et al. find that the development of digital technologies indirectly reduces domestic embedded carbon intensity by reducing the intensity of energy consumption and increasing the input intensity of foreign services [20]. From the perspective of micro level, Yuan & Pan find that digital technology applications can effectively promote green innovation in firms and that the green innovation effect of digital technology applications is stronger in state-owned enterprises and firms in highly competitive industries [21].

Green Total Factor Productivity

With the deepening of the concept of sustainable development, green total factor productivity has also gradually moved from being an essential indicator of the quality of national economic development. Total factor productivity was proposed by Solow as a comprehensive indicator to measure the level of factor allocation, and efficiency of technological progress [22]. Färe et al. (1996) argued that the assumption of zero harmful inputs or outputs causes measurement bias in total factor productivity [23]. Some scholars have incorporated energy consumption and environmental pollution into the total factor productivity measurement framework to obtain green total factor productivity [24-25]. Green total factor productivity is an improvement of the original total factor productivity. Compared with traditional total factor productivity, green total factor productivity not only measures the input and output of capital, labor, and other factors but also takes into account the consumption of green production factors and environmental energy.

Related investigations have looked at the variables affecting green total factor productivity from several angles, including: (1) Level of economic development. The current research findings on the connection between the degree of economic development and green total factors productivity are contradictory. According to some studies, when economic development levels rise, more resources are allocated to production, adding to the strain on those resources and harming green total factors productivity [26]. In addition, several studies shows that when economic development rises, more high-quality production components are attracted, and production input is optimized, which raises the level of green total factor productivity [27]. (2) Technological innovation. From the perspective of innovation-driven direction, technological innovation shifting to green technological progress can effectively promote green economic growth [28]. However, the interaction between technological innovation and the level of economic development has a significant negative effect on green total factor productivity [29]. (3) Environmental regulation. The cost hypothesis states that environmental regulations raise the cost of production and operation for businesses, requiring them to implement technical innovation to meet the objectives of energy conservation and emission reduction [30]. According to the innovation compensation concept, businesses' expenses associated with energy conservation and emissions reduction can be offset by the utility that results from technological innovation in environmental control [31-32]. (4) Green finance. Green finance emerged to meet the financial needs of green growth and sustainable development [33]. Establishing and implementing a green finance system will help to achieve sustainable green growth through economics and environmental harmony [34]. Lee & Lee found that the development of green finance greatly increased the level of green total factor productivity, and that the promotion of green finance was greater in regions with better economic and social conditions, lower public participation in environmental protection, and higher levels of pollution [35].

Impact of Digital Technology on Green Total Factor Productivity

More scholars have recently started to focus on the effect of the digital economy on green total factor productivity. Region-level analysis results show that the digital economy has a positive direct impact and spatial spillover effects on green total factor productivity with a significant "U" shape, and these effects mainly stem from the digital economy's promotion of green technological progress [36]. However, digital economy agglomeration will exacerbate regional green total factor productivity disparity due to uneven industrial upgrading mechanisms [37]. Firm-level analysis results show that digital transformation increases firms' green total factor productivity, and that structural optimization and green technology innovation effects are two key paths through which digital transformation affects firms' green total factor productivity [38].

Concerning digital technology, related studies have analyzed the impact of digital technology on green economic development. However, there are no studies explore the impact of digital technology on green total factor productivity. Berkhout and Hertin pointed out that digital technology affects changes in the economic structure in the process of production and distribution of digital products, and the expansion of the production scale of digital products accelerates the upgrading, resulting in the problem of excessive energy consumption [39]. Zhou et al. consider the sources, transfers, and drivers of ICT, pointing out that the massive expansion of ICT products' end demand leads to an increase in carbon emissions and affects the greening of the industrial production environment [40]. Contrary to the conclusions obtained from the above studies, Koomey et al. point out that, in contrast to the findings of the aforementioned studies, the impact of digital technology on upstream and downstream industries' ability to reduce emissions is superior to that of the digital industry as a whole [41]. Gelenbe and Caseau evaluate the energy consumption and carbon dioxide emission levels of various ICT sectors. The study discovered that while the energy consumption of the ICT industry was quite high throughout the development of digital technology, such was not the case when digital technology-enabled transportation, medical care. The sector has made major strides in reducing carbon dioxide emissions, improving energy consumption efficiency in crucial divisions, and achieving some degree of green growth [42]. Wang et al. believe that digital technology promotes economic growth and at the same time, cross-industry empowerment continues to have spillover effects, optimize the industrial structure, give full play to the emission reduction effect of technology spillovers, and realize the optimization of green energy structure [43].

In summary, existing studies have explored the impact of digital economy development on green total factor productivity from multiple perspectives.

At the same time, existing research has also focused on the impact of digital technologies on green development, particularly carbon emissions. Given that digital technology is the core of the digital economy, and improving green total factor productivity is the guarantee for realizing green development, studying the impact of digital technology on green total factor productivity has become an issue that needs to be focused on in related research. Still, no study has yet focused on the effects of digital technology development on green total factor productivitIn the early stage of data technology development, digital technology is integrated into the operation and development of the real economy through a shared platform to realize digital industrialization, create a primary environment for the digitization of traditional high-consumption factors of production [44-45], reduce information asymmetry in supply and demand, and effectively improve green total factors productivity. In the later stages of digital technology development, digital technology can achieve efficient changes and realize industrial digitization by replacing traditional physical capital. Data elements will become the center of the production process and play a decisive role in changing the conventional information flow mode and overcoming the total amount of conventional production factor resources. In this process, digital technology, based on its advantages in information dissemination, resource sharing, and cost reduction, effectively solves the problem of high cost and high consumption in the process of economic development, accelerates the greening of the production process, and promotes the improvement of green total factor productivity. Digital technology enables rapid and efficient transmission of information, facilitating the flow of knowledge, ideas, and market trends. This enhanced connectivity allows businesses and individuals to access valuable resources, collaborate across boundaries, and tap into global markets, thus promoting efficient allocation of resources. Additionally, digital platforms enable the sharing economy, empowering individuals and businesses to leverage underutilized resources, resulting in reduced waste and greater sustainability. Furthermore, digital technology optimizes operational processes, introducing automation and streamlining workflows, which contribute to significant cost reductions and increased productivity. Therefore, according to Fig. 2, digital technology development can boost green total factor productivity.

This paper takes China as a research sample, as the largest developing country, China vigorously promotes the development strategy of digital economy and the green development strategy, and the study of the impact of China's digital technology on green total factor productivity can provide a reference for related countries. In the analysis process, macro data are comprehensively utilized to deal with regional total factor productivity indicators, and micro data are utilized to deal with regional digital technology indicators. Fixed-effects and moderating-effects models are used to examine the effect of digital technology on green total factor productivity and the possible moderating effect of capital accumulation.

Method and Data

Panel Regression Model

In this paper, the effect of digital technology on green total factor productivity is examined using a two-way fixed effects model, and the basic econometric model is constructed as shown in Equation (1).

$$gtfp_{it} = \beta_0 + \beta_1 ict_{it} + \sum_m \beta_m CV_{it} + \nu_{\mathrm{i}} + \mu_{\mathrm{t}} + \varepsilon_{it} \quad (1)$$

where $gtfp_{it}$ denotes green total factor productivity in province i in year t, ict_{it} denotes the level of digital technology in province i in year t, and CV_{it} is a control variable that controls for other influencing factors mainly from the perspectives of economic size, economic structure, economic external dependence, and government fiscal intervention. v_i denotes regional fixed effects, μ_t denotes time-fixed effects, and ε_{it} denotes the random error term.

In order to test the moderating effect of capital accumulation, an interaction term model is constructed.

$$gtfp_{it} = \omega_0 + \omega_1 ict_{it} + \omega_2 cap_{it} + \omega_3 ict\_cap_{it} + \sum_{m=1}^{4} \omega_m CV_{it} + \nu_{\mathrm{i}} + \mu_t + \xi_{it} \quad (2)$$

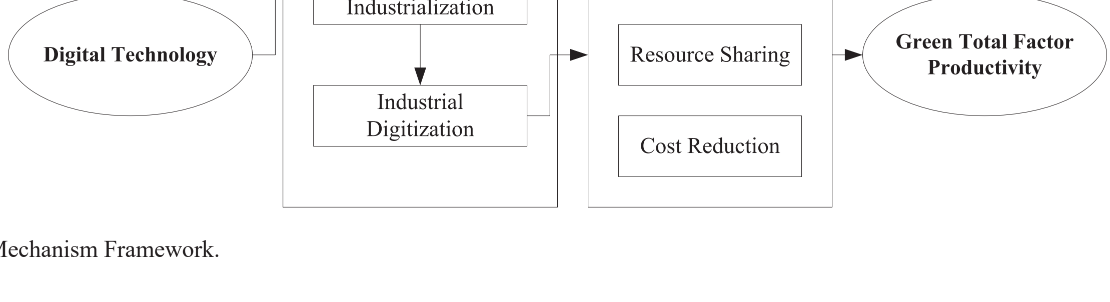

Fig. 2. Mechanism Framework.

where *cap* represents capital accumulation in province *i* in year *t*, measured using the capital stock ratio on GDP, and *ict_cap* represents the interaction term between digital technology and capital accumulation, both variables are decentered, and the control variables are consistent with the above.

Indicators and Data

The sample selected in this paper is the data from 30 provinces in mainland China excluding the Tibetan region, from 2000-2017. The data of the explanatory and control variables are obtained from the website of the National Bureau of Statistics, the China Energy Statistical Yearbook, the China Statistical Yearbook from 2001-2018, and the statistical yearbooks of each province from 2001-2018, the Cnopendata database.

Treatment of the explanatory variable green total factor productivity (*gtfp*). In this paper, the Global Malmquist-Luenberger index method based on the SBM directional distance function is used to measure green total factor productivity in 30 Chinese provinces from 2000-2017. Labor, capital, and energy consumption were used as input variables, real GDP excluding prices in each area is used as desired output, and carbon dioxide emissions in each area were used as non-desired output. Current methods for the measures of green total factor productivity mainly use data envelopment analysis [46-47]. The global SBM directional distance index is constructed based on the SBM directional distance function considering the resource environment [48]. The desired output and non-desired output are simultaneously incorporated into the model by constructing the Malmquist-Luenberger index model, but this method suffers from non-transmissibility and is prone to linear programming misinterpretation problems in measuring the directional distance function in the mixed period. To avoid such problems, this paper measures green total factor productivity based on the SBM directional distance index that considers the environment, with reference to the Global Malmquist-Luenberger index proposed by Oh [49].

Input indicators include labor, capital, and energy inputs. Labor input is represented by the total number of employees in each province selected for labor input data for the calendar year. The capital stock is measured based on three types of data, namely regional capital stock in 2000, fixed capital formation from 2000 to 2017, and fixed asset investment price index (*IP*), and the capital depreciation rate (δ) is set at 9.6%, and the capital stock with the base period of 2000 is calculated using the perpetual inventory method with the formula $K_t = (1-\delta)\ K_{t-1}+I_t/IP_t$. The capital energy input is based on the total energy consumption data of each area.

Output indicators include expected output and undesired output. The expected output is the real GDP of each province, taking 2000 as the base period and excluding prices. The undesired output is measured by the carbon dioxide emission indicators of each province. Considering that carbon dioxide emissions are mainly from the consumption of coal, crude oil, and natural gas, the estimation method of carbon dioxide emissions in the National Greenhouse Gas Emission Inventory prepared by the Intergovernmental Panel on Climate Change is used, the formula is as follows [50].

$$CO_2 = \sum_{i=1}^{3} E_i \times NCV_i \times CEF_i \times COF_i \times \frac{44}{12} \tag{3}$$

Among them, the consumption of coal, crude oil, and natural gas is represented by E_i (i = 1,2,3), NCV_i represents the average low-level calorific value of the three energy sources, CEF_i represents the carbon emission coefficient in the greenhouse gas inventory, and COF_i is the carbon oxidation factor.

Treatment of explanatory variables digital technology (*ict*). Digital transformation has penetrated all areas of the economy and society, profoundly changing the global production organization and trade structure 10. In this paper, the number of ICT patent applications granted is chosen as a proxy variable for digital technology. The specific approach is as follows: according to the definition of ICT subfields and the international patent classification number IPC in the OECD Patent Statistics Bulletin, all the patents applied for and granted in the ICT field in China are retrieved with the help of the "Patent Information Analysis" software developed by the State Intellectual Property Office, and then the number of patents applied for and granted is summed up according to the provinces corresponding to the number of patents applied for and granted. The number of ICT patent applications presented in the region is obtained by summing up the number of patents used by enterprises and research institutions. Then the number of ICT patents raised each year compared with the number of patents increased by enterprises and research institutions to measure the regional digital technology level.

Treatment of control variables. Economic size (*lngdp*) is measured using the log of GDP. It is tested that there is no multicollinearity between economic size and green total factor productivity. Economic structure (*stru*) is measured using the value added of the tertiary sector as a share of GDP. External economic dependence (*open*) is calculated using the size of imports and exports as a percentage of GDP. Government fiscal intervention (*gov*) is measured by the share of local general budget fiscal expenditure in GDP. The statistical characteristics of all variables are reported in Table 1.

Analysis of Green Total Factor Productivity and Digital Technology

Fig. 3 display the outcome of the green total factor productivity measurement. Green production factors in China exhibit an upward trend, with the average national value increasing from 0.9972 in 2001 to 2.1070

Table 1. Descriptive statistics of the variables.

Variable	Obs	mean	Std. Dev.	Min	Max
gtfp	510	1.3166	0.5417	0.4284	3.4681
ict	540	0.1590	0.1089	0.0000	0.6569
lngdp	540	8.7201	1.0547	5.5747	11.0355
stru	540	0.4231	0.0832	0.2830	0.8056
open	540	0.3100	0.3830	0.0169	1.7222
gov	540	0.0965	0.0338	0.0479	0.2452

in 2017. Among them, the growth rate of China's green total factor productivity increased noticeably from 2010 to 2017, indicating that China's industry has recently concentrated on technological innovation and has consistently gotten behind initiatives that require a lot of knowledge and technology. This is also closely related to the Chinese government's proposal to achieve "green development and establish a resource-saving and environment-friendly society" in the 12th Five-Year Plan, which placed a high priority on the creative growth of green industries.

Fig. 4 displays the findings of the digital technology level measurement. Overall, there is a changing upward trend in the level of digital technology at the national level, with rising digitization rates and increasing IT innovation capacities. As the Chinese economy made the switch to a high-quality development stage, China's digital transformation entered an accelerated development stage, as demonstrated by the fact that the growth rate of digital technology among them significantly increased between 2002 and 2004, 2006 and 2008, and after 2013.

From the perspective of correlation, according to Fig. 5, thre is a positive correlation between digital technology and green total factor productivity with a correlation coefficient of 0.5179 and significant at the 1% level.

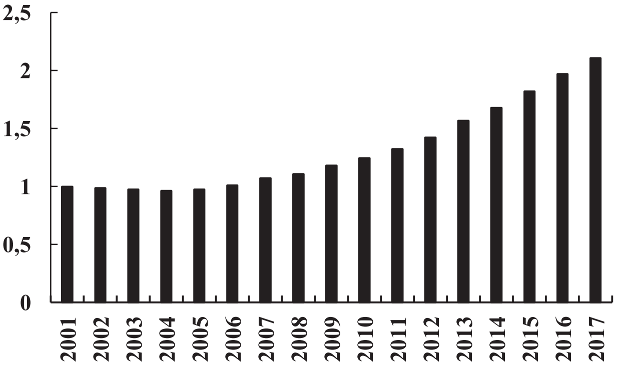

Fig. 3. Green Total Factor Productivity for the Nation.

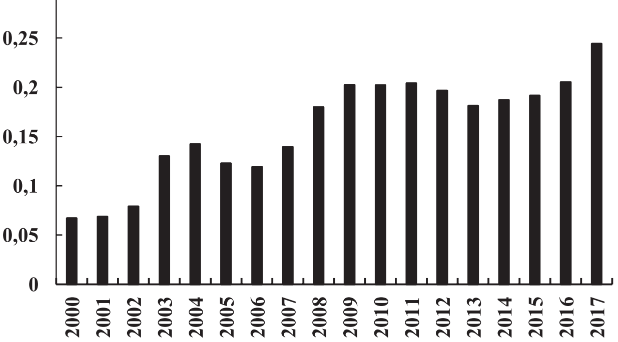

Fig. 4. Digital Technology Levels in the Nation.

Results and Discussion

National-Level Analysis

From the regression results at the national level, according to Table 2, before the inclusion of control variables, the regression results show that the regression coefficient of digital technology on green total factor productivity is positive and passes the 1% significance test, indicating that digital technology development can improve green total factor productivity. After the inclusion of all control variables, the regression

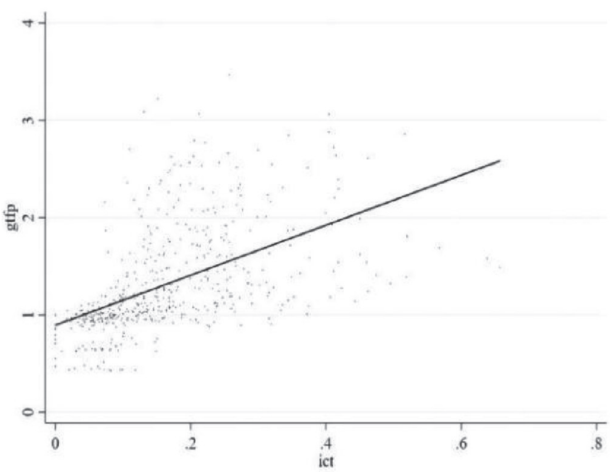

Fig. 5. Digital Technology and Green Total Factor Productivity Correlation Chart.

Table 2. National-level regression results.

	(1)	(2)
ict	1.0569***	1.0510***
	(0.2605)	(0.2518)
lngdp		0.3927*
		(0.1809)
stru		0.7710
		(0.3985)
open		-0.7968***
		(0.1031)
gov		-2.6783**
		(0.9005)
C	0.9246***	-2.0883
	(0.0470)	(1.4600)
N	510	510
R^2	0.7273	0.7628
Province	Yes	Yes
Year	Yes	Yes

Note: Standard errors are in parentheses; *, **, *** indicate significance at the 10%, 5%, and 1% levels.

results show that the coefficient of digital technology is positive and passes the 1% level test, indicating that the driving effect of digital technology on green total factor productivity is robust. The improvement of industrial structure and an increase in economic scale both have a good effect on the productivity of green total factors, according to the regression results of the control variables, but only the positive impact of economic scale is statistically significant. The increase in economic dependence on foreign countries and the increase in government fiscal intervention has negative effects on green total factor productivity, and the negative effects are all significant.

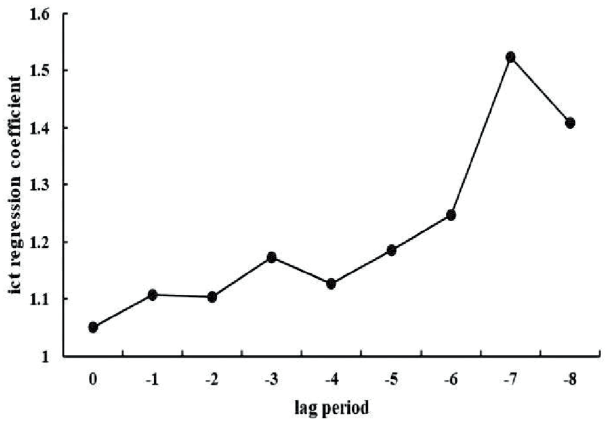

Fig. 6. Regression coefficients with different lags of *ict.*

The previous analysis pointed out that the impact of digital technology development on green total factor productivity is sustainable, and the long-term impact may be greater. Therefore, this paper treats digital technology with a lag and examines the impact of digital technology on green total factor productivity. According to Fig. 6, all lagged periods of digital technology can promote green total factor productivity, and the magnitude of the impact of lagged digital technology is greater than that of the current period, indicating that the effects of digital technology on green total factor productivity is persistent and the long-term impact is indeed somewhat more significant.

The paper next examines the robustness of the findings of the previous analysis using replacement variable treatments, replacement model estimation methods, and instrumental variable methods. First, the dependent and independent variable treatments are replaced and logarithmicized to mitigate the effect of data heteroskedasticity on the results of the previous analysis. According to model (1) in Table 3, after replacing the variable treatments, digital technology development still drives green total factor productivity and the effect is significant.

Second, the model estimation method is replaced with a mixed regression model estimation method without considering fixed effects to examine the impact of the model estimation method on the results of the previous analysis. According to model (2) in Table 3, digital technology development can still drive green total factor productivity after adopting the mixed regression model estimation method, and the effect is significant.

To further address the bias caused by the endogenous problem, a generalized two-stage least squares test is conducted using the total post and telecommunications business in 1996 as an instrumental variable to measure the level of information and communication. The total post and telecommunications business as an instrumental variable takes into account two aspects. On the one hand, the total post and telecommunications business reflects to some extent the level of information and communication technology in cities, which is closely related to digital technology, also for different cities, the improvement of the local communication technology level relies heavily on the development of information technology in the city. On the other hand, the total post and telecommunications business has a more natural exogenous characteristic, which can well satisfy the exogenous assumption of effective instrumental variables. Measuring the level of digital technology by the level of ICT, this instrumental variable is not much correlated with the explanatory and control variables. However, this instrumental variable still has shortcomings. Regarding the data characteristics, the total postal and telecommunication services in 1984 are urban cross-sectional data, while all other variables are panel data. As for the economic characteristics, there may be temporal differences between the impact of ICT and digital technology, and it is urgent to fully consider the time dimension differences. For these reasons, this paper refers to Angrist & Krueger who treat the instrumental variable of birth quarters and introduces the cross-multiplication term of total postal and telecommunication business and annual dummy variables in 1984 as an instrumental variable, which overcomes the limitation that total postal and telecommunication business is cross-sectional data and shows the effect of instrumental variables on endogenous variables in different years [51]. According to model (3) in Table 3, the regression coefficients are significantly positive before the inclusion of control variables. After the inclusion of control variables, the regression coefficients are still positive and the development of digital technology is beneficial to the improvement of green total factor productivity, which is consistent with the previous results.

The results of the above analysis indicate that promoting the development of digital technology can improve green total factor productivity, and the results of the robustness analysis support the above conclusions. The above results affirm the promotion of digital economy development on green total factor productivity from the perspective of digital technology [36, 38], suggesting that digital technology will improve green total factor productivity through the perspectives of improving the efficiency of information matching, the sharing economy, and cost reduction. The impact of digital economy on green total factor productivity is sustainable [52] and marginal increase [53], while the results of the time lag term analysis in this paper indicate that the driving effect of digital technology on green total factor productivity is also sustainable and marginal increase. Based on the conclusions of the above analysis at the national level, in the next step to promote the green development process, we should pay attention to the role of digital technology to promote the development of digital technology to formulate a corresponding development plan.

Table 3. Robust analysis regression results.

	lngtfp	*gtfp*	*gtfp*
lnict	0.0722***		
	(0.0198)		
ict		1.0754***	1.4996***
		(0.2104)	(0.4679)
Controls	Yes	Yes	Yes
c	-2.0155**	-2.1354***	
	(0.8945)	(0.1978)	
IV			0.0031***
			(13.3246)
Controls			Yes
N	502	510	510
R^2	0.7840	0.5439	
Province	Yes	No	Yes
Year	Yes	No	Yes
Cragg-Donald Wald F			177.4740 (16.38)

Note: Standard errors are in parentheses; *, **, *** indicate significance at the 10%, 5%, and 1% levels. The original hypothesis of the Cragg-Donald Wald F test is that the instrumental variables are weakly instrumental, and the critical value of the 10% significance level corresponding to the test is reported in parentheses.

Heterogeneity Analysis

Due to the obvious differences in economic development between regions in China, a heterogeneity analysis is required to systematically understand the impact of digital technology development on green total factor productivity. This paper next develops the heterogeneity analysis from the perspective of sub-regions and sub-year. The analysis at the sub-regional level includes two levels of analysis: inland and coastal regions, and northern and southern regions. The analysis at the sub-regional level includes two levels of analysis: inland and coastal regions, and northern and southern regions. At the coastal and inland region levels[1], according to Table 4, digital technology has a positive impact on green total factor productivity in all regions, and the impact is significant in both regions. In terms of the magnitude of the impact, digital technology development has a greater impact on green total factor productivity in the coastal regions. At the level of the northern and southern regions, refer to the criteria of Sheng et al. [54] for the division of northern and southern regions[2]. According to Table 4, digital technology has a positive impact on green total factor productivity in all regions, and the impact is significant in both regions. In terms of the magnitude of the impact, digital technology development has a greater impact on green total factor productivity in the southern region. The results of the above heterogeneity analysis indicate that although digital technology has a significant driving effect on green total factor productivity at all sub-regional levels, there are still large differences in the magnitude of the impact. It has been found that there is regional heterogeneity in the impact of

[1] The coastal regions include Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan, and other provinces in mainland China belong to the inland regions.

[2] The northern region includes Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Beijing, Tianjin, Shanxi, Shaanxi, Ningxia, Gansu, Xinjiang, Qinghai, and the other provinces in mainland China belong to the southern region.

Table 4. Regression results of sub-regional heterogeneity analysis.

	National	Costal	Inland	Northern	Southern
	(1)	(2)	(3)	(5)	(6)
ict	1.0510***	1.1622***	0.9208**	0.9659***	1.6247***
	(0.2518)	(0.2841)	(0.3727)	(0.2640)	(0.5287)
Controls	Yes	Yes	Yes	Yes	Yes
C	-2.0886	-5.0710**	-3.3564*	-3.5997**	6.7368**
	(1.4600)	(2.3513)	(1.9224)	(1.7861)	(2.6296)
N	510	187	323	289	221
R^2	0.7628	0.9078	0.6832	0.8745	0.6683
Province	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes

Note: Standard errors are in parentheses; *, **, *** indicate significance at the 10%, 5%, and 1% levels.

digital technology on green total factor productivity, for example, Liu et al. find that the digital economy has a significant driving effect on green total factor productivity in the eastern and central regions, while it has a non-significant inhibitory effect on the western region [52]; Lee et al. find that the digital economy has a more pronounced driving effect on green total factor productivity in the provincial capitals and economically developed cities [55]. Combined with the results of the regional heterogeneity analysis in this paper, the impact of digital technology on green total factor productivity is more significant in coastal cities with a higher level of economic development and in southern cities with a more active private economy, because these regions have a greater demand for digital technology, and the degree of penetration of digital technology into the economic development of these regions is higher, which has a more significant driving effect on green total factor productivity. The results of the above analysis of subregional heterogeneity show that different regions can accelerate green development through the promotion of digital technology. However, it is still necessary to formulate development programs according to local conditions, especially in coastal and southern regions, which need to pay more attention to the promotion of digital technology and incorporate the promotion program of digital technology into the regional digital economy development plan.

Next, this paper further examines the heterogeneity of the impact of digital technology development on green total factor productivity from the perspective of the external environment, mainly using the interaction term model. This paper will analyze four perspectives, including economic scale, industrial structure, external economic dependence, and government fiscal intervention. At the economic scale level, according to the regression results of model (2) in Table 5, the coefficient of the interaction term between digital technology and the economic scale is significantly negative, indicating that the larger the economic scale, the smaller the magnitude of the impact of digital technology development on green total factor productivity, and the economic scale will have a hedging effect. At the level of industrial structure, according to the regression results of model (3) in Table 5, the coefficient of the interaction term between digital technology and industrial structure is positive but not significant, indicating that industrial structure does not affect the relationship between digital technology and green total factor productivity. At the level of foreign economic dependence, according to the regression results of model (4) in Table 5, the coefficient of the interaction term between digital technology and foreign economic dependence is significantly negative, indicating that the higher the foreign economic dependence, the smaller the magnitude of the impact of digital technology development on green total factor productivity, and the foreign economic dependence will have a hedging effect. At the level of government fiscal intervention, according to the regression results of model (5) in Table 5, the coefficient of the interaction term between digital technology and government fiscal intervention is significantly negative, indicating that the higher the degree of government fiscal intervention, the smaller the magnitude of the impact of digital technology development on green total factor productivity, and government fiscal intervention will have a hedging effect.

Exiting studies have directly explored the effects of foreign economic dependence [56] and government fiscal intervention [57] on green total factor productivity. This paper focuses on how economy size, foreign economic dependence, and government fiscal intervention affect the relationship between digital technology and green total factor productivity. The analysis results show that the greater the economic scale, the greater the level of foreign economic dependence and the higher the degree of government fiscal intervention, the smaller the driving effect of digital technology development

Table 5. Regression results of external environment heterogeneity analysis.

	National	National	National	National	National
	(1)	(2)	(3)	(5)	(6)
ict	1.0510***				
	(0.2518)				
ict×lngdp		-1.9289***			
		(0.5332)			
ict×stru			-7.0325		
			(5.8168)		
ict×open				-3.7025***	
				(1.2564)	
ict×gov					-43.1873***
					(13.1158)
Controls	Yes	Yes	Yes	Yes	Yes
C	-2.0886	-2.3880*	-2.2457	-2.5662*	-2.4138*
	(1.4600)	(1.4435)	(1.4650)	(1.4570)	(1.4480)
N	510	510	510	510	510
R^2	0.7628	0.7694	0.7636	0.7672	0.7683
Province	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes

Note: Standard errors are in parentheses; *, **, *** indicate significance at the 10%, 5%, and 1% levels.

on green total factor productivity. Since different external economic environments affect the relationship between digital technology and green total factor productivity, policies with differentiation based on regional economic development are needed to better utilize the driving role of digital technology. The results of the above analysis suggest that building an appropriate external environment will help to stimulate the contribution of digital technologies to green development, such as the need to focus on relying on domestic demand in the domestic market and reducing excessive government fiscal spending.

Analysis of the Moderating Effect

This paper analyzes the moderating effect of capital stocks. According to Table 6, regardless of the control variables, digital technology development still has a significant driving effect on green total factor productivity after adding the capital stock and the interaction term. In contrast, both the capital stock and the interaction terms of digital technology and capital stock have a significant inhibiting effect on green total factor productivity. The above analysis shows that accelerated capital accumulation is not conducive to green economic development, and it weakens the driving effect of digital technology development on green economic development. From another perspective, in the context of the shift from an investment-driven

Table 6. National-level regression results.

	(1)	(2)
ict	0.4376*	0.5241**
	(0.2307)	(0.2281)
cap	-0.2497***	-0.2741***
	(0.0219)	(0.0263)
ict_cap	-0.7257***	-0.6779**
	(0.2753)	(0.2671)
Controls	no	Yes
C	1.2340***	-0.9368
	(0.0332)	(0.9775)
N	540	540
R^2	0.7325	0.7626
Province	Yes	Yes
Year	Yes	Yes

Note: Standard errors are in parentheses; *, **, *** indicate significance at the 10%, 5%, and 1% levels.

to an innovation-driven economic growth model, the dependence of economic growth on capital accumulation is reduced, which in turn is conducive to amplifying the driving effect of digital technology development on the green development of the economy. Lee et al. find that human capital accumulation not only directly improves green total factor productivity, but also amplifies the role of the digital economy in promoting green total factor productivity [55]. Combined with the findings of the moderating effect in this paper, in the context of the rapid development of the digital economy, human capital accumulation can more effectively release the enabling effect of the digital economy on green development compared to physical capital accumulation. Therefore, accelerating the transformation of the economic growth model, encouraging innovative activities, emphasizing the accumulation of human capital and relying on innovation to drive economic growth are crucial to unleashing the driving force of digital technology.

Conclusions and Recommendations

Conclusions

China has executed the national big data strategy, the "Internet Plus" action plan, and the policy of bolstering the nation through the Internet in succession against the backdrop of nations across the world actively encouraging the development of the digital economy. The range of how digital technology is used and applied has been broadening. The development of services has surpassed the traditional innovation model [58-59], and the use of digital technology to promote high-quality economic development has become an inevitable development trend in the digital economy era [59]. Although existing research focuses on the impact of digital economy on green total factor productivity, ignoring digital technology, which is a key technology for improving efficiency to achieve green development. Exploring the impact of digital technologies on green total factor productivity helps to understand the impact of digital economic development on green development from an internal perspective of the digital economy. This paper thoroughly investigates the impact of digital technology on green total factor productivity and its heterogeneity. This paper uses an SBM-GML index to measure regional green total factor productivity based on provincial level data and innovatively constructs digital technology indicators based on micro-level ICT patent data in China. Fixed-effects model is used to study the impact of digital technology on green total factor productivity and moderating model is used to examine the moderating effect of capital accumulation. It also looks at the economic effects of the development of the digital economy from the standpoint of green economic development and offers a new analytical perspective for fostering sustainable economic development.

The following are the conclusions: (1) digital technology can significantly improve green total factor productivity, and the results of the robustness analysis support the above conclusions. From a dynamic long-term impact perspective, the effect of digital technology development on green total factor productivity is showing an increasing trend. (2) The results of the heterogeneity analysis show that there is heterogeneity in the driving effect of digital technology development on green total factor productivity, but this heterogeneity is mainly in the magnitude of the impact. At the sub-regional level, digital technology development has a greater impact on green total factor productivity in coastal or southern regions. At the external environment level, digital technology development has a greater impact on green total factor productivity in regions with smaller economies, less external economic dependence, and less government fiscal intervention. (3) Capital accumulation has moderating effect in the process of digital technology affecting green total factor productivity which will inhibit the improvement of digital technology development on green total factor productivity.

Recommendations

The following policy recommendations are made in this study based on the aforementioned research findings: (1) As a result of rational planning for the growth of the digital economy, governments at all levels have upgraded and improved digital platforms and infrastructure, creating favorable conditions for the integration of digital technology into traditional industries, the real economy, and the improvement of green total factor productivity. (2) With a focus on regional coordination of the development of digital technology, it is necessary to encourage the development of this technology by local conditions, formulate differentiated development policies by regional development levels, drive industrialization with digital industrialization, and drive the digitalization of industries in surrounding areas with the digitalization of industries in the central area, thereby promoting green economic trends. (3) According to the moderating impact analysis results, increasing domestic demand, encouraging entrepreneurship, and reducing reliance on capital accumulation will increase the driving force of consumption and innovation for economic growth, thereby amplifying the driving effect of digital technology development on the green development of the economy. Therefore, to increase the total factor productivity, the government should pay more attention to consumption demand and human capital accumulation.

This paper explores the impact of digital technology on green total factor productivity, providing new perspectives on promoting green development from the internal perspective of the digital economy, but there are some areas for further research. (1) Explore the mechanism by which digital technology affects green total factor productivity. Understanding the impact mechanism of digital technology on green total factor productivity helps to construct a more complete analytical framework from the theoretical level on the one hand, and help to put forward more diversified policy recommendations on the other. (2) Utilizing the database constructed in this paper, the effect of digital technology on green total factor productivity is explored from a more micro level. Since the data used in the empirical analysis of this paper is aggregated from micro to macro, the data can be used to further analyze the relevant issues at the city level and enterprise level, and then test the conclusions obtained in this paper from a more micro perspective. (3) Expanding the object of analysis of the regulatory effect and incorporating economic development factors into the empirical analysis framework. The research in this paper focuses on the moderating effect of capital accumulation, and the use of the moderating effect model to explore the moderating effect of economic development factors will help deepen the understanding of the economic effects of digital technology.

Acknowledgments

This paper is supported by the National Natural Science Foundation of China (No. 72004202), and the Natural Science Foundation of Zhejiang (No. LQ21G030004).

Conflict of Interest

The authors declare no conflict of interest.

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