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Original Research

Rural Digital Economy, Agricultural Green Technology Innovation, and Agricultural Carbon Emissions – Based on Panel Data from 30 Provinces in China between 2012 and 2021

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Abstract

The impact of the rural digital economy on agricultural carbon emissions and green technological innovation is fragmented, while the influence of the digital economy and carbon emissions on urban and industrial areas has attracted the attention of many scholars. It is necessary to further investigate the relationship between the rural digital economy and its impact on agricultural carbon emissions and green technological innovation. This study explores the impact of agricultural green technological innovation on carbon emissions and its transmission mechanism. It examines the effects of rural digital economy on agricultural carbon emissions, as well as the intermediary effect of agricultural green technology innovation, using panel data from 30 provinces in China (excluding Xizang, Hong Kong, Macao and Taiwan) between 2012 and 2021. The results indicate that the rural digital economy has a significant impact on reducing agricultural carbon emissions. This effect remains robust even after conducting a series of rigorous tests, including substituting the dependent variable. Additionally, the influence of the rural digital economy on agricultural carbon emissions is particularly notable in the western and northeast regions, as well as in provinces with limited levels of rural digital economic growth. Furthermore, promoting innovation in green agricultural technology through the advancement of the digital economy in rural areas can lead to a reduction in carbon emissions from agriculture. The research findings suggest promoting distinctive growth in the rural digital economy, elevating the standard of eco-friendly technology innovation in agriculture, and advancing the eco-friendly and low-carbon progress of both the rural digital economy and agriculture.

Keywords: rural digital economy, agricultural green technology innovation, agricultural carbon emissions

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Introduction

Carbon dioxide is a greenhouse gas that contributes to global warming, which has significant impacts on people's livelihoods, as well as economic and social development, and poses numerous challenges and risks to the Earth's ecological environment. China has a strong tradition of agriculture, with a significant scale of production. However, the continuous use of large amounts of chemical fertilizers, pesticides, agricultural films, conventional diesel equipment, excessive irrigation, and depletion of the land's carbon pool through unsophisticated farming methods result in a significant generation of carbon emissions. As a novel economic model, the digital economy is progressively infiltrating agricultural and rural domains, creating a seamless integration between the digital economy and agricultural systems. This is done to promote the digital transformation of agriculture and rural areas, while accelerating research and development in environmentally friendly agricultural technologies, thereby promoting the transformation and modernization of conventional agriculture. Additionally, it contributes to the goal of achieving carbon peaking and carbon neutrality.

Moreover, the penetration of China's digital economy in agriculture and rural areas remains low (only 8.9% in 2020). How can digital rural economics promote carbon reduction in agriculture? This text combines the 'digital rural' strategy to investigate how the digital economy reshapes the internal mechanism of agricultural development. The reduction of carbon emissions from China's agricultural sector is an urgent issue that is in need of attention. This text analyzes the relationship between the rural digital economy and agricultural carbon emissions from the perspective of agricultural green technology innovation. The results aim to enrich the theoretical system of agricultural development and technological innovation and provide references for the formulation of policies on agricultural energy conservation, emission reduction, and low-carbon green development.

Literature Review

Rural Digital Economy

The digital economy encompasses a range of economic activities that rely on data resources as primary production factors and modern information networks as key carriers. This sector is driven by the effective use of information and communication technologies, which play a vital role in improving efficiency and optimizing economic structures [1]. Furthermore, the digital economy contributes to rural resource allocation, innovation, entrepreneurship, and carbon emission reduction [2]. Firstly, the rural digital economy facilitates the revival of rural industries by optimally allocating and utilizing rural resources, effectively connecting urban and rural markets, and integrating and developing industries [3]. Secondly, the growth of the digital economy can facilitate rural regeneration, bridge the 'digital divide' between urban and rural development, and provide a strong foundation for shaping a digital urban-rural integration development pattern [4]. Drones, Internet of Things sensors, cloud computing, and big data analysis represent some of the most advantageous technologies in agriculture [5]. This technology effectively enhances the rural e-commerce sector of China [6], improves family members' technological competence, and boosts non-farm employment. Assisting rural families in generating wealth and boosting income [7], it has emerged as an essential propelling force for rural low-carbon development [8]. The implementation of the Internet+agricultural supply chain model [9] has been proven to be effective and has led to the advancement of new industries and business models in rural areas. Additionally, this approach has significantly elevated the innovation level of rural public services. Digital finance simultaneously promotes the upgrading of farmers' consumption and economic growth [10]. The development of digital inclusive finance establishes a robust rural financial ecosystem, enables the integration of the rural three industries [11], reduces the probability of households experiencing relative poverty, encourages entrepreneurial activities of farmers [12], boosts employment rates [13], and enhances the entrepreneurial environment for farmers.

Agricultural Carbon Emissions

China's agricultural sector is responsible for 17% of the world's total carbon emissions. Despite this, it still faces significant challenges. The main factors influencing agricultural greenhouse gas emissions are the total power of agricultural machinery, the amount of agricultural diesel fuel and the amount of fertilizer applied. Additionally, agricultural carbon emissions are significantly impacted by the industrial structure, the level of agricultural economy, the demographic structure, agricultural financial support and the degree of agricultural disaster [14]. Studies have shown that agricultural carbon emissions can be effectively reduced through breakthroughs in agricultural energy efficiency, non-agricultural employment, promotion of agricultural industrial structure upgrading [15], expansion of renewable energy [16], development of digital finance [17], and promotion of agricultural technological progress [14]. This can lead to a reduction in the total amount, intensity, and density of agricultural carbon emissions, as well as a decrease in carbon emissions generated by fertilizer, pesticide, agricultural film, and machinery fuel in the production process [14]. By considering the benefits of carbon emissions in agriculture and addressing the issue of spillover internalization in low-carbon agricultural production, it is possible to increase economic benefits for farmers while reducing agricultural carbon emissions.

Agricultural Green Technology Innovation

Green technology plays a crucial role in addressing China's latest technological advancements and ecological issues. In agriculture, it serves as a significant impetus for overall eco-friendly transformation and development while improving resource allocation efficiency and reducing carbon emissions [18]. According to the 'Green List of International Patent Classification' published by the World Intellectual Property Organization, green agriculture encompasses alternate irrigation technologies, pesticide substitutes, soil improvement, and organic fertilizers made from waste. By implementing environmental regulations and investing in government research and development, along with increasing gross agricultural output and productivity, they can significantly enhance green agricultural innovations [19]. This can improve energy efficiency, reduce environmental pollution caused by agriculture, lower pollutant emissions and effectively promote the growth of green, healthy and sustainable agriculture in the country. Additionally, it can help stimulate soil organic carbon sequestration functions, thereby promoting agricultural production goal of creating a high-carbon sink [20].

Research Gaps in the Existing Literature

The influence of the digital economy and carbon emissions on urban and industrial areas has attracted attention from many scholars, but the impact of the rural digital economy on agricultural carbon emissions and green technological innovation is fragmented. In this study, we explored the impact on agricultural carbon emissions and the transmission mechanism of agricultural green technological innovation. This paper presented a rural-focused index for developing the digital economy, quantified agricultural carbon emissions, defined the boundaries of agricultural green technology innovation, and examined the transmission and consequences of rural digital economy, agricultural green technology innovation, and agricultural carbon emissions through empirical analysis. This would enhance the use of agricultural resources in China's rural digital economy development and decrease agricultural carbon emissions.

Theoretical Analysis and Assumptions

Low Carbon Economy Theory

This thesis analyzes the internal mechanism of the rural digital economy to promote technological innovation and reduce carbon emissions, based on the theory of the low-carbon economy. The theory of low-carbon economics aims to reduce greenhouse gas emissions as its core objective, achieving a balance between economic development and environmental protection. Promoting, operating, and developing the digital economy can unleash innovation and endogenous power in technology, data, and management, based on the principles of low-carbon economics. This can lead to optimized resource and energy efficiency, reduced energy consumption, and decreased energy and resource consumption per unit of output [21]. The outcome is a mutually beneficial scenario for both economic growth and the reduction of carbon emissions, effectively and comprehensively enhancing carbon emission efficiency.

Rural Digital Economy and Agricultural Carbon Emissions

The advancement of the rural digital economy facilitates the digital industrialization of agriculture and the digitization of the agricultural industry by upgrading rural digital infrastructure and constructing a comprehensive industry chain for environmentally friendly production, distribution and consumption. The initial impact of the rural digital economy is the direct boost it provides to low-carbon agricultural development. Firstly, the aim is to encourage the adoption of environmentally friendly and sustainable alternatives in agricultural production methods, with the goal of reducing greenhouse gas emissions and minimizing environmental pollution. Secondly, it accelerates the low-carbon transition of farmers' lifestyles by using clean energy and minimizing resource waste. Thirdly, it enhances the quality and effectiveness of government oversight, regulates conduct, improves efficiency, and mitigates carbon emissions from agriculture. The digital economy in rural areas utilizes digital technologies such as the Internet, blockchain, big data, and artificial intelligence, to support agriculture. Primarily, it aids in the transformation and modernization of conventional agriculture, highlights the efficacy of scientific advancements, and emphasizes industry advancements. Secondly, it facilitates the efficient allocation of agricultural production resources and enhances agricultural production structure and the framework for agricultural supply. Thirdly, it facilitates the growth of new agricultural sectors, establishes an online and big data platform for distinctive agricultural sectors, and subsequently advances agricultural industrial restructuring. This helps to reduce the prevalence of polluted agriculture, enhance energy utilization efficiency, and mitigate agricultural carbon emissions [22].

Hypothesis H1 suggests that the development of rural digital economy helps to reduce agricultural carbon emissions.

Mechanisms of Green Technology Innovation in Agriculture

Green technological innovation is an essential means for the digital economy to achieve high-quality economic development and upgrade industrial structure [23]. It is crucial to building an environmentally friendly society and achieving the "dual-carbon" goal provides a new perspective [24]. Furthermore, promoting the development of green technology in agriculture is essential to achieve low-carbon and environmentally sustainable agricultural practices, as well as to advance agricultural science and technology towards modernization. The digital transformation of agriculture has a significant impact on promoting agricultural green growth, primarily through green technological innovations [25]. Firstly, innovations can enhance the total factor productivity of agriculture through specialization, scaling, and intensification [26], resulting in reduced costs of agricultural innovation factors. Secondly, they can strengthen research and development of agricultural innovation knowledge, broaden market demand, improve the efficiency of agricultural production, and promote sustainable agricultural development, ultimately improving the quality of agricultural products. Thirdly, the aim is to enhance the diffusion of agricultural innovation knowledge, elevate the scientific and technological culture of farmers, and increase the yield of innovative outcomes. Promoting the acceptance of environmentally friendly products by consumers [24]. The primary route to reduce agricultural carbon emissions in the long run is through the advancement of 'clean' agricultural technologies [27-30]. On one hand, the task involves innovating agricultural green technologies to increase energy efficiency, reduce energy consumption, and promote the adoption of renewable energy. The second aspect involves using clean energy, promoting the recycling of agricultural resources, supporting the development of green agriculture, and achieving agricultural emission reduction [31]. Upon synthesizing the literature outlined above, it is evident that the rural digital economy has emerged as a new driving force in modern agriculture. It facilitates low-carbon agricultural development, here achieved through agricultural green technology innovation.

Accordingly, we propose hypothesis H2 that the rural digital economy reduces agricultural carbon emissions through the innovation of agricultural green technology.

Research Methodology

Modelling Design

Standard Regression Model

To evaluate the impact of the rural digital economy on agricultural carbon emissions, we create a baseline regression model based on the research of Zhao Tao et al. [32]. The model employs the intensity of agricultural carbon emissions as the explanatory variable and the rural digital economy development index as the primary explanatory variable. It also includes five control variables: the income of rural residents, rural human capital, degree of agricultural disaster, agricultural industry structure, and level of urbanization. The specific model is as follows:

$$lnACEI_{it} = \alpha_0 + \alpha_1 lnRDE_{it} + \alpha_2 lnX_{it} + \mu_i + \gamma_i + \varepsilon_{it} \quad (1)$$

Where the subscript i and t represent provinces and years, respectively. The explanatory variable $lnACEI_{it}$ is the logarithmic value of the agricultural carbon emission intensity of province i in year t. The key explanatory variable $lnRDE_{it}$ is the logarithmic value of the level of provincial rural digital economy development in year t. The main focus of this paper is α_1 the coefficient. A α_1 significantly negative coefficient suggests that rural digital economy development can effectively reduce the intensity of agricultural carbon emissions. X_{it} are various control variables for the region. Additionally, μ_i are individual fixed effects for province i that remain constant over time, and γ_i is time fixed effects. Lastly, ε_{it} are random error terms.

Testing the Model of the Role Mechanism of Agricultural Green Technology Innovation

This study investigates the impact of agricultural green technology innovation on agricultural carbon emissions in the rural digital economy. The findings suggest that the technological advancements play a significant role in reducing agricultural carbon emissions. This paper aims to explore the relationship between the rural digital economy and agricultural carbon emissions. To address the endogeneity issues in the third step of the conventional three-step mediation effect test, a more precise mediation effect model needs to be developed for further empirical examinations. Based on the research conducted by Guo Feng [33], a more prescriptive model should be constructed. This study uses a conventional three-step mediation effect test, focusing only on the second step, to investigate the impact of the rural digital economy and agricultural green technological innovation mechanism. Based on literature and logical reasoning, the study explains how agricultural green technology innovation mediates the relationship between the rural digital economy and agricultural carbon emissions. The basic model is described below:

$$M_{it} = \beta_0 + \beta_1 RDE_{it} + \beta_2 X_{it} + \mu_i + \gamma_i + \varepsilon_{it} \quad (2)$$

The given recursive equation represents the mediating variable M_{it} of agricultural green technological innovation (AGTI), which includes the number of agricultural green patent applications (NOAGPA1) and authorizations (NOAGPA2). The paper focuses on the coefficient is β_1, and if β_1 is significantly positive coefficient, it indicates that the growth of the rural digital economy can effectively enhance the level of innovation in agricultural green technology.

Description of Variable Selection and Data Sources

Explanatory Variable

This paper presents a study on the calculation of agricultural carbon emissions in agriculture, specifically focusing on plantations. The research serves as the basis for this study [14]. The sources of carbon emissions from plantations are classified into six categories: fertilizers, pesticides, agricultural films, irrigation, ploughing and agricultural diesel. The study measures all six categories of agricultural carbon emissions. The calculation methodology for assessing carbon emissions in agriculture was developed using figures from the China Rural Statistics Yearbook and the China Energy Statistics Yearbook.

$$TACE = \sum_{i=1}^{n} ACE_i = \sum_{i=1}^{n} C_i \times \delta_i \tag{3}$$

TACE is the sum of carbon emissions from various sources in agriculture, where n is the total number of carbon sources for agricultural input. ACE_i represents the carbon emissions of the ith agricultural input element, C_i refers to the ith agricultural input element's number, and δ_i presents the carbon emission coefficient of the ith agricultural input element (Table 1).

Calculation of agricultural carbon intensity. A formula was constructed to calculate the carbon intensity of agriculture:

$$ACEI = TACE/VAOTPI \tag{4}$$

Among these factors, ACEI refers to the intensity of carbon emissions from agriculture, while TACE is the carbon emissions from agriculture calculated using equation (3), and VAOTPI is the value added in the primary industry sector. To ensure more objective and accurate data that can be referenced, it is necessary to consider each region comprehensively, which improves comparability. After calculating the average carbon emission of agriculture for each province, the top five were found to be Xinjiang, Ningxia, Shanghai, Gansu, and Jilin. It was observed that higher values of gross agricultural output indicate more developed agriculture, leading to higher agricultural carbon emission intensity. Conversely, the bottom five provinces with lower gross agricultural output values, including Qinghai, Guizhou, Hainan, Sichuan, and Fujian, had lower levels of carbon emissions from agriculture. From 2012 to 2021, the carbon emission intensity of agricultural practices in all provinces has decreased significantly. This suggests that China's active implementation of low-carbon agricultural development mechanisms, digital transformation of rural agriculture and farmers, and prioritization of agricultural science and technology innovation and development have had a clear and substantial impact.

Core Explanatory Variables

Construction of the rural digital economy indicator system. Based on the findings of Qi Jiang and colleagues [25], a comprehensive rural digital economy indicator system will be developed. This system aims to measure the level of digital economy development in rural areas based on three main indicators: the status of rural digital infrastructure development, the digitalization of agriculture, and the digitalization of the agricultural industry, consisting of eight secondary indicators. Details of the specific indicators can be found in Table 2.

Choice of measurement method: Entropy value method. In order to accurately measure the level of development of the rural digital economy, we need to determine the weights of the specific indicators that make up the digital economy. Based on the research of Guo Feng et al. [33], we have selected the entropy value method of the objective allocation method. This method calculates the weights of the constructed rural digital economy indicators, resulting in an accurate index for measuring its level of development.

Table 1. Carbon emission factors for agricultural input factors.

Agricultural input factors	Carbon emission factor	Reference sources
Fertilizer	0.89kg/kg	Oak Ridge National Laboratory, United States [34]
Pesticides	4.93kg/kg	Oak Ridge National Laboratory, United States [34]
Agro-film	5.18 kg/kg	Institute of Agricultural Resources and Ecological Environment, Nanjing Agricultural University [35]
Irrigated	266.48kg/hm^2	Tian [36]
Cultivation	312.60kg/km^2	Li Bo et al [37]
Agricultural diesel	0.59kg/kg	IPCC2013 [38]

Table 2. Indicator system for the level of development of the digital economy.

Main indicators	Secondary indicators	Interpretation of indicators	Indicator properties	Proportion	Data sources
Rural digital economy infrastructure	Rural Internet Penetration rate	Rural broadband access users as a proportion of the rural population in the area	Positive	6.22%	(China Statistical Yearbook)
	Rural Smartphone Penetration rate	Average number of mobile phones per 100 rural households	Positive	3.28%	(China Statistical Yearbook)
	Agrometeorological observation Station coverage	Number of agrometeorological observation stations	Positive	2.98%	(China Statistical Yearbook)
Digitization of agriculture	Scale of digitalized transactions in agricultural products	Online retail sales of agricultural products in counties nationwide	Positive	18.78%	(National County Digital Agriculture Rural E-Commerce Development Report)
	Agricultural infrastructure development	Investment in fixed assets in agriculture, forestry, livestock, fisheries, etc.	Positive	7.99%	(China Fixed Asset Investment Statistical Yearbook), (Statistical Yearbook of China's Investment Sector)
	Digital Industry Support	Percentage of City IT Service Workers	Positive	22.66%	(China Population and Employment Statistics Yearbook), (China Statistical Yearbook)
Digitization of the agricultural industry	Internet of Things (IoT) technology applications	Number of postal outlets	Reverse	0.46%	(China Statistical Yearbook)
	Rural digital base	Number of Taobao villages	Positive	37.63%	Ali Research Institute

The digital economy indicators for rural areas presented in this paper are standardized and have positive and negative values. The calculation methodology is as follows:

Positive indicators:

$$x_{ij}=\frac{x_{ij}-min\{x_j\}}{max\{x_j\}-min\{x_j\}} \quad (5)$$

Negative indicators:

$$x_{ij}=\frac{max\{x_j\}-x_{ij}}{max\{x_j\}-min\{x_j\}} \quad (6)$$

$max\{x_j\}$ is the maximum value of the j evaluation indicator for all years, $min\{x_j\}$ is the minimum value of the j evaluation indicator for all years. x_{ij} is the value of the jth evaluation indicator in year j, dimensionless results. The objective weights of each evaluation indicator were calculated using the procedures of the entropy method.

Calculation of evaluation indicator j's share in year i:

$$y_{ij}=\frac{x_{ij}}{\sum_{i=1}^{m}x_{ij}} \quad (7)$$

Calculation of information entropy of evaluation indicators:

$$e_j=-\frac{1}{lnm}\sum_{i=1}^{m}y_{ij}\times lny_{ij} \quad (8)$$

Calculating information entropy redundancy:

$$d_j=1-e_j \quad (9)$$

m is the evaluation year.

Calculation of indicator weights using information entropy redundancy:

$$w_j=\frac{d_j}{\sum_{i=1}^{m}d_j} \quad (10)$$

Based on the standardized indicators and indicator weights obtained, the level of the rural digital economic development index is calculated via weighted multiple linear functions:

$$RDE_i=\sum_{i=1}^{m}\times w_j \quad (11)$$

Where 'RDE_i' represents the level of the composite index for the development of digital economy in rural areas of province 'i', between 0 and 1. A higher value of 'RDE_i' indicates a greater degree of development in the rural digital economy, while a smaller value of 'RDE_i' corresponds to a lower level of development.

Control Variable

In a truly objective environment, the intensity of agricultural carbon emissions is determined by the synergistic effect of multiple variables. To systematically investigate the impact of the rural digital economy on these emissions, we built on the work of Liu Songqi et al. [39] and added five control variables: rural income level (RIL), rural human capital (RHC), crop disaster severity (EOCD), agricultural industrial structure (AIS) and urbanization level (UL). We obtained data from the China Rural Statistical Yearbook and the China Population and Employment Statistical Yearbook. In the empirical process, to avoid the influence of extreme values and effectively satisfy the classical linear assumption, we adopted a logarithmic treatment for the intensity of agricultural carbon emission intensity, the rural digital economy index, and the control variables. Some missing data were interpolated.

Intermediary Variable

Scholars have used various measures of innovation, such as sales of new products and patents. This paper argues that patent data is a more appropriate indicator of the technological aspects of agricultural innovation, especially when combined with the mediating variable of agricultural green technology innovation. In addition, patents are better suited to integrate technological innovation within the scope of green agriculture. Currently, there is no clear division of agricultural patents within the International Patent Classification (IPC), and no unified standard for IPC classification of agricultural patents has been developed. This paper refers to the study by Liu Lijun et al. [40], which is based on the range of IPC classification numbers of agricultural patents and incorporates the 'International Patent Classification Green List' published by the World Intellectual Property Organization.

The level of innovation in agricultural green technology in each province was measured by the number of agricultural green patent applications (NOAGPA1) and the number of agricultural green patents granted (NOAGPA2). The data on agricultural green patents in this paper only include agricultural green inventions and agricultural green utility models. This is because it is impossible to identify the sector to which the patent classification of the design corresponds. For the purposes of this study, it is necessary to start from an agricultural perspective, hence the exclusion of design patents. Table 3 shows the descriptive statistics of the variables.

Results and Analyses

Regression to Baseline

Empirical data on the effect of the rural digital economy on agricultural carbon emissions using empirical data is presented in Table 4. To ensure comparability with other studies, this report includes regression results for both random effects and double fixed effects models. Column 1 excludes control variables and excludes time and area effects. Column 2 omits control variables but considers fixed effects for time and area. Column 3 includes control variables but still does not adjust for fixed effects related to time and area. Finally, column 4 takes into account control variables and fixed effects for time and area. The regression analyses indicate a significantly adverse impact of the rural digital economy on agricultural carbon emissions, suggesting that the rural digital economy helps to reduce

Table 3. Results of descriptive statistics of variables.

Variables	Unit	Observations	Mean	Std. Dev	Min	Max
Carbon intensity of agriculture (ACEI)	%	300	0.17	0.07	0.049	0.36
Rural digital economy (RDE)	%	300	0.11	0.08	0.01	0.59
Rural income levels (RIL)	%	300	1.05	0.36	0.57	2.25
Rural human capital (RHC)	%	300	0.04	0.024	0.01	0.17
Extent of crop damage (EOCD)	%	300	0.14	0.11	0.00	0.70
Agricultural industrial structure (AIS)	%	300	0.53	0.086	0.36	0.74
Urbanization level (UL)	%	300	0.60	0.12	0.36	0.90
Agricultural Green Patent Applications (NOAGPA1)	PC_S	300	215.70	227.50	2.00	1,249.00
Number of green patents granted in agriculture (NOAGPA2)	P_CS	300	85.20	83.06	1.00	538.00

such emissions. In model (4), the coefficient for the digital economy is -0.133, which is significant at the 1% level. This suggests that for every 1% increase in the level of the rural digital economy, the average intensity of agricultural carbon emissions decreases by 0.133%. The results indicate that rural digital economy helps to reduce agricultural carbon emissions. The coefficients for the rural digital economy have a significant negative impact on both random and fixed effects. This supports hypothesis H1, indicating that the growth of rural digital economy contributes to the reduction of carbon emissions in agriculture. Possible improved version: There are potential reasons to support the role of rural digital economy in mitigating carbon emissions from agriculture. Firstly, it could encourage agricultural economic growth and facilitate the green transformation and upgrading of agricultural businesses. Secondly, rural digital infrastructure should be implemented to support rural agriculture and aid in its development, driving the adoption and improvement of agricultural technology and surpassing current limitations. This includes measures to improve the rural Internet penetration rate, as well as the adoption of information technology in agricultural machinery and equipment, enhancement of rural logistics infrastructure, and overall development of the e-commerce environment. With these improvements, the development of the rural economy can be accelerated and carbon emissions in agriculture can be reduced. Thirdly, the rapid expansion of the rural digital economy has gradually changed farmers' perceptions of production and marketing. This has led to the adoption of online practices as a new trend and has increased farmers' awareness of ecological conservation, effectively reducing carbon emissions from agricultural activities.

Of the control variables, it was found that rural income and urbanization levels had a significantly negative impact on agricultural carbon emissions. The adoption of low-carbon development techniques in farming and the reduction of agricultural carbon emissions may be influenced by two factors. Firstly, farmers with higher disposable income are more likely to adopt these techniques, which is suggested by the rural income level. Secondly, the level of urbanization reflects the degree of influence on agriculture in the process of industrialized technological progress. As people in cities actively seek environmentally friendly, pollution-free, and high-quality agricultural products, farmers may need to adjust their production techniques, leading to a reduction in agricultural carbon emissions.

Robustness Analyses

Substitution of Explanatory Variables

The regression analysis is based on the intensity of agricultural carbon emissions. To strengthen the reliability of this paper's outcomes, explanatory variables are substituted with TACE (total agricultural carbon emissions, with lnTACE as the logarithmic value) and PCCEIRA (per capita carbon emissions, with lnPCCEIRA as the logarithmic value). The results

Table 4. Benchmark regression results.

Variables	(1)	(2)	(3)	(4)
lnRDE	-0.337*** (0.0175)	-0.180*** (0.0281)	-0.112*** (0.0275)	-0.133*** (0.0264)
lnRIL			0.396** (0.171)	-0.730*** (0.228)
lnRHC			-0.134*** (0.0373)	-0.0530 (0.0333)
lnEOCD			0.000920 (0.00810)	0.00784 (0.00597)
lnAIS			0.201 (0.148)	-0.140 (0.118)
lnUL			-1.091*** (0.196)	-0.739*** (0.203)
_cons	-2.663*** (0.0805)	-2.121*** (0.0822)	-3.005*** (0.137))	-2.721*** (0.203)
Year fixed	NO	YES	NO	YES
Province fixed	NO	YES	NO	YES
Observations	300	300	300	300
adj. R^2		0.784		0.824

Note: The significance levels of 10%, 5%, and 1% are denoted by *, **, and ***, respectively. Standard errors are shown in parentheses, as shown below.

in columns (1-2) of Table 5 reveal that the negative regression coefficients of the rural digital economy are significant at both the 5% and 1% levels.

Extended Time Window

This paper examines the impact of the rural digital economy on agricultural carbon emission intensity. It includes the explanatory variables of agricultural carbon emission intensity for one period (F.lnACEI) and two periods (F2.lnACEI) in advance. The findings, displayed in columns (3-4) of Table 5, show that the regression coefficient of the rural digital economy remains significantly negative at the 5% level.

Exclusion of Samples

Due to the substantial dissimilarity between the four municipal administrations of Beijing, Tianjin, Shanghai, Chongqing, and other provinces, it was imperative to exclude these four samples from the regression test. The outcomes are displayed in the first column of Table 6, where the regression coefficient of rural digital economy continues to hold negative significance at the 1% level.

Variable Indentation

To remove outliers from the data, both the explanatory and control variables are trimmed at the upper and lower 1% levels. The results show that the regression coefficient for the rural digital economy remains significantly negative at the 1% level, as shown in column (2) of Table 6.

Adding Control Variables

The rural population size and the proportion of agricultural chemical inputs have an impact on agricultural carbon emissions. These factors are added as control variables, with rural population size measured by the number of individuals in the village, and agricultural chemical inputs measured as the ratio of fertilizer use to the sown area of crops. The findings displayed in column (3) of Table 6 demonstrate that the regression coefficient for rural digital economy remains notably negative at the 1% level.

Table 5. Robustness test results (1).

Variables	(1)	(2)	(3)	(4)
lnRDE	-0.0463** (0.0194)	-0.0836*** (0.0224)	-0.0978** (0.0263)	-0.0590** (0.0268)
Control variable	YES	YES	YES	YES
_cons	6.078*** (0.149)	-0.870*** (0.172)	-2.628*** (0.197)	-2.484*** (0.198)
Year fixed	YES	YES	YES	YES
Province fixed	YES	YES	YES	YES
Observations	300	300	300	300
adj. R^2	0.496	0.354	0.833	0.844

Table 6. Robustness test results (2).

Variables	(1)	(2)	(3)	(4)
lnRDE	-0.136*** (0.0258)		-0.125*** (0.0270)	-0.102** (0.0428)
lnRDE_w		-0.146*** (0.0279)		
Control variable	YES	YES	YES	YES
_cons	-3.233*** (0.233)	-2.731*** (0.204)	0.609 (1.580)	-2.782*** (0.258)
Year fixed	YES	YES	YES	YES
Province fixed	YES	YES	YES	YES
Observations	260	300	300	210
adj. R^2	0.856	0.822	0.831	0.849

Adjustment of Sample Period

Since 2015, China's digital economy has experienced rapid development. To ensure the robustness of our results, we shortened the sample period to 2015-2021. The results show that a significantly negative regression coefficient of the rural digital economy was observed at the 5% level (Table 6).

The aforementioned examination of robustness demonstrates that the development of the rural digital economy helps to reduce agricultural carbon emissions. This confirms the validity of the findings presented in this manuscript.

Heterogeneity Analysis

Regional Heterogeneity

China's vast expanse results in significant variations in factor endowments, the resource environment and levels of economic development between regions. As a result, rural digital economy development and agricultural green technology innovation vary throughout the country, leading to regional heterogeneity. To verify the hypothesis that regional variations in the rural digital economy impact agricultural carbon emissions, this study will reference 'Several Opinions of the Central Committee of the Communist Party of China and the State Council on the Promotion of the Rise of the Central Region' and 'The State Council of China Issued the Implementing Opinions on Several Policies and Measures for the Development of the Western Region' Based on the 16th National Congress of the Communist Party of China's report, the provinces have been divided into four regions: the East, the Central, the West and the Northeast[1] [41].This categorization enables regression analysis to explore the impact of regional differences in rural digital economy development on agricultural carbon emissions.

The results indicated that the regression analysis of the rural digital economy in the eastern and central regions was not significant (Table 7). However, the coefficients were negative, suggesting that the growth of the rural digital economy led to a decrease in agricultural carbon emissions in these areas. Conversely, the regression coefficients of rural digital economy in the western and northeastern regions were significantly negative at the 5% and 10% levels, respectively. These results suggest that the expansion of the rural digital economy in these regions led to a reduction in agricultural carbon emissions. Possible explanations are: The rural digital economy in the eastern and central regions of the country has progressed at a faster rate, resulting in a higher overall level of rural digital economy and improved digital infrastructure development. Furthermore, there is a greater degree of integration and development with agriculture, including a higher utilization rate of emerging information technologies such as the Internet of Things, cloud computing, big data, and mobile internet. A significant number of scientific and technological experts collaborate to optimize the industrial structure, resulting in a reduction of carbon emissions in agriculture. It is important to note, however, that the primary factor influencing agricultural carbon emission reduction is not the rural digital economy. Although the expansion of the digital economy in rural regions of the west is currently in its nascent stage, it is rapidly gaining momentum with vast potential for growth. The digital sector is playing a crucial role in reducing carbon emissions from agriculture. The agricultural sector in the Northeast region of the UK is sizeable and primarily characterized by traditional production methods. The industry structure is relatively homogenous, with a high level of dispersion in agricultural operations and limited uptake of technological innovations, resulting in lower economic returns. Although the rural digital economy is still in its early stages, recent advancements in rural digital infrastructure, digital finance, and the digitization of agriculture have resulted in significant progress. This has led to increased integration and development of the rural digital economy, resulting in a substantial reduction in carbon emissions attributable to agriculture.

Heterogeneity in the Level of Development of the Rural Digital Economy

A regression test was conducted to account for the differences in agricultural economic development, rural digital economy, and technological innovation among the provinces in China. The provinces were divided into two categories based on their 2021 ranking of rural digital economy development: high(provinces ranked 1-15) and low(provinces ranked 16-30)[2]. The regression coefficients of the rural digital economy for high-level provinces are significantly negative at the 10% level, while those for low-level provinces are significantly negative at the 1% level. Please refer to columns (5-6) of Table 7 for the presented results. Meanwhile, the rural digital economy in rural areas of more developed

[1] The eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; the central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan; the western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang; the northeastern region includes Liaoning, Jilin, and Heilongjiang.

[2] Provinces ranked 1-15 includes Beijing, Hebei, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Shandong, Henan, Hubei, Hunan, Guangdong Sichuan, Yunnan, and Shaanxi. Provinces ranked 16-30 includes Tianjin, Shaanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Jiangxi, Guangxi, Hainan, Chongqing, Guizhou, Gansu, Qinghai, Ningxia, and Xinjiang.

Table 7. Results of heterogeneity test.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
lnRDE	-0.0314 (0.0474)	-0.0558 (0.0465)	-0.147** (0.0572)	-1.239* (0.582)	-0.0706* (0.0404)	-0.241*** (0.0474)
Control variable	YES	YES	YES	YES	YES	YES
_cons	-2.469*** (0.360)	0.136 (0.362)	-4.351*** (0.345)	-3.827 (1.750)	-2.271*** (0.349)	-2.895*** (0.329)
Year fixed	YES	YES	YES	YES	YES	YES
Province fixed	YES	YES	YES	YES	YES	YES
Observations	100	60	110	30	150	150
adj. R^2	0.815	0.946	0.917	0.696	0.852	0.811

provinces has a higher level of development and agricultural activity, which has a comparatively smaller impact on agricultural carbon emissions.

Examining the Role Mechanism of Agricultural Green Technology Innovation

The regression findings for the rural digital economy mechanism and its effect on agricultural green technology innovation are presented in Table 8. The explanatory variable number used is the number of agricultural green patent applications. The results show a statistically significant positive regression coefficient for the rural digital economy at the 1% level (Table 8 (columns 1-2)). Similarly, it shows that the number of agricultural green patent grants has a significant positive impact on the rural digital economy at the 1% level of significance. This suggests that there is a positive correlation between the growth of the rural digital economy and the level of agricultural green technological innovation (Table 8 (columns 3-4)). These findings are consistent with the results presented in columns (3) and (4) of Table 8. Increasing the lag of the rural digital economy by one period when testing the number of authorized agricultural green patents results in significantly positive coefficients of rural digital economy at a 5% level in column (5) of Table 8 due to a longer time lag effect in the authorization of agricultural green patents. Furthermore, the development of rural digital economy significantly improves the level of green technological innovation in agriculture in the second year. The above demonstrates that the growth of digital economies in rural areas leads to increased innovation in green agricultural technology.

Technological advances are crucial in reducing carbon emissions in agriculture [28, 42]. However, not all forms of technological progress contribute to this reduction. Only 'clean' agricultural technology leads to a decrease in carbon emissions [27-30, 43]. Agricultural green technology is one such 'clean' technology that can effectively reduce environmental pollution, energy, and raw material consumption when compared to traditional agricultural production techniques [44]. The implementation of innovative green agricultural technologies in agricultural production can reduce or modify the input factors, decrease pollution from surface sources, improve energy efficiency, lower production costs, increase productivity, and reduce agricultural carbon emissions. Secondly, the implementation of green agricultural technology innovations such as new agricultural varieties and the promotion of the green revolution [45], can effectively enhance the transformation and upgrading of the agricultural industry structure. The objective of this approach is to implement environmentally friendly production practices throughout all stages of agricultural product development, including production, processing, packaging, cold chain storage, sales, and beyond. This will enable the creation of a green production model, green supply chain, green logistics, green consumption, and agricultural carbon emission reductions. Technical abbreviations will be explained upon first use. Thirdly, prioritize the integration of agricultural green technology across various sectors such as planting, animal husbandry, fisheries and seed industry, through industrial links. This approach enables the full utilization of the spillover effects of agricultural green technology and fosters interconnectivity and knowledge sharing between neighboring provinces to achieve carbon emission reduction in the agricultural sector. The rural digital economy has the potential to contribute to reducing agricultural carbon emissions through the agricultural 'technology effect'. Agricultural green technology innovation acts as an intermediary mechanism for carbon emission reduction and is of paramount importance [46]. The development of rural digital economy has a significant positive impact on the reduction of agricultural carbon emissions by enhancing agricultural green technology innovation. This supports hypothesis 2, which suggests that implementing agricultural green technology innovation in rural digital economies can reduce agricultural carbon emissions.

Table 8. Regression results of the role mechanism of agricultural green technology innovation.

Variables	(1)	(2)	(3)	(4)	(5)
RDE	1171.3*** (147.5)	989.7*** (153.3)	375.8*** (57.75)	229.3*** (50.73)	
L.RDE					142.9** (65.11)
Control variable	YES	YES	YES	YES	YES
_cons	-67.78 (188.9)	210.5 (321.6)	-11.21 (65.16)	140.2 (106.4)	170.4 (151.2)
Year fixed	NO	YES	NO	YES	YES
Province fixed	NO	YES	NO	YES	YES
Observations	300	300	300	300	300
adj. R^2		0.411		0.507	0.456

Conclusions and Recommendations

Conclusions

This study analyzes the impact of the rural digital economy on agricultural carbon emissions in China between 2012 and 2021, using panel data collected from 30 provinces. Empirical methods were employed to investigate the relationship between the two variables. The results indicate a significant reduction in emissions, (Table 4). Following robustness tests, such as variable replacements and extended timescales (Tables 5-6), the impact remains consistently significant. Heterogeneity analyses indicate that the impact of the rural digital economy has a more pronounced effect on reducing agricultural carbon emissions in the western and northeastern regions, while it is insignificant in both the eastern and central regions (Table 7). Furthermore, the effect of the rural digital economy on reducing agricultural carbon emissions is more pronounced in provinces with lower levels of rural digital economy development than in those with higher levels of rural digital economy development (Table 7). The mediation process indicates that the development of the rural digital economy improves the level of agricultural green technological innovation and reduces agricultural carbon emissions by the use of agricultural green technology. This is evidenced by the number of agricultural green patent applications and agricultural green patents (Table 8).

Recommendations

Promoting a Differentiated Rural Digital Economy

In contrast to the eastern and central regions and provinces which exhibit a high level of rural digital economic development, the western and northeastern regions and provinces display a lower level of rural digital infrastructure construction and a relatively weaker ability to apply and innovate in agricultural digital technology. Therefore, it is essential to concentrate on coordinated regional development and implement differentiated management based on the level of rural economic development and the specific characteristics of agricultural development in each locality. The eastern, central, western, and northeastern regions should collaborate to exploit the low-cost and resource-based benefits of the western and northeastern regions, alongside the cutting-edge technologies, favorable markets, and digital industry advantages of the eastern and central regions. This will create a mechanism for developing the rural digital economy, fostering complementary advantages, mutual benefits, and synergistic development. To improve rural economies in the western and northeastern regions, digital infrastructure development should be accelerated while reducing data processing expenses in the eastern and central areas. Additionally, rural digital technology use should be enhanced in the east, and innovation in agricultural digital technology should be promoted to have spillover effects on the central, western, and northeastern areas. Finally, the government should guide universities, scientific research institutions, and enterprises to impart replicable and scalable technological know-how and experience to rural areas, in order to enhance digital technology exchange and cooperation in agriculture between the Eastern, Central, Western, and Northeastern regions. This will accelerate the development of digital modernization in agriculture and rural areas.

Upgrading Innovation in Agricultural Green Technology

Firstly, digital financial products such as tax relief, green financing, and green credit should be actively launched. Research institutes and enterprises should be guided to enhance research and development on agricultural green technology innovation. Peer-to-peer funding support should be prioritized. Secondly, an agricultural big data platform should be established utilizing the Internet and 5G networks. This will enhance agricultural green technology innovation and reinforce the protection of intellectual property rights related to green technology. To address the national initiative for environmentally-friendly and low-carbon progress in agriculture, it is essential to create an assessment scheme for agricultural innovations regarding their environmental impact. Additionally, supporting the cultivation and recruitment of individuals with expertise in sustainable agricultural technology is crucial. Policies should be used efficiently to direct skilled workers to agribusinesses as a priority. Finally, digital technology can be used to integrate resources for innovative agricultural green technologies, facilitate cooperation and support in all areas of society, achieve connectivity and increase the efficiency of transformation of agricultural green technology successes.

Promoting the Rural Digital Economy and Encouraging Environmentally Friendly and Low-Carbon Agricultural Development

The rural digital economy still has several shortcomings. To address these issues, it is crucial to seize the opportunities for development while placing great emphasis on basic research, promoting independent innovation and making up for the shortfall. It is important to monitor the changes in market technology and ensure efficient cooperation between industry, universities and research institutes to focus on utilizing open market technology [1]. Efforts to promote green and low-carbon agriculture should be taken. To achieve this, policy-level leadership and support must be enhanced to expedite the construction of rural digital infrastructure. Rural network facilities should also be upgraded, and digital developments in rural water conservancy, highways, and electric power should be accelerated. Furthermore, it is important to enhance green and low-carbon development in traditional agriculture in conjunction with 'Internet +' initiatives. Secondly, we will promote rural digital finance, integrate the digital economy with agriculture and rural areas, establish a comprehensive system for rural environmental protection, endorse a sustainable and environmentally-friendly way of life, and prioritize the implementation of diversified and market-oriented collaboration mechanisms. Establishing an agricultural big data monitoring platform, enhancing monitoring of the agricultural ecological environment, improving the utilization of agricultural input records, facilitating precision reduction, and promoting low-carbon agricultural development are essential. Additionally, we need to expedite the interconnection and sharing of rural digital information. Offline and online training services should be offered to farmers to produce agricultural and rural experts who are passionate about agriculture, business-savvy, and technologically skilled. Moreover, it is important to utilize the guidance provided by village cadres, college student village officials, and 'science and technology specialists' to direct the development of rural informatization. Additionally, it is crucial to promote the growth of low-carbon and eco-friendly agriculture. Another important aspect is to increase investment in research and development of digital technology for agriculture. Agricultural digitalization should be actively developed using modern information technologies such as the Internet of Things, cloud computing, and artificial intelligence. These technologies should be actively applied to agriculture production, circulation, processing, and sales to promote green, low-carbon agriculture development.

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Conflict of Interest

The authors declare no competing financial interest.

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