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Digital Transformation in Agriculture, Resilience of Agricultural Supply, and Agriculture Green Total Factor Productivity

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Abstract: *Digital construction has presented an opportunity for the transformation of agricultural productivity. Based on the panel data of 30 Chinese provinces from 2011 to 2020, this study systematically explores the impact and mechanisms of agricultural digitalization on agricultural green total - factor productivity (AGTFP), incorporating the mediating effect of supply resilience into the theoretical framework. The research reveals that regions with advanced digitalization are approaching the exhaustion of marginal dividends, while those with underdeveloped digitalization are on the verge of a growth spurt. It deconstructs the potential factors in rural digitalization that drive productivity growth, which can assist local governments in deriving policy - making basis, discerning the future potential of agricultural digitalization and productivity development from multiple perspectives, and promoting the high - quality development of China's agriculture in a targeted manner.*

Keywords: *Digital Transformation, Supply Resilience, Green Total Factor Productivity, High Quality Development of Agriculture*

1. Introduction

In its strategy to achieve high-quality development, China has clearly identified agriculture as one of the priority areas for development. In the context of the current rapid development of the global economy, digital information technology is innovating various industries at an unprecedented speed. Based on this background, agricultural digital transformation is not only an important strategy to achieve rural revitalization and agricultural modernization, but also a necessary means to enhance agricultural resilience and improve industrial risk response ability.

Existing research indicates that digital technology serves as an efficient medium for the widespread dissemination of agricultural market information and technical knowledge among agricultural producers[1]. This enables producers to promptly capture industry - related information and regulate the supply volume[2] and selling price[3] of their products. Moreover, rural e - commerce has resolved the external sales problem of mismatched supply - demand relationships[4]. However, in reality, compared with the digitalization of industry and service sectors, agricultural digitalization remains at an initial stage. In recent years, enhancing the resilience of the agricultural industry has become an increasingly crucial part of maintaining the stability of the national economy and social environment. Meanwhile, under the requirement of actively building new - quality productive forces in the industry, improving the green total factor productivity has become a core topic in current agricultural economic research. Based on the above - mentioned background, this paper uses the panel data of 30 provinces in China (excluding Tibet, Hong Kong, Macao, and Taiwan regions) from 2011 to 2020, incorporating agricultural digital transformation, supply resilience, and green total factor productivity into the same analytical framework for empirical testing. The research of this paper is conducive to enriching the theories related to the impact of digital technology on agricultural production, the direction of forging industrial resilience in the digital age, and the possibility of greening and improving agricultural productivity. It provides decision - making references for China to narrow the urban - rural gap, boost production and income of low - income farmer groups, improve the overall living standards of the nation, and promote the high - quality development of agriculture.

2. Study Hypothesis

2.1. Agricultural digital transformation promotes the improvement of AGTFP

Agricultural digital transformation plays a key role in promoting agricultural scale management and technological progress[5][6]. Digitalization optimizes the rural information exchange environment, reduces the opportunity cost of production activities, and thus promotes agricultural scale management. For example, the digital rural information platform provides timely and accurate market information, promotes the market-oriented reform of land elements, thereby reducing land transaction costs, stimulating land circulation, and effectively improving rural land management efficiency[7]. In addition, digitization provides convenience for farmers to learn new technologies, reduces the cost of technology learning and mastering, promotes the wide application and promotion of green production technologies, and achieves the goal of green production. The digital transformation of agriculture promotes the efficient use of resources by optimizing resource allocation[8], and realizes the optimal allocation of resources, reduces energy consumption, and achieves the dual goals of environmental protection and resource conservation by giving play to the reproducibility, renewability, non-consumability and sharing of data. In summary, research hypothesis H1 is proposed: agricultural digital transformation significantly improves AGTFP.

2.2. Agricultural digital transformation strengthens the resilience of agricultural supply through digital construction

The digital transformation of agriculture has significantly improved the resilience of agricultural supply. First of all, digital economy breaks through the blockage points and connection breakpoints of the industrial chain through new data elements[9]. Data-driven industrial chain management improves agricultural production efficiency and enhances agriculture's ability to resist external shocks. Secondly, digital infrastructure construction plays a key role in data generation, recording, collection, storage and use, providing multifaceted support for agricultural production activities[10]. In recent years, the application of e-commerce, as a digital landmark product, in the field of agriculture has significantly promoted the increase of farmers' income[11]. To sum up, H2 is proposed: agricultural digital transformation has a significantly positive effect on agricultural supply resilience.

2.3. Resilience of agricultural supply Increases AGTFP through green, coordinated and sustainable development

Agricultural digital transformation further promotes the improvement of agricultural green TFP by enhancing the supply capacity of agricultural output. The application of digital technology in agricultural production can break the time and space limitation through network media and platform channels, promote the integration of the three industries of agriculture, effectively improve the total value of agricultural production and the efficiency of product circulation, and lay a foundation for the improvement of agricultural green TFP. In addition, the application of digital technology effectively regulates the relationship between agricultural production and consumption, enhances the adaptability and resilience of the agricultural system[12], promotes the interconnection of grain production, trading and service links by providing complete information, optimizes the allocation of production factors and improves the decision-making efficiency of operators in the industrial chain. Enable agricultural systems to quickly recover and adapt to new growth paths and strengthen supply resilience. To sum up, we put forward research hypothesis H3: agricultural supply resilience plays an intermediary role in the process of agricultural digital transformation affecting AGTFP.

2.4. Agricultural technology innovation enables agricultural digitalization to improve AGTFP

Agricultural technological innovation can empower the promoting effect of agricultural digital transformation on AGTFP by enhancing the level of technology application[13]. Firstly, agricultural digital transformation relies on big data and new technologies to reconfigure agricultural factor allocation, making resource input in agricultural production more precise and efficient. The continuous innovation of agricultural technology brings breakthroughs to agricultural production and helps to enhance AGTFP. For instance, the application of new agricultural technologies brought about by technological innovation, such as 5G, artificial intelligence, and the Internet of Things, has greatly promoted the intelligence and greening of agricultural production[14]. Agricultural digitalization utilizes new information technologies such as cloud computing and blockchain to support the management model of agricultural enterprises to develop towards high efficiency and greenness, improving agricultural production efficiency and reducing environmental pollution, thus achieving the practical goal of enhancing AGTFP. In conclusion, the research hypothesis H4 is proposed: Agricultural technological innovation plays a positive moderating role in the process of agricultural digital transformation influencing AGTFP.

3. Variables and model design

3.1. Indicator system of variables

Agricultural digital transformation covers three aspects: digital construction foundation, digital agricultural operation and digital life service for farmers, corresponding to three elements: material and technical support, digital program operation and farmers' habit formation. The specific evaluation system is shown in Table 1.

Table 1 Definition of agricultural digital transformation evaluation index system

Dimension	Indicator	Unit
Agricultural Digital Foundation	Telecommunication Business Volume per 10,000 People	100 million yuan / 10,000 people
	Internet Communication Level	10,000 units
	Social Digital Industry Fixed Investment	10,000 yuan
	Social Digital Service Fixed Investment	10,000 yuan
Production Digitalization	Agricultural Production Environment Monitoring Situation	unit
Business Digitalization	Number of Enterprise Websites per 100 Enterprises	unit
	Activity Level of Enterprises Participating in E - commerce	%
	E - commerce Sales Volume	100 million yuan
	E - commerce Purchase Volume	100 million yuan
Circulation Digitalization	Rural Postal Communication Service Level	person / unit
	Rural Delivery Routes (Logistics)	km
	Proportion of Villages with Access to Postal Service (Logistics)	%
Life Service Digitalization	Quantity and Scale of Rural Network Investment	-
	Quantity and Scale of Rural Network Payment	-
	Rural Residents' Communication and Transportation Expenditure Level	%

Referring to He Yali's explanation of the concept of resilience of agricultural economy, this paper starts from three aspects: modern technology support, solid self-generation and self-healing ability, and long-term stability[15], and describes the resilience of agricultural supply with the core meaning of "promoting production and ensuring supply." The details are shown in Table 2.

Table 2 Definition of agricultural output supply resilience evaluation index system

Capability	Indicator	Unit
Production - Supply - Chain - Building Ability	Total output value of the primary industry / GDP	%
	Total grain output	10,000 tons
	Total output value of agriculture, forestry, animal husbandry and fishery	10,000 yuan
	Fixed - asset investment of rural households in agriculture, forestry, animal husbandry and fishery	100 million yuan
	Local fiscal expenditure on agriculture, forestry and water affairs	100 million yuan
Coordination - Chain - Consolidation Ability	Rural consumer goods retail sales / social consumer goods retail sales	%
	Proportion of rural residents' household food consumption	%
	Rural per - capita disposable income	Yuan / person
	Rural residents' per - capita consumption expenditure	Yuan / person
Innovation - Chain - Stabilization Ability	Number of personnel in agricultural science and technology activities	Persons
	Local fiscal expenditure on science and technology	100 million yuan

This paper will use the GML index method to measure AGTFP. Referring to the practice of Gao Fan[16] and Jin Shaorang[5], we selected employees in the primary industry, total power of agricultural machinery, actual application rate of agricultural chemical fertilizer, total sower area of crops, effective irrigation area, added value of the primary industry (2010 is taken as the base period, and the multiplicative index is used to eliminate the impact of price), and carbon emissions of agricultural production as inputs, desired outputs and undesirable outputs. The details are shown in Table 3.

Table 3 Description of the selection of agricultural green TFP measurement indicators

Type	indicator	Description	Unit
Input	Agricultural Labor Force	The number of employees in the primary industry	10,000 people
	Agricultural Machinery	The total power of agricultural machinery	10,000 kW
	Fertilizer Application	The actual application amount of agricultural fertilizers (pure)	10,000 t
	Land use	The total sown area of crops	10,000 hm^2
	Irrigation Area	The effective irrigation area	10,000 hm^2
Desired Output	Agricultural Output Value	The added value of the primary industry	100 million yuan
Undesired Output	Agricultural Carbon Emissions	The amount of carbon emissions from agricultural production	10,000 t

This paper starts from the input level of technological innovation and attempts to construct an accurate level of agricultural technological innovation. Tang Weibing proposed two measurement methods[17]: one is to use the proportion of R & D expenditure in GDP, and the other is to use the proportion of scientific and technological innovation input in GDP. This paper will adopt the second method and establish the formula “agricultural technological innovation level = agricultural scientific research input / total output value of agriculture, forestry, animal husbandry and fishery” for measurement. Since the agricultural scientific research input cannot be directly obtained from the existing statistical data, and considering that the ultimate goal of scientific research input is to achieve technological innovation in new processes, new materials, components, manufacturing drawings, etc., a regulation coefficient is constructed from the perspective of the number of patent applications authorized, and the formula “agricultural scientific research input = internal R & D expenditure × (the number of authorized agricultural three - type patents / the number of domestic three - type patents)” is established for measurement. The specific calculations are shown in formulas(1) and (2).

$$ARinvest = R\,\&\,D \times \left(\frac{AP}{P}\right) \tag{1}$$

$$ATinovation = \frac{ARinvest}{AGDP} \tag{2}$$

Among them, $ARinvest$ represents agricultural research investment, $R\,\&\,D$ represents internal R&D investment, AP represents the number of three types of agricultural patents authorized, P represents the number of three types of domestic patents authorized, $ATinovation$ represents the level of agricultural technology innovation, and $AGDP$ is the total output value of agriculture, forestry, animal husbandry and fishery.

Finally, combined with the existing relevant literature[18][19] and based on the research theme of this paper, four variables related to agricultural green TFP, namely urbanization rate (Urban), rural Road level (Road), Telecom development level (Telecom) and agricultural industrial Structure adjustment index (Structure), are selected as control variables. To more accurately measure the relationship between the studied variables.

3.2. Research scope and data sources

In this study, the data of 30 provinces (municipalities and autonomous regions) in China from 2010 to 2020 are collected, and the balanced panel data from 2011 to 2020 are synthesized and calculated by entropy method as the research scope. The data come from China Statistical Yearbook, China Rural Statistical Yearbook, China Statistical Yearbook on Environment, China Statistical Yearbook on Trade

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and Foreign Economy, China Statistical Yearbook on Fixed Assets, China Statistical Yearbook on Science and Technology, annual provincial data of the National Bureau of Statistics, CNKI Patent Database, CSMAR database, Peking University Digital Inclusive Finance Index, and A Li Research Institute report, China agricultural products import and export monthly statistical report.

3.3. Design of Mediating Effect Model

In order to test the coefficient c of the total effect of agricultural digital transformation on agricultural green TFP, the basic model is constructed as shown in Formula (3), and the significance of coefficient c is observed:

$$AGTFP_{it} = \beta_0 + c \cdot DIG_{it} + d_0 \cdot Controls_{it} + \sum province + \sum year + \varphi_i + \mu_t + \varepsilon_{it} \tag{3}$$

Among them, $AGTFP_{it}$ represents the AGTFP of region i in year t; β_0 is the intercept; c is the total - effect coefficient of agricultural digital transformation; DIG_{it} is the level of agricultural digital transformation of region i in year t; ε_{it} is the residual; $Controls_{it}$ is a series of control variables; d_0 is the regression coefficient of the control variables; φ_i is the individual fixed effect; and μ_t is the time fixed effect.

To test whether the α coefficient of the indirect impact of agricultural digital transformation on agricultural supply resilience is significant, the benchmark model is constructed as shown in formula (4).

$$RES_{it} = \gamma_0 + a \cdot DIG_{it} + d_1 \cdot Controls_{it} + \sum province + \sum year + \varphi_i + \mu_t + \varepsilon_{it} \tag{4}$$

In this context, RES_{it} is the agricultural supply resilience of region i in year t ; γ_0 is the intercept; α is the indirect - effect coefficient of agricultural digital transformation; ε_{it} is the residual.

To test whether agricultural supply resilience has a mediating effect on the impact of agricultural digital transformation on AGTFP and to what extent it acts, the model is constructed as shown in the formula, and the significance of the direct - effect coefficient c' and the indirect coefficient b is examined. Based on formula (3), the linear regression model formula (5) for agricultural digital transformation, agricultural supply resilience, and AGTFP is constructed.

$$AGTFP_{it} = \delta_0 + c' \cdot DIG_{it} + b \cdot RES_{it} + d_2 \cdot Controls_{it} + \sum province + \sum year + \varphi_i + \mu_t + \varepsilon_{it} \tag{5}$$

Among them, δ_0 is the intercept; c' is the direct - effect coefficient of agricultural digital transformation; b is the indirect - effect coefficient of agricultural supply resilience; ε_{it} is the residual.

3.4. Design of Moderating Effect Model

To explore the moderating effects under different levels of agricultural technological innovation, the following moderating effect model (6) is constructed:

$$AGTFP_{it} = \chi_0 + \chi_1 DIG_{it} + \chi_2 TEC + \chi_3 DIG_{it} \cdot TEC_{it} + \lambda Controls_{it} + \sum province + \sum year + \varphi_i + \mu_t + \varepsilon_{it} \tag{6}$$

Among them, TEC_{it} is the level of agricultural technological innovation in region i in year t, that is, the moderating variable. If χ_1 is significantly positive and χ_3 is significantly positive, it means that the moderating variable enhances the promotion effect of digital transformation on AGTFP. If χ_1 is significantly positive and χ_3 is significantly negative, it means that the moderating variable reduces the promotion effect of digital transformation on AGTFP. If χ_1 is not significant or χ_3 is not significant, it indicates that the moderating effect does not exist.

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4. Empirical Process and Result Analysis

4.1. Benchmark Regression

To eliminate the potential biased impacts of individuals and time on the model estimation, a time - individual double fixed - effect model is adopted for empirical regression (and the fixed - effect model is used in all subsequent tests). The results are shown in Table 4.

In Table 4, Model (1) aims to test the impact of agricultural digital transformation on AGTFP; Model (2) examines the impact of DIG on agricultural supply resilience; Model (3) takes into account the simultaneous effects of agricultural digital transformation and agricultural supply resilience on AGTFP, and the results show the mediating role played by agricultural supply resilience; Model (4) is a mechanism test for the role of the level of agricultural technological innovation as a moderating variable. The above - mentioned empirical results verify Hypotheses H1, H2, H3, and H4, and all are significant at the 1% or 5% level.

Table 4 Benchmark regression

	(1)	(2)	(3)	(4)
	AGTFP	RES	AGTFP	AGTFP
DIG	0.2120^{**}	0.5403^{***}	0.0538	0.2439^{**}
	(0.0893)	(0.0400)	(0.1160)	(0.0945)
RES			0.2928^{**}	
			(0.1385)	
DIGTEC				3.6823^{***}
				(1.1314)
TEC				-2.0045^{***}
				(0.6273)
Control Variables	Y	Y	Y	Y
Time Effect	Y	Y	Y	Y
Individual Effect	Y	Y	Y	Y
_cons	0.5717^{***}	-0.2234^{***}	0.6371^{***}	-0.0297
	(0.1152)	(0.0517)	(0.1186)	(0.2023)
N	300	300	300	300
adj. R^2	0.6092	0.8967	0.6145	0.8296

Note: *, **, and *** denote significance at the 10%, 5%, and 1% statistical levels respectively; the values in parentheses are robust standard errors.

4.2. Robustness Test

This paper conducts robustness tests by adjusting the sample interval and using instrumental variables. (1) Since the 18th National Congress of the Communist Party of China, China has attached even greater importance to rural digitalization, ecological civilization construction, and the construction of high - standard farmland. A series of appropriate policies have emerged in an endless stream. The "Two - Mountain Theory" and the "High - quality Development Goals", which embody the concept of sustainable development, have gradually penetrated into various industries and become strict operating standards. Therefore, the original sample interval is adjusted, and the data from 2013 to 2020 are used to measure the impact of digital transformation on agricultural economic resilience and AGTFP. (2) Aspects such as infrastructure building, technology application, and talent cultivation involved in agricultural digital construction all require a certain amount of time to truly integrate into all aspects of rural production and life. For example, in the initial stage, rural digitalization mainly focuses on the expansion of hardware equipment and network coverage. The educational level of farmers also affects their need to spend more time accepting new technologies. Based on the general characteristic of the lag in the impact of digitalization on agricultural economic development, the digital transformation is lagged by one period, and the impact of digital transformation on agricultural economic resilience and AGTFP is measured. The test results are shown in Table 5. The test results remain robust.

Table 5 Robustness Test

	Adjust the sample interval(2013-2020)		Instrumental variable	
	AGTFP	RES	AGTFP	RES
DIG	0.1877**	0.4957***		
	(0.0939)	(0.0419)		
DIGt-1			0.1769*	0.5476***
			(0.0975)	(0.0462)
Control Variables	Y	Y	Y	Y
Time Effect	Y	Y	Y	Y
Individual Effect	Y	Y	Y	Y
_cons	0.6682***	-0.2412***	0.6775***	-0.2230***
	(0.1397)	(0.0623)	(0.1214)	(0.0575)
N	240	240	270	270
adj. R2	0.6168	0.8655	0.6324	0.8779

4.3. Heterogeneity Test

To explore whether the degree of agricultural digital transformation leads to heterogeneity, this paper calculates the average value of the entropy scores of digital transformation in 30 regions over 10 years. Then, based on the average value, the regions are ranked. The top 14 regions in terms of scores are selected as the strong - digitalization group, and the bottom 14 regions are selected as the weak - digitalization group. The middle - ranked regions are excluded to form two experimental groups.

After distinguishing the strong and weak degrees of digital transformation, as can be seen from the test results in Table 6, agricultural digital transformation still has a significant positive impact on agricultural supply resilience. In regions with relatively complete digitalization, the impact of digitalization on AGTFP is not significant. This may be because the digital construction in these regions is approaching saturation. Due to the law of diminishing marginal returns, the contribution of digitalization to the growth of AGTFP is weakened (the coefficient is smaller than that of the weak - digitalization group) or not obvious. The positive moderating effect of technological innovation in regions with weak digitalization remains significant.

Table 6 Regression Results by Degree of Digitalization Grouping

	Strong - digitalization Group			Weak - digitalization Group		
	(1)	(2)	(3)	(1)	(2)	(3)
	AGTFP	RES	AGTFP	AGTFP	RES	AGTFP
DIG	0.1967	0.4795***	0.1483	0.8568***	0.3649***	0.8810***
	(0.1810)	(0.0519)	(0.1780)	(0.2253)	(0.1138)	(0.1961)
DIGTEC			5.0682**			42.0541***
			(1.9499)			(6.9403)
TEC			-2.5015**			1.9840**
			(1.2206)			(0.8396)
Control Variables	Y	Y	Y	Y	Y	Y
Time Effect	Y	Y	Y	Y	Y	Y
Individual Effect	Y	Y	Y	Y	Y	Y
_cons	0.3397	-0.4849***	-0.2962	1.0115***	0.0922	0.3312*
	(0.2517)	(0.0722)	(0.4995)	(0.1319)	(0.0666)	(0.1785)
N	140	140	140	140	140	140
adj. R2	0.5242	0.9568	0.8405	0.7175	0.8663	0.8418

5. Conclusions and Recommendations

5.1. Research Conclusions

Through empirical tests, it has been proven that agricultural digital transformation indeed promotes agricultural green total factor productivity (AGTFP). Agricultural supply resilience acts as a positive mediator in this process, and agricultural technological innovation serves as a positive moderating variable. That is, technological innovation can amplify the positive impact of digital transformation on

AGTFP.

In the heterogeneity test: In regions with a relatively high degree of digital transformation, due to the law of diminishing marginal returns, the contribution of digital construction to the growth of AGTFP is weak. In regions with a relatively low degree of digitalization, they can still enjoy the growth dividends of digital construction for AGTFP. That is, in these regions, the potential of digital transformation has not been fully exploited, and there is still significant room for growth. Moreover, agricultural technological innovation plays a positive moderating role.

5.2. Policy Recommendations

Based on the above research conclusions, in order to promote agricultural digital transformation, enhance supply resilience and green total factor productivity, it is necessary to prioritize the strengthening of digital infrastructure construction, ensure the coverage of rural 4G and 5G networks, and eliminate regional gaps in digital construction as soon as possible. Additionally, financial subsidies and preferential loans should be provided to support the popularization of intelligent devices such as drones and intelligent irrigation systems, so as to improve the level of production automation and precision. The government needs to set up special funds to support the research and development of digital agricultural technologies that are low - cost, high - performance, and adaptable to local characteristics, and widely promote the application of these technologies, enabling more regions to enjoy the productivity growth dividends brought about by digitalization.

Furthermore, led by the government and assisted by society, a unified agricultural big data platform should be constructed to achieve the sharing and interconnection of agricultural data, and improve the scientific nature of management and decision - making. The platform must provide timely and accurate market prices, supply - demand information, and policy updates to help farmers make scientific decisions, avoid market risks, and enhance their market adaptability. In terms of policy standards, relevant standards and specifications for digital agriculture should be further formulated and promoted to ensure data interconnection and technological consistency. Relevant laws and regulations should be revised and improved to protect farmers' rights and interests and data security, prevent risks, and maintain a fair market environment. Local governments should coordinate local agricultural digital construction, allocate resources, and implement policies to ensure shared development opportunities. They should also strengthen regional cooperation to avoid redundant construction and maximize the productivity - promoting effect of digital transformation.

Finally, efforts should be made to strengthen professional education and training in agricultural digitalization, cultivate professional talents, establish a farmer training system, improve farmers' awareness and application ability of digital agricultural technologies, support the development of agricultural researchers and technology extension personnel, and promote the integration of technological innovation and practical application. The government should strengthen cooperation with enterprises to promote coordinated development between the government and enterprises, integrate resources from multiple parties, enhance supply resilience and productivity. It should encourage universities and research institutions to participate in digital agricultural research and practice, and promote the transformation and application of agricultural scientific and technological achievements.

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