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How does the development of rural broadband in China affect agricultural total factor productivity? Evidence from agriculture-related loans

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Introduction: The construction of digital villages is widely acknowledged as a way to achieve the "dual goals" of high quality of the agricultural and rural economy and common prosperity under the digital China strategy. Studies have explored the socio-economic benefits of different aspects of rural digitization, but few have focused on the productivity role of rural broadband development in the context of the urban-rural broadband divide. The purpose of this paper is to explore the relationship between rural broadband development and agricultural total factor productivity (TFP) and the intrinsic mechanism of action, and to provide empirical evidence on the productivity effect of promoting digital transformation in rural agriculture.

Methods: Using panel data from 31 provinces in China from 2011 to 2020, this paper investigates the impact and mechanism of rural broadband development on agricultural TFP from the perspective of agriculture-related loans by setting up a two-way fixed effects model, a mechanism effects model and a threshold effects model.

Results: The results find that rural broadband development has a significant role in enhancing agricultural TFP. Heterogeneity analysis indicates that the productivity-enhancing effect of rural broadband development is remarkable only in the central region and the region with higher rural disposable income. Mechanism analysis points out that rural broadband development can increase agricultural TFP by influencing the share of farm-related loans. Threshold analysis further reveals that the role of increasing the share of farm-related loans on agricultural TFP is marked only after rural broadband development reaches a certain level.

Discussion: These findings can provide practical guidance for other developing countries in accelerating the digital transformation of villages and optimizing factor allocation to achieve high-quality agricultural development.

KEYWORDS

agricultural total factor productivity, rural broadband development, agriculture related loans, China, digitalization

1 Introduction

With the promotion, application, innovation, and upgrading of the new generation of information technology, the digital economy has become a new form of economic development in various countries (Pan et al., 2022). Relevant data show that the scale of digital economic value added in 47 countries reached 38.1 trillion US dollars in 2021, with 45 percent of gross domestic product (GDP) providing important support for the global economic recovery, of which the industrial digitization scale is $32.4 trillion.[1] As an important engine of the digital economy, industrial digitization refers to the increase in output and efficiency brought about by the application of digital technology in traditional industries. With the increasing penetration of digital technology in various stages, such as production, distribution, and sales, scholars have conducted a series of studies on industrial digitalization, combining digital technology application practices (Malik et al., 2022) and application prospects (Deller et al., 2021). Although the level of agricultural digitization is relatively low due to the characteristics of the industry (Rijswijk et al., 2021), the regional digital divide (Philip and Williams, 2019), and other constraints, its importance to the development of the agricultural economy, the importance of social harmony and stability and the transformation of the national economy, and the related issues that determine the interaction between digital technology and the development of the agricultural industry will remain a focus of attention for stakeholders in the future.

According to a McKinsey research report[2], by 2030, the widespread adoption of agricultural internet could bring an additional value of $500 billion to the global GDP, which is 7 to 9% higher than the previously expected total. To ensure interconnectivity between rural households, farms, and businesses, the US Department of Agriculture (USDA) invested $1.3 billion in rural broadband infrastructure in 2020[3]. As a digital technology, broadband internet has obvious advantages in reducing the time cost of production and marketing information transmission (Ogutu et al., 2014; Fernando, 2021). Scholars have studied the utility of different digital tools in terms of technology adoption (Zhu et al., 2021), poverty reduction, and income generation (Leng, 2022) in the context of their practical application, but the relationship with agricultural productivity has been less explored. Existing studies on agricultural productivity have centered on its measurement and evolution (Wang et al., 2019), influencing factors (Fabregas et al., 2019), allocative efficiency (Liu D. et al., 2023; Liu S. et al., 2023; Zhang A. et al., 2023; Zhang X. et al., 2023), etc. The digital transformation of agriculture in the digital era adjusts the dynamics of agricultural economic growth (Fu and Zhang, 2022; Shen et al., 2022) and creates opportunities to improve the long-standing factor-input-led agricultural economic growth (Gong, 2018). As a key to agricultural digitization, rural broadband development can provide a strong and reliable network base for diverse digital technology applications (Malik et al., 2022). Therefore, this paper attempts to analyze the relationship between rural broadband development and agricultural TFP at the macro level in order to strengthen the general understanding of the sharing of digital dividends on the production side of agriculture and to help scale and intensify the development of agricultural and rural digitization.

Credit is a crucial component of agricultural production systems that can provide producers with financing for production (Feder et al., 1990), but credit constraints have been a significant factor contributing to the adoption of modern agricultural technologies and low agricultural productivity in l middle- and low-income countries (Balana et al., 2022). Smallholder farmers, in particular, have long been constrained in their production investment decisions by the financial market environment (Karlan et al., 2014). Governments have actively formulated differentiated lending policies and fiscal policies to guide the flow of financial capital to rural areas and agriculture to reduce credit constraints, such as China's agricultural loan increase incentive policy in 2009. Compared with other informal financial institutions, agriculture-related financial institutions can, to a certain extent, alleviate the exclusion of investment in the "three rural" sectors by the profit-oriented attributes of the capital market. The purpose of obtaining credit is to finance agricultural production (Ai et al., 2023), and formal sources of credit have higher rates of technology adoption (Regassa and Melesse, 2023). So, can rural broadband development in the context of digitization leverage its advantages in reducing market information uncertainty (Crawford et al., 2018) and innovating financial products (Niu et al., 2022) to ease agricultural credit constraints and enhance agricultural TFP? Therefore, this paper focuses on refining the role of Internet broadband technology in both new technological innovations and the reduction of information asymmetry, drawing the logical framework shown in Figure 1.

This research uses data from provincial panel surveys from 2011 to 2020 in China to investigate the mechanisms and impacts of rural broadband development on agricultural TFP from the perspective of loans related to agriculture. The possible contributions of this paper are as follows: first, although the existing literature has explored the impact of different aspects of rural digital transformation on agricultural total factor productivity, this paper finds ways to improve the rate of agricultural total factor productivity development by analyzing the impact of rural broadband development on agricultural total factor productivity based on the fact of the digital access gap between urban and rural areas in China and in light of the importance that countries have attached to investment in rural broadband development. Second, based on the importance of credit to agricultural production, this paper analyzes the role of agriculture-related loans in the relationship between rural broadband development and agricultural total factor productivity and broadens the path for improving agricultural total factor productivity in the digital transformation of the countryside. Third, this study further points out the variability of the role constraints and effects that rural broadband development has on productivity in different agriculture-related loan allocations, providing ideas for optimizing factor allocation.

The remainder of the study is structured as follows: Section 2 gives the theoretical mechanisms and research hypotheses. Section 3 is the research design. Section 4 is the analysis of the empirical results. Section 5 is the discussion. Section 6 presents the conclusion and policy recommendations.

2 Theoretical mechanism and research hypothesis

2.1 Relationship between rural broadband development and agricultural TFP in China

The advancement of agricultural TFP has long been the subject of research since it is a crucial sign of high-quality agricultural development (Fan, 1991; Bustos et al., 2016; Gebresilasse, 2023). In addition to being the cornerstone of sustainable economic development and the foundation of national economic growth (Gong, 2020), improving agricultural TFP is a key strategy for enhancing food conversion efficiency (Searchinger et al., 2018) and optimizing the rural industrial structure (Bustos et al., 2016). In the past, expansion based on inputs was the primary driver of agricultural output growth. In order to change the resource and environmental destruction caused by past input-based agricultural growth patterns, alleviate the current

1 http://www.caict.ac.cn/kxyj/qwfb/bps/202212/t20221207_412453.htm.

2 https://www.mckinsey.com/.

3 Secretary Perdue Applauds USDA's 2020 Accomplishments USDA.

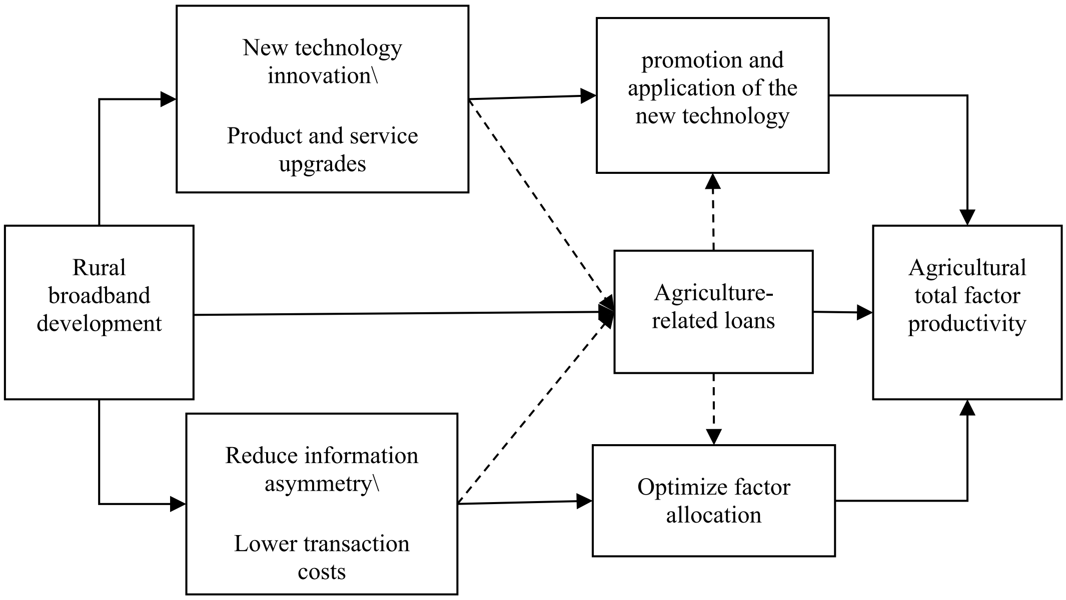

FIGURE 1
Logical framework of the mechanism.

pressure of rising factor costs, and meet future demands for healthy and nutritious food, institutional changes (Sheng et al., 2019), technological advances (Gong, 2018; Chambers and Pieralli, 2020) are needed to enhance the ability to respond to technological frontiers for to cope with weather changes and increase agricultural productivity.

The innovative application of diverse digital technologies such as IoT and blockchain under the rapid growth of information and communication technologies has created conditions for the digitalization of agriculture (Shen et al., 2022). Among them, agricultural broadband development can provide a reliable and powerful network foundation for its digital transformation and scale development. First, rural broadband development has the generic attributes of information and communication technology, which can break the spatial and temporal barriers of information transmission (Wu and Zhang, 2020). The negative impact of market information asymmetry and long distribution channels on the total and structural imbalance between supply and demand of farm products has seriously hindered the improvement of agricultural production efficiency and effectiveness, while the construction of network bridges under rural broadband development can increase the connectivity density between the main bodies, and improve the access to the market for small farmers (Ogutu et al., 2014).

Second, rural broadband growth is conducive to the subjects' enrichment of technology access and innovation of production and business models (Pant and Odame, 2017). Such as small farmers can use cell phones and computers to obtain production technology guidance (Zhu et al., 2021), and adjust agricultural fertilizer and other factor inputs (Ma and Zheng, 2021). At the same time, as the "last mile" of the digital divide, the scaled-up growth of rural broadband can maximize the digital dividend brought by market connectivity and make up for the higher construction costs (Hambly and Rajabiun, 2021). The emergence of distinctive "Taobao villages"[4] across China in recent years is also a manifestation of the large-scale expansion of rural expansion, which has effectively improved the structure of the rural labor force and promoted qualitative agricultural development.

Third, the expansion of rural broadband could provide the network infrastructure that smart agriculture and precision agriculture require (Jiang et al., 2022). The integration of various digital technologies can improve the accuracy of factor inputs, achieve product traceability, innovate industrial organization, and increase productivity (Gebbers and Adamchuk, 2010; Fu and Zhang, 2022), but the realization of all these utilities is based on the premise of information interconnection, real-time data transmission, and effective analysis of the whole agricultural industry chain. Finger et al. (2019) also clearly stated that providing high-speed internet access to farmers is the essence of precision agriculture extension. Therefore, regardless of whether rural broadband is a communication infrastructure or an information delivery vehicle, the agricultural sector can maximize economic benefits through technological change (Farrokhi and Pellegrina, 2023).

> *Hypothesis 1*: China's rural broadband development can boost agricultural TFP.

2.2 The mechanism of rural broadband development's effects on China's agricultural TFP

Credit constraints have always been one of the main reasons for the low adoption of modern agricultural technologies and low agricultural productivity in middle- and low-income countries (Balana et al., 2022). This is partly related to historical factors, such as the reallocation of rural savings to urban areas due to the scissor effect between agriculture and industry during the process of

4 aliresearch.com. the 1% Change: 2020 China Taobao Village Research Report.

economic development (Tsai, 2004), as well as by smallholder farmers' own factors, such as limited knowledge of market information, fear of uncertain risks, and insufficient collateral (Balana et al., 2022). The market-oriented development of finance and the imperfection of rural credit institutions further induce small farmers to invest their surplus savings in other regions or nonagricultural industries, exacerbating the impact of credit constraints on agricultural production development. Scholars have explored a great deal around credit and agricultural production (Feder et al., 1990; Burgess and Pande, 2005). For example, land titling can alleviate the credit constraints of smallholder farmers with insufficient collateral (Gong and Elahi, 2022), access to credit can facilitate smallholder farmers' choice of more productive technologies (Hossain et al., 2018), and sufficient credit funds can also increase agriculture inputs or make other productive investments.

ICTs have revolutionized the financial sector landscape (Niu et al., 2022). First, rural broadband can take advantage of ICTs in overcoming spatial and temporal constraints on information dissemination, reducing information asymmetry, and search costs (Wu and Zhang, 2020). Small farmers can utilize rural broadband for multi-subject online exchanges, access to production experience, and credit knowledge, and reduce uncertain risks, and can also accumulate human capital, and social capital to improve credit levels and broaden credit access channels. The current innovation of digital financial products and services has also alleviated, to a certain extent, the constraints of market uncertainty and lack of collateral faced by traditional finance (Crawford et al., 2018). Second, the innovative use of various digital technologies under rural broadband growth facilitates precise factor inputs, directly reduces production costs (Fabregas et al., 2019), and promotes the digital transformation of agriculture (Malik et al., 2022).

> *Hypothesis 2*: China's rural broadband development can affect agricultural TFP through agricultural loans and unleash the contribution of the ratio of farm-related loans to agricultural TFP.

ICTs can contribute directly to economic growth and can also increase the indirect effects of financial development on economic growth after a certain level of development (Gheraia et al., 2021). In terms of the economic growth effect of agriculture-related loans, although credit support can promote the adoption of higher productivity technologies, the increase in investment efficiency or profitability is also influenced by other factors (Hossain et al., 2018). For instance, by distributing risk and covering losses, agricultural insurance may expand the amount of credit available to farmers (Ai et al., 2023) and boost smallholder investment (Karlan et al., 2014). In contrast, rural broadband connectivity can mitigate market investment risks caused by information asymmetry, and the corresponding scale of development and the application of diverse digital technologies can enhance the early warning of natural risks, thus fundamentally and multidimensionally enhancing the efficiency-enhancing role of agriculture-related loans.

> *Hypothesis 3*: The productivity-enhancing effect of the agri-related loan share is affected by rural broadband growth, and the contribution of the ratio to TFP in agriculture will be noteworthy only when rural broadband development reaches a certain level.

Based on the above analysis, Figure 2 presents a simple theoretical analysis diagram.

3 Data sources and methodology

3.1 Data sources

Combined with the availability of relevant variables in the research question, this paper selects 31 provincial panel data from 2011 to 2020 in China to analyze the impact and mechanism of rural broadband development on agricultural TFP based on agricultural loans. The following are the specific data sources. (1) The China Statistical Yearbook, China Population and Employment Statistics Yearbook, and statistical yearbooks for various Chinese provinces and cities are the sources of the input–output indicators of agricultural TFP, rural broadband growth indicators, and crucial control variables. (2) The primary sources of information regarding loan indicators relating to agriculture are the China Financial Statistics Yearbook and the China Rural Financial Services Report. (3) The digital finance index is from the Digital Finance Research Center of Peking University.

3.2 Variables

3.2.1 Dependent variable

This study utilizes the MaxDEA 7 Ultra software to measure the Global Malmquist index (GMI) as an indicator for calculating the TFP in agriculture. Considering the decomposability of the GMI, this index can be further defined as shown in Equation (1):

$$GMI_g\left(x^{t+1}, y^{t+1}, x^t, y^t\right) = \frac{E^g\left(x^{t+1}, y^{t+1}\right)}{E^g\left(x^t, y^t\right)} = \frac{E^{t+1}\left(x^{t+1}, y^{t+1}\right)}{E^t\left(x^t, y^t\right)} \left(\frac{E^g\left(x^{t+1}, y^{t+1}\right)}{E^{t+1}\left(x^{t+1}, y^{t+1}\right)} \frac{E^t\left(x^t, y^t\right)}{E^g\left(x^t, y^t\right)}\right) = EC_g * TC_g \quad (1)$$

where $E^g\left(x^{t+1}, y^{t+1}\right)$ and $E^g\left(x^t, y^t\right)$ denote the global distance indices in period t + 1 and period t, respectively. Considering the cumulative nature of the GMI index, namely TFP, this analysis uses 2011 as the base period for the gross output value of agriculture, forestry, animal husbandry, and fishery at constant prices. The input indicators specifically represent the input quantities of labor, land, machinery, fertilizer, and water resources, respectively. They include the total number of employees in the primary industry (10,000 people), the total area used for cultivation and aquaculture (1,000 hectares), the total power of agricultural machinery (10,000 kilowatts), the pure amount of chemical fertilizer applied (10,000 tons), and the amount of agricultural water consumed (100,000,000 cubic meters).

3.2.2 Independent variable

In terms of rural broadband development, this study adopts the rural *per capita* internet broadband penetration rate as its alternative variable, specifically measured by the ratio of the number of rural

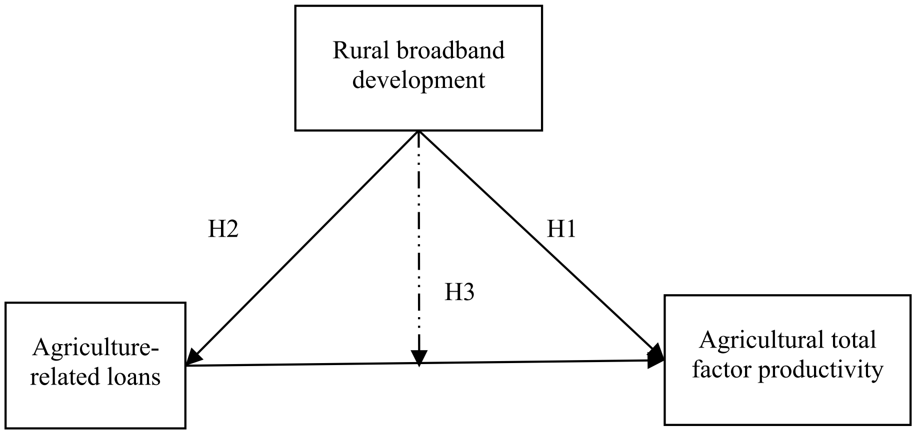

FIGURE 2
Theoretical analysis diagram.

internet broadband access households to the number of rural households. On the one hand, this is because the rural labor force's current organizational structure favors the use of mobile phones and other internet technologies more for communication and leisure than for production and operations. On the other hand, effective connectivity of rural broadband internet and network sharing can lower the scale-related costs of production and operations for the labor force involved in returning to their hometown for entrepreneurship, contributing to sustainable development. Philip and Williams (2019) also argued that it is important to focus on the availability and degree of rural broadband connectivity to drive the digital transformation of rural agriculture.

3.2.3 Control variables

By combing through the existing literature, this study further controls for other variables that may affect agricultural TFP (Fang et al., 2021; Hu et al., 2021; Zheng and Ma, 2021; Sun, 2022; Liu D. et al., 2023; Liu S. et al., 2023). First, the level of economic development and industrialization of a region is specifically measured by the *per capita* GDP and the share of value added of the secondary industry in the GDP. In general, regions with higher levels of economic development and industrialization will have more diversified demands for the quantity and quality of agricultural products, and provide more material products or technical support for agricultural production. Second, financial support for agricultural production is considered from both financial and technical aspects, using the share of regional public budget expenditure on agricultural, forestry, and water affairs and the digital financial index as its proxy variables, respectively. For a long time, credit constraint has been an important hurdle for agricultural production, farmers' income, and rural prosperity. Increasing regional financial support for agriculture can directly alleviate financial constraints, such as reducing costs and improving operational efficiency through production subsidies or technology promotion. Digital finance, on the other hand, is an innovative form of financing with the rapid popularization and diversified application of Internet technology. Digital finance can reduce the degree of asymmetry of information in the trading market, broaden the subject's access to financial support channels, and improve production and operation, but there are certain requirements for the level of digitalization of the region and individual digital literacy.

Third, the scale of agricultural production, the degree of mechanization, and the level of disaster will also affect the efficiency of agricultural production. In this paper, using the *per capita* sown area of crops, the ratio of the total power of agricultural machinery to the sown area of crops, and the ratio of the affected area of crops to the total area of crops to measure them, respectively. The degree of agricultural scale and the degree of mechanization can reflect the transformation of the mode of agricultural production and operation, and the improvement of the former also indicates the optimization of agricultural labor allocation. However, the productivity-enhancing effect of the degree of agricultural mechanization may also be affected by the matching of technology demand and supply, especially in the face of the increasing demand for functional innovations in machinery in the development of digital agriculture. In addition, the level of agricultural disaster affects agricultural total factor productivity negatively, but it is also likely to gradually weaken its impact on agricultural production with economic development and technological progress.

3.2.4 Other variables

This study primarily analyzes the effect and process of rural broadband development on agricultural TFP using the viewpoint of agriculture loans in light of the financial exclusion faced in the course of agricultural growth, rural transformation, and farmers' income increase. The proportion of agro-related loans in each loan is used to illustrate the amount of support from financial institutions in the agricultural sector, taking into account the allocation of funds by financial institutions in the agricultural and nonagricultural sectors. Although Kassouri and Kacou (2021) found that the structure of the credit market influences agricultural development, not all farmers face credit constraints (Feder et al., 1990). The share of loans for agriculture, forestry, animal husbandry, fisheries, rural loans, and household loans within agricultural loans are further investigated to examine the structural effects and differences in the allocation of agricultural loans among different purposes, regions, and entities while considering the characteristics of agriculture, rural development, and farmers' needs. Table 1 shows the statistic descriptions of the variables.

TABLE 1 Evaluation index system of rural industrial integration.

Variables and symbols sample	Size	Mean	S.D	Min	Max
Total factor productivity (lnTFP)	310	0.165	0.179	−0.285	0.719
Technical progress (lnTC)	310	0.164	0.167	−0.238	0.609
Technical efficiency (lnEC)	310	0.000	0.102	−0.284	0.342
Rural broadband development (x)	310	0.398	0.341	0.000	1.869
Level of economic development (lnpgdp)	310	10.825	0.443	9.707	11.961
Level of industrialization (industry)	310	0.430	0.087	0.158	0.590
Level of financial support for agriculture (fin)	310	0.116	0.034	0.041	0.204
Digital finance index (dfin)	310	216.235	97.03	16.22	431.928
Intensity of agricultural mechanization (mech)	310	6.847	3.501	2.639	24.626
Scale of agricultural operations (scale)	310	0.711	0.354	0.209	2.771
Degree of damage to agriculture (disas)	310	0.147	0.114	0.006	0.618
Proportion of agricultural loans (arelo)	310	0.289	0.113	0.022	0.463
Percentage of agriculture, forestry, and fisheries loans (am1)	310	0.161	0.083	0.034	0.400
Proportion of rural loans (am2)	310	0.753	0.165	0.246	0.995
Proportion of loans to farmers (am3)	310	0.242	0.113	0.011	0.791

3.3 Model setting

3.3.1 Basic model

This study explores the effects of rural broadband development on agricultural TFP by using the Hausman test results and building a two-way fixed effects model, as defined in Eq. 2.

$$lnTFP_{it} = \alpha_0 + \alpha_1 x_{it} + \alpha_2 z_{it} + \alpha_3 provi_i + \alpha_4 year_t + \varepsilon_{it} \quad (2)$$

Where x_{it} is a series of control variables affecting agricultural TFP, $provi_i$ denotes province fixed effects, $year_t$ denotes time fixed effects, and ε_{it} denotes random error term.

This research builds two-way fixed effects models and random effects models to examine the impact of rural broadband expansion on agricultural technological progress and agricultural technical efficiency, respectively. This analysis helps to further understand the driving factors of agricultural TFP at the structural level. Therefore, Eqs. (3) and (4) correspond to the model estimation equations at the structural level, respectively:

$$lnTC_{it} = b_0 + b_1 x_{it} + b_2 z_{it} + b_3 provi_i + b_4 year_t + \varepsilon_{it} \quad (3)$$

$$lnEC_{it} = c_0 + c_1 x_{it} + c_2 z_{it} + \varepsilon_{it} \quad (4)$$

3.3.2 Mechanism analysis model

This study aims to evaluate the mechanism by which rural broadband development impacts TFP in agriculture from the standpoint of agricultural loans. Therefore, the following direct relationship and interaction effect between rural broadband expansion and agricultural loans are taken into consideration when building the econometric models, as defined in Eqs. (5) and (6).

$$arelo_{it} = d_0 + d_1 x_{it} + d_2 z_{it} + d_3 provi_i + d_4 year_t + \varepsilon_{it} \quad (5)$$

$$lnTFP_{it} = e_0 + e_1 x_{it} + e_2 arelo_{it} + e_3 x_{it} * arelo_{it} + e_4 provi_i + e_5 year_t + \varepsilon_{it} \quad (6)$$

Furthermore, with the advancement of the digital China initiative, the digital rural strategy, and the digital transformation of agriculture and rural areas, rural broadband growth can both represent and release the nonlinear effects of digital technology or data elements on the relationship between agricultural loans and agricultural TFP, as well as reflect and unleash the efficiency improvement of rural digital infrastructure. This study offers the following model based on the fixed effects threshold model by Hansen (1999).

$$lnTFP_{it} = \varphi_0 + \varphi_1 arelo_{it} * I\left(x_{it} \le \theta\right) + \varphi_2 arelo_{it} * I\left(x > \theta\right) + \varphi_3 z_{it} + \varphi_4 provi_i + \varphi_5 year_t + \varepsilon_{it} \quad (7)$$

Where x_{it} is the threshold value of rural broadband development, and $I(\cdot)$ is the indicator function, which takes a value of 1 if the threshold condition in parentheses is satisfied and 0 otherwise. Based on the outcomes of the threshold effect tests, Eq. 7 gives a single threshold model that can be expanded to many threshold scenarios. This study further examines the threshold effects of rural broadband development on the relationship between various structural aspects of agricultural loans and agricultural TFP by taking differentiation criteria into account, such as the percentage of agricultural loans, rural loans, and household loans in agricultural loans.

4 Empirical results and analysis

4.1 Benchmark regression analysis

The effect of rural broadband development on China's agricultural TFP is shown in Table 2. To determine the effect of rural broadband

TABLE 2 Benchmark regression results.

Model	(1)	(2)	(3)	(4)	(5)	(6)
Variable	lnTFP				lnTC	lnEC
x	0.141*	0.125***	0.145***	0.136***	0.071***	0.072**
	(0.070)	(0.029)	(0.028)	(0.026)	(0.025)	(0.028)
lnpgdp		0.353***	0.301***	0.227**	−0.053	0.073**
		(0.121)	(0.114)	(0.108)	(0.108)	(0.036)
industry		0.109	0.434***	0.641***	0.745***	−0.042
		(0.162)	(0.160)	(0.145)	(0.148)	(0.102)
fin			0.983***	1.018***	0.149	0.935***
			(0.350)	(0.318)	(0.316)	(0.349)
dfin			−0.003***	−0.002***	−0.002***	−0.000***
			(0.001)	(0.001)	(0.001)	(0.000)
mech				−0.019***	−0.008**	−0.006***
				(0.004)	(0.004)	(0.002)
scale				0.162***	0.146***	0.065*
				(0.034)	(0.033)	(0.038)
disas				−0.022	−0.038	−0.004
				(0.041)	(0.041)	(0.034)
_cons	−0.023	−3.771***	−3.384***	−2.727**	0.216	−0.839**
	(0.016)	(1.248)	(1.170)	(1.104)	(1.095)	(0.391)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	–
Province fixed effects	Yes	Yes	Yes	Yes	Yes	–
N	310	310	310	310	310	310
Adjust R-squared	0.828	0.835	0.857	0.883	0.867	–

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$, the robust standard error is given in (). Same tables below.

development on agricultural TFP, Models (1) to (4) gradually incorporate numerous control variables, including economic considerations, capital, and the agricultural production environment. The structural elements of agricultural TFP, namely agricultural technological advancement and agricultural technical efficiency, are specifically examined in Models (5) and (6). First, the regression analysis of Models (1) to (4) demonstrates that the growth of rural broadband greatly raises TFP in agriculture. The effect size of rural broadband development on agricultural TFP at a significant level of 1% is thus 0.136, supporting Hypothesis 1 when taking into account economic and capital control factors together. This also proves that the country's efforts to establish a strategy for constructing the digital countryside and actively promoting the digital transformation of agriculture have achieved some results in agriculture's economic growth.

Second, the level of GDP *per capita*, the level of industrialization development, funding for agriculture, and the scale of agricultural production and operation all have a significant positive effect on agricultural TFP, and the efficiency enhancement effect of financial support for agriculture is the greatest. This finding suggests that financial support is still a key factor in advancing agricultural TFP. This implies that improving agricultural TFP can be facilitated by increasing or optimizing fiscal assistance for agriculture, as well as enhancing agricultural financial support forms. The negative impact of digital finance and agricultural mechanization intensity on agricultural TFP may be due to the relative complexity of the efficiency-enhancing effects of the two, such as the existence of a non-linear connection or restrictions by other factors. For instance, the degree of agricultural and rural digitization, the digital literacy of different business subjects, and the suitability of the supply and demand for machinery intelligence.

In addition, model (5) and model (6) set out the relationship between rural broadband development on agricultural technological progress and agricultural technological efficiency. Specifically, rural broadband development contributes 0.071 and 0.072 to agricultural technical advancement and agricultural technical effectiveness at the 1 and 5% significance levels, respectively. This result suggests that rural broadband growth can help improve the "single-wheel-drive" effect of agricultural technological progress on agricultural TFP, and liberates the previously underappreciated promotional value of agriculture technical efficiency on agricultural TFP.

4.2 Robustness test

To some extent, this study partially addresses the endogeneity issue caused by time-invariant, unobservable, and omitted variables by establishing a two-way fixed effects model and accounting for additional variables that influence agricultural TFP. In this paper, further tests are conducted in the following aspects, and the specific results are shown in Table 3.

TABLE 3 Robustness test.

Model	(1)	(2)	(3)	(4)	(5)
	Ln(x)	L.x	N = 26	T = 2014 ~ 2020	High-order Interaction
Variable	LnTFP				
x	0.019**	0.117**	0.124***	0.159***	0.132**
	(0.007)	(0.047)	(0.031)	(0.043)	(0.051)
Control variables	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes	Yes	Yes
Province * Year fixed effects	No	No	No	No	Yes
N	300	279	260	217	310
Adjust *R*-squared	0.900	0.889	0.930	0.889	0.883

**$p < 0.05$, ***$p < 0.01$.

TABLE 4 Endogeneity test.

Model	(1)	(2)
	IV (L.x and L2.x)	IV (Third moment (Skewness))
The Second stage		
x	0.162***	0.068**
	(0.039)	(0.032)
Control variables	Yes	Yes
Year fixed effects	Yes	Yes
Province fixed effects	Yes	Yes
Kleibergen–Paap rk LM Statistic	39.940	12.870
	(0.000)	(0.000)
Kleibergen–Paap rk Wald F Statistic	34.328	41.09
	(19.930)	(16.38)
Hansen J Statistic	0.597	–
	(0.440)	–
N	248	310
Adjust *R*-squared	0.886	0.880
The First stage		
L.x	0.744***(0.125)	
L2.x	0.011(0.119)	
Iv3		0.377***(0.059)
F-value Test	34.33(0.000)	41.09(0.000)

**$p < 0.05$, ***$p < 0.01$. critical values or p-value in () for IV tests.

(1) Change the core explanatory factor. Combined with the research (Yu et al., 2021), this article investigates the association between rural broadband development and agricultural TFP by using the logarithmic value of rural broadband internet access subscribers, the first-order lagged term as a proxy for the core explanatory variables, respectively.

(2) Alter the sample size. Considering the proportion of the agricultural economy and the completeness of data in the four municipalities of Beijing, Tianjin, Shanghai, and Chongqing, as well as in Tibet, this study excludes these five samples and uses data from the remaining 26 provinces during the same period to evaluate the effect of rural broadband on agricultural TFP.

(3) Adjust the sample duration. Current digitalization, driven by various digital technologies such as the internet, has been a new driver in boosting the economies of various countries. However, the concept of "Internet Plus" as a national strategy in China was first proposed in 2015, and the rise of "Taobao Villages" occurred in 2014. It is possible that the subsequent expansion of rural broadband has had a more significant impact on agricultural TFP. Therefore, this study further examines the connection between these two factors using panel data from 31 provinces and cities in China from 2014 to 2020.

(4) Apply a new econometric model. Following Moser and Voena's (2012) research, this study extends the two-way fixed effects model to include the province–time interaction term.

All the regression findings, which correspond to Models (1) through (5) in Table 3, are consistent with the idea that rural broadband expansion considerably increases agricultural TFP. The outcomes of Model (4), which has the highest coefficient estimate, also imply that the efficiency-improving impact of rural broadband development is increasingly noticeable.

4.3 Endogenous test

This study expands on prior research (Lewbel, 1997; Bellemare et al., 2017) in order to reduce the endogeneity issue caused by other factors such as mutual causation. It then tests the basic model with the one-period and two-period lag terms of the core explanatory variables as well as the third-order moments to construct the two types of instrumental variables for rural broadband growth, respectively. The findings in Table 4 show that both models estimates are consistent with the claim that China's rural broadband development greatly enhances agricultural TFP.

4.4 Heterogeneity analysis

The level of rural broadband development and utilization in different regions may vary somewhat, and the corresponding

TABLE 5 Heterogeneity analysis.

Model	(1) Eastern region	(2) Central region	(3) Western region	(4) Low income	(5) High income
Variable	lnTFP				
x	0.080	0.118**	0.052	0.070	0.105*
	(0.063)	(0.050)	(0.132)	(0.094)	(0.059)
Control variables	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes	Yes	Yes
N	120	90	100	152	155
Adjust R-squared	0.843	0.958	0.905	0.877	0.789

$*p < 0.10$, $**p < 0.05$.

TABLE 6 Mechanism analysis.

Model	(1)	(2)	(3)	(4)
Variable	arelo	lnTFP		
x	−0.048***	0.136***	0.149**	0.179***
	(0.015)	(0.026)	(0.066)	(0.057)
arelo			0.263	0.490**
			(0.204)	(0.182)
x * arelo				0.734*
				(0.384)
Control variables	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes	Yes
N	310	310	310	310
Adjust R-squared	0.554	0.883	0.884	0.891

$*p < 0.1$, $**p < 0.05$, $***p < 0.01$.

efficiency-enhancing effects may also be heterogeneous. Therefore, this study splits the sample according to the east, center, and west regions and the average value of disposable income of rural residents for further analysis.

The regression results in Table 5 show that while the efficiency-enhancing effect of rural broadband in the eastern and western regions does not reach a significant level, the contribution of rural broadband development to agricultural TFP in the central region is significant at the 5 % level. Only the high-income samples show a substantial correlation between rural broadband expansion and agricultural TFP in terms of income levels. These findings imply that rural inhabitants across areas, especially those with varying income levels, do not equally benefit from the digital dividends of rural broadband growth. This may be connected to the rural dwellers' economic pattern, which includes the rate of wage income and income from family businesses.

4.5 Mechanism analysis

Table 6 reports the impact of rural broadband development on agricultural TFP from the perspective of farm-related loans. Model (1) indicates that the negative contribution of rural broadband development to the agricultural loan share is significant at the 1% level. It also suggests that rural broadband development may have a greater promotion effect on non-agriculture-related loans. Well, can rural broadband development contribute to the increase of farm-related loans? The article analyzes the effect of rural broadband development on the non-farm related loan share and the agricultural loan absolute amount. To eliminate the unit effect, take the logarithmic value of the absolute value of the agricultural loan, the results are shown in the attached table. The study found that rural broadband development has a significant positive contribution to the share of non-farm-related loans, and the positive impact on the absolute value of farm-related loans did not reach a significant level.

Although rural broadband development negatively affects the share of farm-related loans, it does change the allocation of farm-related and non-farm-related loans in financial institutions, which in turn can affect agricultural productivity. Therefore, this paper further analyzes the relationship between rural broadband development, the share of farm-related loans, and agricultural TFP by combining the mediating and interaction effects. Comparing models (2), (3), and (4), it is found that when rural broadband growth and the share of farm-related loans are considered together, only the promotion effect of rural broadband development on agricultural TFP is significant at the 5% level. When further considering the interaction of the two, the productivity-enhancing effects of rural broadband development, the share of farm-related loans, and the interaction term are significant at the 1, 5, and 10% significance levels, respectively, with corresponding coefficient sizes of 0.179, 0.490, and 0.734. This suggests that the productivity-enhancing effects of rural broadband development and farm-related loans may be relatively complex and interactive. While comprehensively understanding the effect of rural broadband development on the farm-related loan share or total amount, it is also necessary to pay attention to the constraints on the agricultural broadband development level faced by the productivity-enhancing effect of the farm-related loan share.

4.6 Further analysis

In addition to the study mentioned above, the article uses the threshold effect model to examine the relationship between rural broadband development, agricultural loans, their structure, and agricultural TFP. Following the threshold effect tests and threshold estimation (See Supplementary Tables S1, S2), it is found that the growth of rural broadband has a single threshold effect on the efficiency improvement of the ratios of loans for agriculture, forestry, animal husbandry, and fisheries, loans to farmers, and loans to rural areas. The threshold values for rural broadband growth, namely 0.591, 0.422, 0.591, and 0.611, are all higher than the average development level of 0.398. Still, a major disparity remains in contrast to the maximum value of 1.869. This outcome also reflects regional disparities in rural broadband deployment, and the resulting digital dividends will likewise vary widely.

Table 7 shows that when rural broadband expansion exceeds the threshold value, the farm-related loan share has a considerable efficiency-boosting effect at the 10% level, with a magnitude of 0.317. Regarding the structure for specific farm-related loans, the amount of the efficiency-boosting impact of the agriculture, forestry, animal husbandry, and fishery loan ratio rises from 0.182 at the 10% level to 0.482 at the 1% level, which is a notable effect, given as rural broadband access keeps maturing. For the allocation of agriculture-related loans between different regions and subjects, when the level of rural broadband development exceeds the threshold value, the negative effect of the rural loan share on agricultural TFP is not significant; the direction of the efficiency effect of the loans to farmers is changed from negative to positive, but only the negative effect is significant. This indicates that the financial distribution among rural industries may also have some effect on the efficiency-enhancing impact of rural agricultural loans. It also shows that rural broadband expansion helps mitigate the production constraints caused by farmers' inability to obtain credit; however, future agricultural lending should be optimized based on unique circumstances.

5 Discussion

This paper mainly examines the impact and mechanism of rural broadband development on agricultural TFP in China and conducts heterogeneity analysis and threshold effect analysis to provide ideas for exploring the path of high-quality development of agriculture and rural areas in the context of digital transformation.

TABLE 7 Analysis of threshold effects.

Model	(1)	(2)	(3)	(4)
Variable	I = arelo	I = am1	I = am2	I = am3
Th ≤ q1	0.137	0.182*	−0.112	−0.145**
	(0.172)	(0.103)	(0.069)	(0.071)
Th ≤ q1	0.317*	0.482***	−0.0555	0.052
	(0.187)	(0.120)	(0.070)	(0.075)
Control variables	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes	Yes
N	310	310	310	310
Adjust *R*-squared	0.856	0.860	0.855	0.859

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

First, this study concludes that rural broadband development significantly increases agricultural TFP, which is consistent with existing studies (Rao et al., 2022). Other studies, although less focused on the productivity effect of rural broadband development as a single factor, have acknowledged the boosting effect of digitization on agricultural TFP (Jiang et al., 2022). However, in contrast to the majority of studies, which suggest that agricultural TFP is driven by technological progressor technological efficiency, this study suggests that the development of rural broadband can achieve both technological progress and technological efficiency, which provides a way to change the "single-wheel-driven" state of TFP in agriculture. In particular, the study of rural broadband development and its effects during the period of digital transformation can clearly understand the level of access to rural digital infrastructure and create conditions for accurately eliminating the access divide and sharing the development of digital dividends.

The study also identifies significant regional and group differences in the contribution of rural broadband development to agricultural TFP. The previous study (Rao et al., 2022) has also concluded that there is regional heterogeneity in the impact of broadband development on agricultural TFP. This paper explores the reasons for these differences. First, it is related to the level of regional digitization (Fu and Zhang, 2022). In contrast to the higher level of digitization in the eastern region that masks the productivity effect of rural broadband development, the scale of broadband development in the western region may not have reached the level of productivity enhancement. Second, it might be relevant to the disposable income of regional rural residents. This is because the logic behind the impact of digitization on agricultural productivity is based on the use of various digital technologies among different business entities (Ma and Zheng, 2021). Therefore, the income of rural residents should be increased simultaneously to balance efficiency and equality in the digital transformation process.

Third, this study argues that rural broadband development can affect agricultural TFP. through agriculture-related loans. Studies have examined the role of farm-related loans on TFP in agriculture (Wang et al., 2022), but few have explored the role of rural broadband development on agriculture-related loans. Previous studies on the mechanism of rural digitalization affecting agricultural TFP have also not focused on agriculture-related loans (Rao et al., 2022), but broadband development does contribute to the innovation of financial products or services (Niu et al., 2022), so this study helps to fill the gap and broaden the path of agricultural TFP enhancement in the context of digitalization.

Finally, this study further reveals that there is a threshold constraint on the productivity-enhancing effect of rural broadband development on farm-related loans and that there are significant differences in the productivity effects and constraints on different farm-related loan allocations. This is similar to the role of IT diffusion on economic growth (Gheraia et al., 2021). Increasing the total supply of agricultural credit cannot guarantee that production operators increase their real investments and improve their operations when facing various uncertainty risks. Instead, the reduction of market information asymmetry (Ye et al., 2021) and the acceleration of the development of smart and intelligent agricultural and rural products and services (Jiang et al., 2022) by a variety of connected digital technologies can help to diversify risk and promote investment, provided that the level of digitization is commensurate.

6 Conclusions and recommendations

6.1 Conclusion

Rural broadband development, which is the foundation of digital transformation in agriculture and rural areas, plays an important role in optimizing cross-sectoral and cross-regional flows of various factors and creates new opportunities for high-quality agricultural development. Based on China's provincial-level panel data from 2011 to 2020, this study investigates the effects of rural broadband development on agricultural TFP and the mechanisms from the perspective of agriculture-related loans by building a two-way fixed effects model and a threshold effects model. The results of the study are as follows:

(1) Rural broadband development has significantly increased agricultural TFP. At the structural level, rural broadband development can simultaneously achieve technological progress and technical efficiency, effectively improving the "single-wheel drive" state of agricultural TFP.

(2) The impact of rural broadband development on agricultural TFP varies noticeably due to different resource endowments and levels of economic development between regions. Specifically, the productivity enhancement effect of rural broadband development in the central region and areas with higher rural disposable income is obvious.

(3) Rural broadband development can affect agricultural TFP through agriculture-related loans. Rural broadband development significantly reduces the proportion of farm-related loans but can increase the total amount of farm-related loans, effectively releasing the promotion effect of increasing the farm-related loan ratio on agricultural TFP.

(4) Rural broadband development has certain threshold constraints on the agricultural TFP enhancement of the ratio of farm-related loans. For the productivity effect of different allocation structures of agriculture-related loans, the threshold constraints and role of rural broadband development are also heterogeneous.

6.2 Recommendations

(1) Strengthen the support for rural broadband and other digital infrastructure construction, and innovate the way of combining communication consumption. For a long time, technological progress has been regarded as the fundamental driving force for the improvement of agricultural TFP (Fan, 1991; Gong, 2018), but this study argues that rural broadband development can promote technological progress, enhance technological efficiency, change the frontiers of agricultural production, narrow the gap between actual and potential production capacity, and improve agricultural TFP. Based on the existing urban and rural industrial development as well as the personnel structure, the innovation of communication consumption mix may be one of the paths to reduce the digital divide between urban and rural areas. The rural penetration of communication technology not only faces the disadvantage of high-cost construction in terms of distance and remoteness (Salemink et al., 2017) but also suffers from insufficient potential in the consumer market. Following Li Keqiang's policy of speeding up the network and reducing fees in 2017, the Ministry of Industry and Information Technology (MIIT) can further encourage operators to optimize their communication consumption portfolio, such as reducing or eliminating cross-province and cross-region broadband installation fees based on encouraging the bundling of communication fees for affinity numbers. Especially for rural families with migrant workers and those who stay behind, this communication consumption method of sharing network costs between two generations can stimulate the older generation's demand for new technologies, providing opportunities to safeguard connectivity and share digital dividends.

(2) Take advantage of the opportunity of digital transformation to promote the digital innovation of agricultural and rural products and services. Broadband development effectively promotes farmers' income (Leng, 2022), but there is heterogeneity in the level and effect of rural broadband development for residents in different regions or at different income levels. For example, for regions in the central part of the region that provide bulk products such as grain, innovating the intelligence of agricultural machinery and equipment and promoting the digitization and precision of agricultural production may be a breakthrough for the improvement of TFP in agriculture. As for regions with mainly economic crops or characteristic industries, it is fundamental to prioritize the use of digital platforms to ensure the effective matching of product and service information between the supply and demand markets, and then achieve the digital transformation of the whole industrial chain in the process of upgrading information-technology-products-services. Therefore, exploring suitable digital transformation paths and innovating support methods in combination with the characteristics of regional industries and the income structure of residents is the key to improving the suitability of digital tools for supply and demand, optimizing the industrial structure, and ensuring the increase of farmers' incomes and the high-quality development of agriculture and rural areas in each region.

(3) Innovate ways to increase the total volume of agriculture-related loans and optimize the allocation structure of agriculture-related loans. The digital transformation of agriculture and rural areas not only increases the demand for agriculture-related loans, but also creates opportunities for optimizing their allocation and increasing their supply, and gives the possibility of enhancing the TFP of agriculture. Therefore, local governments should combine the different paths of industrial upgrading in the process of rural digital development, such as the intelligent agricultural transformation of production precision and the integrated development of agriculture, culture, and tourism of service diversification, to provide valuable practices of increasing demand for agriculture-related loans and to improve the chances of agriculture-related loan supply growth. In addition, it is available to innovate financial lending methods combined with rural broadband development (Niu et al., 2022) and to optimize the allocation structure of agriculture-related loans in the projects of different target subjects. For such innovations in the way policies are combined in the process of digital transformation for agricultural different production and management segments, rural industries, and different business subjects, efforts should be made to balance efficiency and fairness.

Different from the existing studies focusing on the efficiency-enhancing effect of the overall digital economy or the internet, this research focuses on rural areas and investigates the impact and mechanism of rural broadband development on agricultural TFP, but there are some weaknesses due to various factors. These include (1) constrained by the rural digitalization level, this study analyzes the productivity enhancement role of rural broadband development. The subsequent process can be combined with the construction of digital villages to explore the benefit and efficiency of the different patterns and the integration depth of various types of digital technology and agriculture. (2) As the existing provincial and municipal public data related to agricultural loans are available until 2020, the scope of this study is the data of 31 provinces and municipalities in China from 2011 to 2020, and there is no approach to analyze the change in the operation mechanism of rural broadband productivity enhancement in the past 2 years under this viewpoint. In the future, the mechanism of agricultural TFP advancement can be analyzed from other perspectives based on the availability of data.

Data availability statement

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

Author contributions

YL: Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1332494/full#supplementary-material

References

Ai, T., Zhang, J., and Shao, J. (2023). Study on the coordinated poverty reduction effect of agricultural insurance and agricultural credit and its regional differences in China. *Econ. Anal. Policy* 78, 835–844. doi: 10.1016/j.eap.2023.04.027

Balana, B. B., Mekonnen, D., Haile, B., Hagos, F., Yimam, S. M., and Ringler, C. (2022). Demand and supply constraints of credit in smallholder farming: evidence from Ethiopia and Tanzania. *World Dev.* 159:106033. doi: 10.1016/j.worlddev.2022.106033

Bellemare, M. F., Masaki, T., and Pepinsky, T. B. (2017). Lagged explanatory variables and the estimation of causal effect. *J. Polit.* 79, 949–963. doi: 10.1086/690946

Burgess, R., and Pande, R. (2005). Do rural banks matter? Evidence from the Indian social banking experiment. *Am. Econ. Rev.* 95, 780–795. doi: 10.1257/0002828054201242

Bustos, P., Caprettin Pan, I. B., and Ponticelli, J. (2016). Agricultural productivity and structural transformation: evidence from Brazil. *Am. Econ. Rev.* 106, 1320–1365. doi: 10.1257/aer.20131061

Chambers, R. G., and Pieralli, S. (2020). The sources of measured US agricultural productivity growth: weather, technological change, and adaptation. *Am. J. Agric. Econ.* 102, 1198–1226. doi: 10.1002/ajae.12090

Crawford, G. S., Pavanini, N., and Schivardi, F. (2018). Asymmetric information and imperfect competition in lending markets. *Am. Econ. Rev.* 108, 1659–1701. doi: 10.1257/aer.20150487

Deller, S., Whitacre, B., and Conroy, T. (2021). Rural broadband speeds and business startup rates. *Am. J. Agric. Econ.* 104, 999–1025. doi: 10.1111/ajae.12259

Fabregas, R., Kremer, M., and Schilbach, F. (2019). Realizing the potential of digital development: the case of agricultural advice. *Science* 366:eaay3038. doi: 10.1126/science.aay3038

Fan, S. (1991). Effects of technological change and institutional reform on production growth in Chinese agriculture. *Am. J. Agric. Econ.* 73, 266–275. doi: 10.2307/1242711

Fang, L., Hu, R., Mao, H., and Chen, S. (2021). How crop insurance influences agricultural green total factor productivity: evidence from Chinese farmers. *J. Clean. Prod.* 321:128977. doi: 10.1016/j.jclepro.2021.128977

Farrokhi, F., and Pellegrina, H. S. (2023). Trade, technology, and agricultural productivity. *J. Polit. Econ.* 131, 2509–2555. doi: 10.1086/724319

Feder, G., Lau, L. J., Lin, J. Y., and Luo, X. (1990). The relationship between credit and productivity in Chinese agriculture: a microeconomic model of disequilibrium. *Am. J. Agric. Econ.* 72, 1151–1157. doi: 10.2307/1242524

Fernando, A. N. (2021). Seeking the treated: the impact of mobile extension on farmer information exchange in India. *J. Dev. Econ.* 153:102713. doi: 10.1016/j.jdeveco.2021.102713

Finger, R., Swinton, S. M., Benni, N. E., and Walter, A. (2019). Precision farming at the nexus of agricultural production and the environment. *Ann. Rev. Resour. Econ.* 11, 313–335. doi: 10.1146/annurev-resource-100518-093929

Fu, W., and Zhang, R. (2022). Can digitalization levels affect agricultural Total factor productivity? Evidence from China. *Front. Sustain. Food Syst.* 6:860780. doi: 10.3389/fsufs.2022.860780

Gebbers, R., and Adamchuk, V. I. (2010). Precision agriculture and food security. *Science* 327, 828–831. doi: 10.1126/science.1183899

Gebresilasse, M. M. (2023). Rural roads, agricultural extension, and productivity. *J. Dev. Econ.* 162:103048. doi: 10.1016/j.jdeveco.2023.103048

Gheraia, Z., Abid, M., Sekrafi, H., and Abdelli, H. (2021). The moderating role of ICT diffusion between financial development and economic growth: a bootstrap ARDL approach in Saudi Arabia. *Inf. Technol. Dev.* 28, 816–836. doi: 10.1080/02681102.2021.1998759

Gong, B. (2018). Agricultural reforms and production in China: changes in provincial production function and productivity in 1978–2015. *J. Dev. Econ.* 132, 18–31. doi: 10.1016/j.jdeveco.2017.12.005

Gong, B. (2020). Agricultural productivity convergence in China. *China Econ. Rev.* 60:101423. doi: 10.1016/j.chieco.2020.101423

Gong, M., and Elahi, E. (2022). A nexus between farmland rights, and access, demand, and amount of agricultural loan under the socialist system of China. *Land Use Policy* 120:106279. doi: 10.1016/j.landusepol.2022.106279

Hambly, H., and Rajabiun, R. (2021). Rural broadband: gaps, maps and challenges. *Telematics Inform.* 60:101565. doi: 10.1016/j.tele.2021.101565

Hansen, B. E. (1999). Threshold effects in non-dynamic panels: estimation, testing, and inference. *J. Econ.* 93, 345–368. doi: 10.1016/s0304-4076(99)00025-1

Hossain, M., Malek, M., Hossain, M. A., Reza, M. H., and Ahmed, M. S. (2018). Agricultural microcredit for tenant farmers: evidence from a field experiment in Bangladesh. *Am. J. Agric. Econ.* 101, 692–709. doi: 10.1093/ajae/aay070

Hu, Y., Liu, C., and Peng, J. (2021). Financial inclusion and agricultural total factor productivity growth in China. *Econ. Model.* 96, 68–82. doi: 10.1016/j.econmod.2020.12.021

Jiang, S., Zhou, J., and Qiu, S. (2022). Digital agriculture and urbanization: mechanism and empirical research. *Technol. Forecast. Soc. Chang.* 180:121724. doi: 10.1016/j.techfore.2022.121724

Karlan, D., Osei, R., Osei-Akoto, I., and Udry, C. (2014). Agricultural decisions after relaxing credit and risk constraints. *Q. J. Econ.* 129, 597–652. doi: 10.1093/qje/qju002

Kassouri, Y., and Kacou, K. Y. (2021). Does the structure of credit markets affect agricultural development in west African countries? *Econ. Anal. Policy* 73, 588–601. doi: 10.1016/j.eap.2021.12.015

Leng, X. (2022). Digital revolution and rural family income: evidence from China. *J. Rural. Stud.* 94, 336–343. doi: 10.1016/j.jrurstud.2022.07.004

Lewbel, A. (1997). Constructing instruments for regressions with measurement error when no additional data are available, with an application to patents and R&D. *Econometrica* 65:1201. doi: 10.2307/2171884

Liu, D., Li, Y., You, J., Baležentis, T., and Shen, Z. (2023). Digital inclusive finance and green total factor productivity growth in rural China. *J. Clean. Prod.* 418:138159. doi: 10.1016/j.jclepro.2023.138159

Liu, S., Ma, S., Yin, L., and Zhu, J. (2023). Land titling, human capital misallocation, and agricultural productivity in China. *J. Dev. Econ.* 165:103165. doi: 10.1016/j.jdeveco.2023.103165

Ma, W., and Zheng, H. (2021). Heterogeneous impacts of information technology adoption on pesticide and fertiliser expenditures: evidence from wheat farmers in China*. *Aust. J. Agric. Resour. Econ.* 66, 72–92. doi: 10.1111/1467-8489.12446

Malik, P. K., Singh, R., Gehlot, A., Akram, S. V., and Das, P. K. (2022). Village 4.0: digitalization of village with smart internet of things technologies. *Comput. Ind. Eng.* 165:107938. doi: 10.1016/j.cie.2022.107938

Moser, P., and Voena, A. (2012). Compulsory licensing: evidence from the trading with the enemy act. *Am. Econ. Rev.* 102, 396–427. doi: 10.1257/aer.102.1.396

Niu, G., Jin, X., Wang, Q., and Zhou, Y. (2022). Broadband infrastructure and digital financial inclusion in rural China. *China Econ. Rev.* 76:101853. doi: 10.1016/j.chieco.2022.101853

Ogutu, S. O., Okello, J. J., and Otieno, D. J. (2014). Impact of information and communication technology-based market information services on smallholder farm input use and productivity: the case of Kenya. *World Dev.* 64, 311–321. doi: 10.1016/j.worlddev.2014.06.011

Pan, W., Xie, T., Wang, Z., and Ma, L. (2022). Digital economy: an innovation driver for total factor productivity. *J. Bus. Res.* 139, 303–311. doi: 10.1016/j.jbusres.2021.09.061

Pant, L. P., and Hambly Odame, H. (2017). Broadband for a sustainable digital future of rural communities: a reflexive interactive assessment. *J. Rural. Stud.* 54, 435–450. doi: 10.1016/j.jrurstud.2016.09.003

Philip, L., and Williams, F. (2019). Remote rural home based businesses and digital inequalities: understanding needs and expectations in a digitally underserved community. *J. Rural. Stud.* 68, 306–318. doi: 10.1016/j.jrurstud.2018.09.011

Rao, P., Liu, X., Zhu, S., Kang, X., Zhao, X., and Xie, F. (2022). Does the application of ICTs improve the efficiency of agricultural carbon reduction? Evidence from broadband adoption in rural China. *Int. J. Environ. Res. Public Health* 19:7844. doi: 10.3390/ijerph19137844

Regassa, M., and Melesse, M. B. (2023). Access to credit and heterogeneous effects on agricultural technology adoption: evidence from large rural surveys in Ethiopia. *Can. J. Agric. Econ.* 71, 231–253. doi: 10.1111/cjag.12329

Rijswijk, K., Klerkx, L., Bacco, M., Bartolini, F., Bulten, E., Debruyne, L., et al. (2021). Digital transformation of agriculture and rural areas: a socio-cyber-physical system framework to support responsibilisation. *J. Rural. Stud.* 85, 79–90. doi: 10.1016/j.jrurstud.2021.05.003

Salemink, K., Strijker, D., and Bosworth, G. (2017). Rural development in the digital age: a systematic literature review on unequal ICT availability, adoption, and use in rural areas. *J. Rural. Stud.* 54, 360–371. doi: 10.1016/j.jrurstud.2015.09.001

Searchinger, T. D., Wirsenius, S., Beringer, T., and Dumas, P. (2018). Assessing the efficiency of changes in land use for mitigating climate change. *Nature* 564, 249–253. doi: 10.1038/s41586-018-0757-z

Shen, Z., Wang, S., Boussemart, J., and Hao, Y. (2022). Digital transition and green growth in Chinese agriculture. *Technol. Forecast. Soc. Chang.* 181:121742. doi: 10.1016/j.techfore.2022.121742

Sheng, Y., Tian, X., Qiao, W., and Peng, C. (2019). Measuring agricultural total factor productivity in China: pattern and drivers over the period of 1978-2016. *Aust. J. Agric. Resour. Econ.* 64, 82–103. doi: 10.1111/1467-8489.12327

Sun, Y. (2022). Environmental regulation, agricultural green technology innovation, and agricultural green total factor productivity. *Front. Environ. Sci.* 10:955954. doi: 10.3389/fenvs.2022.955954

Tsai, K. S. (2004). Imperfect substitutes: the local political economy of informal finance and microfinance in rural China and India. *World Dev.* 32, 1487–1507. doi: 10.1016/j.worlddev.2004.06.001

Wang, F., Du, L., and Tian, M. (2022). Does agricultural credit input promote agricultural green total factor productivity? Evidence from spatial panel data of 30 provinces in China. *Int. J. Environ. Res. Public Health* 20:529. doi: 10.3390/ijerph20010529

Wang, S. L., Huang, J., Wang, X., and Tuan, F. (2019). Are China's regional agricultural productivities converging: how and why? *Food Policy* 86:101727. doi: 10.1016/j.foodpol.2019.05.010

Wu, L., and Zhang, Z. (2020). Impact and threshold effect of internet technology upgrade on forestry green total factor productivity: evidence from China. *J. Clean. Prod.* 271:122657. doi: 10.1016/j.jclepro.2020.122657

Ye, L., Pan, S. L., Li, M., Dai, Y., and Dong, X. (2021). The citizen-led information practices of ICT4D in rural communities of China: a mixed-method study. *Int. J. Inform. Manag.* 56:102248. doi: 10.1016/j.ijinfomgt.2020.102248

Yu, D., Li, X., Yu, J., and Li, H. (2021). The impact of the spatial agglomeration of foreign direct investment on green total factor productivity of Chinese cities. *J. Environ. Manag.* 290:112666. doi: 10.1016/j.jenvman.2021.112666

Zhang, A., Chandio, A. A., Yang, T., Ding, Z., and Liu, Y. (2023). Examining how internet use and non-farm employment affect rural households' income gap? Evidence from China. *Front. Sustain. Food Syst.* 7:1173158. doi: 10.3389/fsufs.2023.1173158

Zhang, X., Hu, L., and Yu, X. (2023). Farmland leasing, misallocation reduction, and agricultural total factor productivity: insights from rice production in China. *Food Policy* 119:102518. doi: 10.1016/j.foodpol.2023.102518

Zheng, H., and Ma, W. (2021). The role of resource reallocation in promoting total factor productivity growth: insights from China's agricultural sector. *Rev. Dev. Econ.* 25, 2350–2371. doi: 10.1111/rode.12826

Zhu, X., Hu, R., Zhang, C., and Shi, G. (2021). Does internet use improve technical efficiency? Evidence from apple production in China. *Technol. Forecast. Soc. Chang.* 166:120662. doi: 10.1016/j.techfore.2021.120662