A Study on the Impact of Digital Economy on Agricultural Green Total Factor Productivity—Empirical Analysis Based on Mediating Effect and Threshold Effect

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Abstract. Based on China's provincial panel data from 2011–2019, this paper constructs an indicator system of the digital economy and measures the digital economy and agricultural green total factor productivity using the entropy value method and the SBM super-efficiency model with non-expected output, to explore the impact and mechanism of action of the digital economy on agricultural green total factor productivity. The results show that: (1) the digital economy significantly contributes to the increase of agricultural green total factor productivity and has a significant boosting effect on the three regions of East, Central, and West as well as the two regions of North and South. In addition, the results remained reliable after endogeneity treatment and robustness testing. (2) marketization plays a mediating role in the digital economy's promotion of green total factor productivity in agriculture. (3) the threshold effect test finds that there is a threshold effect on the impact of the digital economy on green total factor productivity in agriculture, and the impact of the digital economy on green total factor productivity in agriculture is significantly positive when the digital economy is above the threshold value of 0.018.

Keywords: digital economy · agricultural green total factor productivity · marketization · intermediation effect · threshold effect

1 Introduction

Agriculture is the lifeblood of the national economy and plays a pivotal role in China's economy. Neoclassical economic theory suggests that the growth of output per capita must shift to rely on technological progress and productivity improvement. The essence of agricultural modernization is to improve the total factor productivity of agriculture. However, total factor productivity in agriculture focuses too much on technology and productivity improvement, while ignoring the environmental and resource issues of agriculture. As early as 2018, the Ministry of Agriculture and Rural Development issued the "Technical Guidelines for Green Development of Agriculture (2018–2030)" to solve the problems of agricultural resource tension and serious soil pollution, etc. Along with the

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requirements of the "14th Five-Year Plan" for high-quality development, China's agricultural production has changed from the traditional improvement of "quantity" to the improvement of "quality". The improvement of agricultural green total factor productivity is the only way to solve the problems of agricultural green development and realize agricultural modernization. However, due to the great differences in resource endowment, cultivation structure, and economic development conditions of different regions, the enhancement of green total factor productivity in agriculture faces great difficulties, which brings a series of challenges to the sustainable development of agriculture and high-quality agricultural development at this stage. With the continuous development of a new generation of information technology, the digital economy has become a new engine to improve agricultural production efficiency. The Internet, big data, and artificial intelligence are continuously integrated with the real economy, and the digital economy has created opportunities for the development of green total factor productivity in agriculture. Therefore, under the background of the continuous development of the digital economy, how to promote the digitization of agriculture, develop smart agriculture, and promote green total factor productivity of agriculture is now a major difficulty to be solved.

The digital economy has played an irreplaceable and positive role in boosting the efficiency, power, and quality change of economic development. Since the 18th Party Congress, the country has attached great importance to the construction of digital agriculture and rural areas, so the "Outline of Digital Countryside Development Strategy", "Digital Agriculture and Rural Development Plan (2019–2025)", "Opinions on Grasping the Key Work in the Field of 'Agriculture, Rural Areas, and Farmers' to Ensure the Realization of a Well-off Society in an All-round Way on Schedule" have been issued one after another to promote the integration of digital economy and agriculture and rural areas, accelerate the penetration of digital technology into agriculture and rural areas, and improve the efficiency of agricultural production with the digital economy. So does the digital economy promote the improvement of agricultural green total factor productivity? What mechanism does it use to promote green total factor productivity in agriculture? Does the digital economy produce heterogeneity for different regions? Research on the above questions can uncover how the digital economy contributes to the improvement of agricultural total factor productivity, and thus provide some theoretical and practical references on how to further promote the improvement of agricultural green total factor productivity and sustainable agricultural development.

Regarding the research on the digital economy and agricultural green total factor productivity, the existing literature focuses on the research on the digital economy on agricultural productivity and the measurement and innovative development mechanism of agricultural green total factor productivity. First, for the study of the digital economy and production efficiency. Tian J and Liu Y used LP and ACF methods to verify that digital infrastructure had a significant positive impact on total factor productivity [1]. Huimei Y et al. and Xinyun H et al. empirically tested that the development of the digital economy significantly contributes to the increase of total factor productivity and there was also a positive spatial spillover effect on total factor productivity using inter-provincial panel data in China [2, 3]. Other scholars argued that there was a mediating mechanism for the digital economy in promoting production efficiency. Yuanfei X and Yao J found that the digital economy improved China's industrial green production efficiency through three mechanisms: the marketization process, industrial structure upgrading, and human capital [4]. Wenpu Y found that the digital economy drove the high-quality development and production efficiency of the economy by boosting the consumption level through the mediating effect model [5]. Second, the study on the measurement of green total factor productivity in agriculture and the mechanism of innovation development. Scholars have used stochastic frontier analysis [6], data envelopment analysis [7], and SBM methods [8] to measure agricultural green total factor productivity. Xiaocang X et al. [9], Bing K et al. [10], and Mengfei G et al. [11] incorporated carbon emissions into the measurement of agricultural total factor productivity and found that there was spatial heterogeneity in agricultural total factor productivity in China. After further research by scholars, Chengjun J explored the convergence of green total factor productivity in China's agriculture and found that there was an absolute β-convergence trend in China's agricultural green total factor productivity [12]. While Haihong G found that agricultural green total factor productivity did not have an absolute σ convergence trend [13].

From the comprehensive literature above, scholars have conducted rich research on the impact of the digital economy on productivity and how to measure green total factor productivity in agriculture, but only a few scholars have studied the impact of the digital economy and green productivity and green development on the two, such as Shengyue F et al. [14], Xiaohui Z et al. [15]. Therefore, based on the shortcomings of the above studies, this paper will try to promote relevant research in the following aspects: (1) Constructing an index system of the digital economy, measuring the indices of the digital economy and agricultural green total factor productivity using the entropy value method and SBM method, respectively, and examining the impact and heterogeneity of the digital economy on agricultural green total factor productivity from theoretical and empirical dimensions using inter-provincial panel data of 30 Chinese provinces from 2011–2019. (2) Exploring the mechanism of the digital economy on green total factor productivity in agriculture in terms of the marketization process. (3) Investigating the threshold effect of the digital economy on green total factor productivity in agriculture by using the digital economy as a threshold variable.

2 Theoretical Analysis and Research Hypothesis

The concept of the digital economy was first proposed by Don Tapscott in 1996, which refers to the use of digital information and knowledge as the key production factors, the modern network as an important carrier, and digital technology to drive economic structure optimization and efficiency improvement, to continuously improve the digitalization, networking, and intelligence of the economy and society. According to the "White Paper on the Development of China's Digital Economy in 2021" published by the China Communications Institute, the scale of China's digital economy reached 39.2 trillion yuan in 2020, accounting for 38.6% of GDP, and the power of digital technology is playing an increasingly important role in the optimization and upgrading of China's industrial structure. With the improvement of people's living standards and the change in diet structure, the traditional crude high-input, high-output, high-pollution way of agricultural development has not adapted to the development of the new century. Therefore, on the one hand, the digital economy penetrates digital technology into rural production and life, reduces the cost of information acquisition and increases social interaction with digital infrastructures such as the Internet and 5G, and widens social channels for farmers, who can use digital platforms to acquire advanced agricultural production technologies and realize scientific agricultural production, thus providing basic conditions for the improvement of green total factor productivity in agriculture. On the other hand, the digital economy, as a model of the new mode and new business, promotes scientific and technological innovation with digital innovation, provides high-quality talents for agricultural development, and promotes green agricultural development; the digital economy also gives birth to several new intelligent and green businesses, such as "Jingdong Digital Science", in the transformation and upgrading of agriculture, to reduce the emission of pollutants, conduct precise testing of the environment, and create a digital agricultural ecology. In addition, the continuous development of the digital economy also drives the development of green agriculture and smart agriculture and provides financing support with digital inclusive finance, thus laying the foundation for the improvement of green total factor productivity in agriculture. Based on the above analysis, the corresponding research hypotheses are proposed, namely:

H1: The digital economy can significantly contribute to the improvement of agricultural green total factor productivity.

With the advancement of digitalization, market-based reforms have been carried out and the level of marketization has been increased, which improves green total factor productivity by improving the path of distortion of factors in rural labor and capital markets [16]. Through marketization, the digital economy enables the most effective resource distribution in rural areas, boosts the effectiveness of factor distribution, transforms farmers' production inputs from "living off the sky" to systematic inputs, and uses digital technology to analyze big data to achieve the most effective seed selection when sowing agricultural products, agricultural products resources get reasonable configuration, and agricultural resources won't run out. Farmers will be better able to carry out green production, which will increase the overall factor productivity of green agriculture, as agricultural marketization advances agricultural science and technology, the agricultural industrial structure is upgraded and optimized, and the flow of agricultural production factors is accelerated. In view of the above analysis, the research hypothesis is proposed, namely:

H2: Marketization plays a mediating role in the digital economy for agricultural green total factor productivity improvement.

As the primary industry, agriculture is strongly related and can drive the development of related industries, such as the agricultural processing industry, foreign trade, and service industry. With the continuous improvement of digital economy technology, the productivity of agricultural green total factor productivity or other related industries will be influenced by the digital economy. When the level of the digital economy is low, it may hinder the improvement of agricultural green total factor productivity, while when the level of the digital economy is high, it will drive the continuous improvement of agriculture green total factor productivity. The impact of the digital economy on agricultural green total factor productivity is both an opportunity and a challenge, and the relationship between the digital economy and agricultural green total factor productivity may be nonlinear with a threshold effect. Based on this, the research hypothesis is proposed, namely:

H3: There is a threshold effect on the impact of the digital economy on agricultural green total factor productivity.

3 Study Resign

3.1 Model Construction

To test hypothesis H1, the following benchmark model is constructed in this paper.

$$GTFP_{\text{it}} = \alpha_0 + \alpha_1 DIG + \gamma X_{it} + \lambda_i + \eta_t + \varepsilon_{it} \tag{1}$$

where the explanatory variable GTFP represents agricultural green total factor productivity. i and t denote regional province and time. The core explanatory variable DIG is the digital economy. X is the control variable. ε_{it} represents the error term. λi and ηt denote individual fixed effects and time fixed effects, respectively, to control for regional omitted variables and time omitted variables. α0 denotes the constant term and α1 and γ are parameters to be estimated.

3.2 Variable Description

1) Explained variable

On the measurement of agricultural green total factor productivity (GTFP), drawing on previous studies [17]. The SBM super-efficiency model with non-expected output is used to measure agricultural green total factor productivity. The agricultural input variables are selected as labor input (number of people in primary industry), land input (agricultural sown area), machinery input (total power of agricultural machinery), irrigation input (effective irrigation area application), fertilizer input (rate of agricultural fertilizer), film input (plastic film), and pesticide input (usage of pesticide); the agricultural desired output is selected as two indicators of total agricultural production value (total output value of agriculture, forestry, animal husbandry, and fishery) and agricultural carbon absorption(carbon sink of agricultural production); the agricultural non-desired output is selected as agricultural carbon emission (the sum of carbon emission from fertilizer, agriculture, film, diesel, and irrigation).

2) Explanatory variable

The explanatory variable in this paper is the digital economy (DIG), referring to the practice of previous scholars [18]. The entropy value method is used to calculate the digital economy index, and relevant indicators are selected from three aspects: digital infrastructure (INFR), digital industrialization (INDU), and digital innovation (INNO). Digital infrastructure mainly reflects the construction of digital economy infrastructure in 6 aspects: telephone penetration rate, length of long-distance fiber optic cable lines, Internet broadband access users, Internet broadband access ports, cell phone exchange capacity, and the number of Internet domain names. Digital industrialization measures the development of digital industrialization in 4 aspects: total telecommunication business, cargo turnover, express business volume, and express business revenue. Digital innovation, mainly from the internal expenditure of research and experimental development (R&D) funds and full-time personnel equivalent, the number of patent applications received and the technology market technology output geography to reflect the strength of innovation in the digital economy.

3) Control variables

Green total factor productivity in agriculture is affected by multiple factors other than the digital economy. To reduce the research bias of the empirical evidence, the average education level of the labor force, environmental regulation, openness to the outside world, financial support for agriculture, and the level of the agricultural structure are selected as control variables in this paper. The average education level of the labor force is expressed as EDU, which is calculated as $EDU = (a * 16 + b * 12 + c * 9 + d * 6)/e$, where a, b, c, d, and e denote the number of people with a college education or above, the number of people with high school, middle school, and elementary school education, and the total population over 6 years old, respectively; environmental regulation (ENVIR) is calculated from industrial wastewater emissions, industrial SO2 emissions, and industrial smoke emissions; the financial support (GOV) for agriculture is measured by the local financial expenditure on agriculture, forestry, and water affairs as a percentage of the total local financial expenditure; the openness to the outside world (OPEN) is calculated by the ratio of total import and export to GDP of the location of the operating unit; the level of agricultural structure (LEVEL) is calculated by the ratio of the added value of the primary industry to the regional GDP.

4) Mediating variable

The intermediary variable measures the process of marketization by the marketization index (MARKET), which is calculated by the method of Gang F et al. [19].

3.3 Data Sources and Descriptive Statistics

Due to the availability of data, the data selected in this paper are for 30 provinces in China from 2011 to 2019 (excluding Tibet, Hong Kong, Macao, and Taiwan). The data for each variable is from the National Bureau of Statistics, China Statistical Yearbook, China Rural Statistical Yearbook, China Statistical Yearbook on Science and Technology, China Statistical Yearbook on Environment, and the statistical yearbooks of each province. The descriptive statistics of the main variables are shown in Table 1.

Table 1. Descriptive statistics of the main variables.

Variable category	Variable symbol	Number of observations	Mean value	Standard deviation	Minimum value	Maximum value
explained variable	*GTFP*	270	0.778	0.153	0.123	1.000
Explanatory variable	*DIG*	270	0.131	0.141	0.002	1.000
	INFR	270	0.192	0.139	0.026	0.799
	INDU	270	0.078	0.116	0.000	0.986
	INNO	270	0.112	0.137	0.001	0.776
control variable	*EDU*	270	9.201	0.887	7.514	12.680
	ENVIR	270	0.521	0.533	0.000	2.585
	OPEN	270	0.279	0.297	0.013	1.464
	GOV	270	0.114	0.032	0.041	0.190
	LEVEL	270	0.099	0.053	0.003	0.258
mediating variable	*MARKET*	270	6.901	2.046	2.372	11.640

Note: the table is original, the same as below

4 Empirical Analysis

4.1 Benchmark Analysis

In this paper, a fixed effects regression analysis is conducted using Stata 16.0. To ensure the rigor of the model, control variables are gradually added by stepwise regression to verify the effect of the digital economy on agricultural green total factor productivity, and the results of the baseline regression are reported in Table 2. From column (1) to column (6), the coefficients of the digital economy are significantly positive at the 1% level, and R^2 is also increasing, which has a significant effect on agricultural green total factor productivity. In column (6), after adding all control variables, the regression coefficient is 0.532, for each unit increase in the digital economy, agricultural green total factor productivity increases by 0.532 units, which shows that the digital economy has a strong direct effect on the total factor productivity of agricultural green, thus verifying hypothesis H1. From the regression results of other control variables, it can be found that: for each unit increase in the average education level of the labor force, agricultural green total factor productivity increases by 0.110 units; for each unit increase in environmental regulation, agricultural green total factor productivity increases by 0.046 units; for each unit increase in the level of external openness, agricultural green total factor productivity increases by 0.169 units; for each unit increase in agricultural financial support, agricultural green total factor productivity increases by 0.729 units; and for each unit increase in the level of agricultural structure, agricultural green total factor productivity increases by 1.149 units. This indicates that each control variable contributes to the increase in agricultural green total factor productivity. To control for

Table 2. The Effect of the digital economy on agricultural green total factor productivity.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	FE	FE	FE	FE	FE	FE	D/Kraay
DIG	0.538***	0.393***	0.365***	0.428***	0.466***	0.532***	0.532***
	(0.054)	(0.061)	(0.062)	(0.071)	(0.073)	(0.076)	(0.027)
EDU		0.090***	0.092***	0.101***	0.085***	0.110***	0.110***
		(0.020)	(0.020)	(0.020)	(0.022)	(0.023)	(0.021)
ENVIR			0.046*	0.043*	0.046**	0.046**	0.046***
			(0.024)	(0.024)	(0.024)	(0.023)	(0.010)
OPEN				0.109*	0.123**	0.169***	0.169**
				(0.061)	(0.061)	(0.062)	(0.058)
GOV					0.782**	0.729**	0.729
					(0.353)	(0.349)	(0.519)
LEVEL						1.149***	1.149***
						(0.407)	(0.272)
Constant	0.708***	−0.100	−0.141	−0.258	−0.214	−0.569**	−0.569**
	(0.008)	(0.181)	(0.181)	(0.192)	(0.191)	(0.227)	(0.224)
R-sq	0.295	0.350	0.360	0.368	0.381	0.401	0.401
Obs	270	270	270	270	270	270	270

Note: ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively, and robust standard errors are within (), the same as below

possible heteroskedasticity, autocorrelation, and cross-sectional correlation, column (7) is regressed with Drisc/Kraay for fixed effects, and the regression coefficient of the digital economy on agricultural green total factor productivity is found to be unchanged and significantly positive at the 1% level, indicating that the digital economy drives the increase in agricultural green total factor productivity.

4.2 Heterogeneity Analysis

The development patterns and development efforts among regions have their characteristics. To examine whether there is a significant difference between the digital economy on agricultural green total factor productivity, according to the policy, this paper divides the sample into three major regions, namely, East, Central, and West, as well as two major regions, North and South, and conducts regressions respectively, and the results are shown in Table 3. According to the regression results in the table, the coefficients of the digital economy variable in the three major regions of the east, central and west are 0.393, 0.543, and 1.346, respectively, and the coefficients of the digital economy variable in the two major regions of north and south are 0.617 and 0.623, and all of

Table 3. Heterogeneity analysis.

Variable	(1)	(2)	(3)	(4)	(6)
	East	Central	West	South	North
DIG	0.393***	0.543***	1.346***	0.617***	0.623***
	(0.083)	(0.189)	(0.297)	(0.090)	(0.203)
Constant	−0.330	0.185	−1.009**	−0.589*	−0.655**
	(0.425)	(0.302)	(0.390)	(0.320)	(0.318)
Control variable	YES	YES	YES	YES	YES
R-sq	0.508	0.374	0.588	0.509	0.389
Obs	108	81	81	135	135

them are significantly positive at the 1% level, indicating that the digital economy can promote agricultural green total factor productivity increase.

4.3 Endogeneity Treatment

Although the regression results in Table 2 indicate that the digital economy has a significant impact on the increase of green total factor productivity in agriculture, the higher the green total factor productivity in agriculture, the higher the level of the digital economy will also be, so the two are mutually causal and generate endogeneity problems. Therefore, this paper will use the instrumental variable method to further identify the impact of the digital economy on agricultural green total factor productivity, and use lags 1 and 2 of the digital economy as instrumental variables [20]. The regression results dealing with endogeneity are shown in Table 4.

Columns (1) and (2) are estimated using 2SLS, columns (3) and (4) are estimated using GMM, and columns (5) and (6) are estimated using LIML. From Table 4, we can see that the p-values of the K-P rk LM statistic for the under-identification test of the instrumental variables are all zero, while the values of the C-D Wald F statistic for the weak identification test are larger than the 10% threshold, indicating that the selected instrumental variables are strongly correlated with the endogenous variables. And the p-values of the Hansen J statistic are all greater than 0.1, which indicates that the instrumental variables are selected effectively. And the coefficient of the digital economy on green total factor productivity in agriculture remains significantly positive, which again supports hypothesis H1.

4.4 Robustness Tests

This paper uses three methods for robustness testing. First, replacing the econometric approach, a dynamic panel model is used to further validate the impact of the digital economy on green total factor productivity in agriculture. Second, the core explanatory variable is replaced and each explicit indicator of the digital economy is sequentially included in the equation for fixed effects regression. Third, using the tailing treatment, considering the influence of the extreme values of the dependent variable on the

Table 4. Endogeneity treatment: instrumental variables.

	(1)	(2)	(3)	(4)	(5)	(6)
	IV-2SLS		IV-GMM		IV-LIML	
DIG	0.626***	0.575***	0.628***	0.576***	0.626***	0.575***
	(0.093)	(0.124)	(0.0919)	(0.124)	(0.092)	(0.124)
Control variable	YES	YES	YES	YES	YES	YES
K-P rk LM statistic	17.634	24.894	17.634	24.894	17.634	24.894
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
C-D Wald F statistic	3676.725	1727.673	3676.725	1727.673	3676.725	1727.673
Hansen J statistic	0.052	0.222	0.052	0.222	0.052	0.222
	[0.819]	[0.638]	[0.819]	[0.638]	[0.819]	[0.638]
R-sq	0.316	0.388	0.316	0.388	0.316	0.388
Obs	270	270	270	270	270	270

regression results. The robustness test results are shown in Table 5, demonstrating the robustness and dependability of the benchmark regression results.

Table 5. Robustness tests.

Variable	(1)	(2)	(3)	(4)	(5)
	Dynamic panel	Replacement of core explanatory variable			Extreme interference
L.GTFP	0.854***				
	(0.148)				
DIG	0.340***				0.530***
	(0.110)				(0.075)
INFR		0.519***			
		(0.072)			
INDU			0.361***		
			(0.064)		
INNO				0.614***	
				(0.107)	
Control variable	YES	YES	YES	YES	YES
R-sq		0.407	0.360	0.364	0.399
Obs	210	270	270	270	270

5 Mediating Effect and Threshold Effect

5.1 Mediating Effect Test

The previous paper finds that the digital economy facilitates the improvement of green total factor productivity in agriculture, so through what mechanism does the digital economy promote the improvement of green total factor productivity in agriculture? In order to explain this mechanism of action, this paper incorporates marketization and tests this mechanism through a mediating effect model test [21]. The constructed model is as follows.

$$MARKET_{\mathrm{it}} = \delta_0 + \delta_1 DIG + \gamma X_{it} + \lambda_i + \eta_t + \varepsilon_{it} \quad (2)$$

$$GTFP_{\mathrm{it}} = \delta_0 + \delta_1 DIG + \delta_2 MARKET_{it} + \gamma X_{it} + \lambda_i + \eta_t + \varepsilon_{it} \quad (3)$$

where MARKET is the mediating variable and the other variables are the same as in the baseline model (1). The results of the mediating effects are shown in Table 6. The coefficient of the digital economy in column (1) is 0.344 and significantly positive at the 1% level, showing that the digital economy encourages the growth of agricultural green total factor productivity; The coefficient of the digital economy is also statistically significant positive at the 1% level in column (2), demonstrating that the digital economy encourages marketization; The marketization is significantly positive at the 5% level in column (3), and after adding the mediating variable, the digital economy is also significantly positive at the same level, demonstrating that the digital economy can support the enhancement of green total factor productivity in agriculture through marketization, supporting hypothesis H2.

In order to test the magnitude of the mediating effect, this paper is tested by Sobel-Goodman, and the results are shown in Table 7. In Table 7, the p-value of the Sobel test is 0.015, which is less than 0.05, indicating that the mediating effect is valid, and

Table 6. Estimation results of the intermediate effects model.

Variable	(1)	(2)	(3)
	GFTP	MARKET	GFTP
DIG	0.344***	7.044***	0.208**
	(0.083)	(0.654)	(0.099)
MARKET			0.019**
			(0.008)
Constant	0.116	3.286***	0.053
	(0.135)	(1.057)	(0.136)
Control variable	YES	YES	YES
R-sq	0.215	0.728	0.233
Obs	270	270	270

Table 7. Sobel-Goodman test.

	Path factor	Standard deviation	Z-value	P > |Z|
Sobel	0.136	0.056	2.426	0.015
Goodman-1 (Aroian)	0.136	0.056	2.416	0.017
Goodman-2	0.136	0.056	2.436	0.015
Indirect effects	0.136	0.056	2.426	0.015
Direct effect	0.208	0.099	2.096	0.036
Total effect	0.344	0.083	4.130	0.000
The proportion of mediating effect in the total effect		0.397		

the proportion of the mediating effect in the total effect is 39.7%, so that marketization plays a mediating role in the influence of the digital economy on agricultural green total factor productivity, which once again verifies that hypothesis H2 is valid, and the digital economy has an indirect effect on agricultural green total factor productivity through marketization.

5.2 Threshold Effect Test

It has been verified in the previous paper that the digital economy can contribute to the enhancement of green total factor productivity in agriculture and the mediating role of marketization, and this paper will further investigate whether this enhancement is linear. Therefore, according to Hansen [22] proposed the panel threshold model to test the relationship between the digital economy and agricultural green total factor productivity. The specific panel threshold model is set as follows.

$$GTFP_{\mathrm{it}} = \alpha_0 + \alpha_1 DIG * I(DIG \leq \Upsilon) + \alpha_2 DIG * I(DIG > \Upsilon) + \gamma X_{it} + \lambda_i + \eta_t + \varepsilon_{it} \tag{4}$$

where the threshold variable is the digital economy (DIG); I(·) denotes the indicator function; ¡ is the threshold to be estimated; the other variables are defined as shown in the previous section.

Bootstrap is used to estimate the threshold value and the corresponding statistics, the specific values are shown in Table 8, from which it can be seen that the single threshold is significant at the 5% level and the double threshold effect is not significant, indicating that the digital economy is not a simple linear relationship on green total factor productivity in agriculture, and there is a single threshold effect between them, which supporting hypothesis H3.

The results of the threshold regression (Table 9) show that when the threshold value is less than 0.018, the coefficient of the digital economy is significantly negative at the 1% level and plays a hindering role in the enhancement of green total factor productivity in agriculture; while when the threshold value prints 0.018, the coefficient of the digital economy is 0.517 and significant at the 1% level, indicating that when the

Table 8. Threshold test result.

	Threshold value	F-value	P-value	Number of BS	Threshold value			95% confidence interval
					10%	5%	1%	
Single threshold	0.018**	26.480	0.038	500	20.822	25.465	35.556	[0.0159,0.0182]
Double threshold	0.019	10.630	0.584	500	22.591	27.027	39.498	[0.0048,0.0194]

Table 9. Threshold regression result.

Variable	Panel Threshold Model	
	Coefficient	Standard error
*DIG*it **I* (¡ ≤ 0.018)	−7.486***	(1.651)
*DIG*it **I* (¡ > 0.018)	0.517***	(0.072)
Constant	−0.360	(0.221)
Control variable	YES	YES
R-sq	0.456	
Obs	270	

digital economy reaches a certain level, the effect on green total factor productivity in agriculture productivity enhancement is enhanced. The reason may be that in the initial stage of the digital economy, digital infrastructure is not perfect, there are high risks and uncertainties in technological innovation, farmers are not motivated to invest in digital technology and lack of incentives. Because uncertainties such as high inputs, high risks, and slow results make the digital economy inhibit the increase of agricultural green total factor productivity in the early stage. With the continuous advancement of science and technology, the digital economy continues to integrate with the real economy, prompting fundamental changes in production patterns and lifestyles within the agricultural sector, bringing a constant impetus to sustainable agricultural development, and the green total factor productivity of agriculture to further enhance.

6 Conclusions

Focusing on the digital economy and agricultural green total factor productivity, this paper measures the level of the digital economy and agricultural green total factor productivity using the entropy value method and the SBM method, respectively, based on panel data of 30 Chinese provinces from 2011–2019, and examines the overall effect, heterogeneous impact and mechanism of action of the digital economy on agricultural green total factor productivity from theoretical derivation and empirical testing. The findings show that, firstly, the digital economy significantly contributes to the improvement of agricultural green total factor productivity and has a significant boosting effect on the three major regions of east, central, and west as well as the two major regions of north and south, and is found to remain significantly positive after the endogeneity of the digital economy is treated by the instrumental variable method. These results remain robust after robustness tests with replacement measures, replacement of core explanatory variables, and taking into account extreme value disturbances. Secondly, the digital economy promotes the improvement of agricultural green total factor productivity through the marketization mechanism, and marketization plays a mediating role in this process. Thirdly, there is a threshold effect on the impact of the digital economy on agricultural green total factor productivity, and the effect between them is negative when the digital economy is below the threshold value of 0.018, while the digital economy can significantly promote agricultural green total factor productivity when the digital economy is above the threshold value of 0.018.

Based on the research conclusions of this paper, the following recommendations are proposed: First of all, increase R&D and investment in digital infrastructure and digital technology, and consolidate the construction of major data centers, cloud platforms, 5G, and other new digital infrastructure. Through top-level design, formulate scientific planning and strategic system, use digital technology to promote the development of “precision” and “green” agriculture, implement "precise monitoring" of agriculture, and actively introduce digital technology talents, especially in the backward regions in the central and western regions, to lay a good foundation for the integration of digital economy and agriculture, so as to release the vitality of the digital economy and cultivate a new engine for the development of green total factor productivity in agriculture. Second, further promote the marketization process and continue to push forward the reform of factor markets. In the development process of the digital economy, the faster the marketization process, the more investment will be made in innovation and R&D for green agricultural development. Therefore, give full play to the decisive role of the market in resource allocation, reduce “excessive government intervention” and lower the barriers to the flow of production factors, empower the digital economy and provide good market conditions for the development of green total factor productivity in agriculture. Finally, explore multi-dimensional ways for the digital economy to promote agricultural green total factor productivity. Facing the double impact of the century change and the COVID-19 pandemic, agriculture, as one of the pillars of the national economy, should promote the continuous integration of the digital economy and agriculture, take the opportunity of the development of the digital economy to break the “neck” of agriculture, promote the improvement of agricultural green total factor productivity, and achieve sustainable and healthy development of agriculture.

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