

Study on the Impact of Digital Economy on Agricultural Carbon Emissions Based on Fixed Effects Modeling

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Abstract. With the rapid development of the digital economy and the increasing global attention to the issue of agricultural carbon emissions, the use of the digital economy to promote agricultural carbon emission reduction has become an inevitable path to achieve sustainable agricultural development. Based on China's provincial panel data from 2015 to 2022, this paper constructs a comprehensive digital economy evaluation index system and empirically analyzes the impact of rural digital economy development on agricultural carbon emissions. The results show that the vigorous development of digital economy significantly reduces agricultural carbon emissions, and effectively promotes the green transformation and sustainable development of agriculture through multiple paths such as optimizing industrial structure, promoting technological innovation, and improving service efficiency.

Keywords: Digital economy, technological progress, agricultural carbon emissions, green and high-quality development of agriculture.

1. Introduction

This study aims to analyse the impact of digital economy on agricultural carbon emission intensity, focusing on the construction of models and algorithms and their application in emission reduction mechanisms [1]. As an emerging driving force, the digital economy shows important potential in improving agricultural production efficiency, optimising agricultural industrial structure and reducing carbon emission intensity [2, 3]. This study empirically analyses the inhibitory effect of digital economy on agricultural carbon emissions by using panel data from 31 provinces (autonomous regions and municipalities directly under the central government) in China from 2015 to 2022 based on the fixed effects model [4]. The study aims to construct and optimise the relevant models to identify how the digital economy can achieve the goal of agricultural carbon emission reduction through the paths of technology-driven, industrial upgrading and service efficiency improvement. By systematically analysing the mechanism of the digital economy and proposing corresponding feasible solutions, this study provides theoretical support and policy recommendations for achieving the green and low-carbon transformation of agriculture and the 'dual-carbon' goal [5, 6].

2. Variable construction

This study involves data on agricultural carbon emissions and digital economy in 31 provinces (autonomous regions and municipalities directly under the central government) from China Rural Statistical Yearbook, China Statistical Yearbook, China Science and Technology Statistical Yearbook, as well as statistical yearbooks of each province and relevant reports of Ali Research Institute, etc., spanning from 2015 to 2022, and some of the missing data are made up by interpolation and averaging methods.

2.1. Explanatory variable

Digital Economy Index (DE): Based on the theoretical connotation of digital economy and guided by the white paper of China's Digital Economy Development Report, this study constructs a regional digital economy development index from four dimensions: digital infrastructure construction, digital innovation, industrial digitization, and level of economic development, and takes it as a core explanatory variable with a view to examining its significant impact on green total factor productivity.

Drawing on existing literature, this paper systematically constructs an evaluation system for the development of rural digital economy by selecting fourteen specific indicators, such as Internet penetration rate and rural broadband penetration level, from the three dimensions of digital infrastructure construction, digital scientific and technological innovation, and digital industry development. Specifically, digital infrastructure construction (M1) includes the Internet penetration rate (i.e., the number of Internet users as a percentage of the total population in the region), computer penetration rate (the number of computers per 100 people), and the level of rural logistics construction (the length of rural delivery routes). For digital science and technology innovation (M2), the scale of agricultural science and technology talents (the number of people engaged in agricultural science and technology activities), and the strength of financial support (expenditure on R&D for high-tech industries) were selected. Digital industry development (M3), on the other hand, includes the level of rural digital e-commerce development (measured by e-commerce sales). In addition, the level of economic development (M4) is measured through the gross rural product (gross value of agricultural, forestry, animal husbandry and fishery output, as a control variable).

2.2. Explanatory variable

Carbon Emissions from Agriculture (CE): In this paper, six aspects of agricultural materials, straw burning, agricultural energy, rice growing process, livestock feeding management, and land management are selected as the main sources of agricultural carbon emissions and are measured using the emission coefficient method.

This paper adopts the emission coefficient method that is most used in carbon emission measurement. That is, on the basis of constructing a carbon emission measurement system, the activity level data of agricultural carbon emission sources are multiplied with the emission coefficients to obtain the emissions of greenhouse gases, which are then transformed into carbon emission equivalents according to the global warming potentials of different gases, and ultimately added to obtain the total amount of agricultural carbon emissions, with the specific calculation formula as follows:

$$E_i = \sum T_{in} \times \delta_{in} \quad (1)$$

$$E = \sum E_i \times \omega_i \quad (2)$$

where E_i is the i -th agricultural GHG emission; T_{in} is the amount of the n th emission source of the i th GHG; δ_{in} is the corresponding emission factor i.e. GHG emissions due to activities per unit of carbon emission source; E is the total amount of agricultural carbon emissions; ω_i is the global warming potential value of the i th agricultural greenhouse gas. According to the IPCC report, the global warming potentials of carbon dioxide, methane, and nitrous oxide are 1, 28, and 265, respectively. According to the needs of this paper, the sources of carbon emissions will be categorized into six aspects: agricultural materials, straw burning, agricultural energy, rice growing process, livestock feeding management, and land management.

In this paper, carbon emissions from the production, transportation and use of agricultural films, fertilizers and pesticides are selected as the main sources of carbon emissions from agricultural materials. This study systematically evaluates the impacts of agricultural films, fertilizers and pesticides on agricultural carbon emissions during their entire life cycle of production, transportation and use, in order to quantify their contribution to the carbon footprint of the agricultural production system, and to provide a scientific basis for the formulation of effective carbon emission reduction

policies. Specifically, the production and use of fertilizers, pesticides and agricultural films lead to about 0.8956, 4.9341 and 5.18 kg of carbon equivalent emissions, respectively. The results of the study show that the carbon emissions of fertilizers mainly originate from energy consumption in production and transportation, pesticides involve the use of high energy consumption in chemical synthesis and subsequent treatment, and the carbon emissions of agricultural films are closely related to the production and waste management of their plastic raw materials. This assessment provides an in-depth understanding of the specific roles and weights of several types of agricultural materials in agricultural carbon emissions, thus providing data support for the development of low-carbon alternatives.

In terms of agricultural energy carbon emissions, this paper selects the main energy sources consumed in the agricultural sector, namely diesel fuel and irrigation electricity, as the sources of agricultural energy carbon emissions. The carbon emission measurement of energy consumption in agriculture is consistent with other fields. The carbon emission factor of irrigation electricity is $20.46 \text{ kg(C)} \cdot \text{kg}^{-1}$, which is like the average thermal power generation factor in China. The carbon emission factor for diesel fuel is $0.5927 \text{ kg(C)} \cdot \text{kg}^{-1}$.

As for the carbon emissions from straw burning, based on the research results of Peng Liquan et al, the carbon emissions from the burning of straw in the open air are calculated as.

$$E = \sum_{k=1}^K (P_k \times C_k \times R_k \times F \times F_{E,k}) \quad (3)$$

Where E is the carbon emission from straw burning; k is the crop category; and P_k is the crop k yield; and C_k is the crop k is the grass to grain ratio of the crop; and R_k is the crop k straw open burning ratio; and F is the burning efficiency; and $F_{E,k}$ is the carbon emission factor for each source category of crop k carbon emission factors of open burning of straw. In this paper, six crops, namely rice, corn, soybean, potato, oilseed, and cotton, are selected as the sources of carbon emissions from straw burning.

The carbon emission factors for the burning of several types of agricultural straw are 1.460, 1.350, 1.445, 1.445, 1.445 and 1.445 for rice, corn, soybean, yams, oilseeds, and cotton, respectively. The straw-to-grain ratio, combustion efficiency and proportion of open burning for various types of crops are as follows: rice 0.90, 0.93, and 26.80%; corn 1.20, 0.92, 17.20%; soybean 9.20, 0.80, 25.10%; yams 1.50, 0.82, 23.20%; oilseeds 1.60, 0.68, 23.20%; cotton 0.50, 0.68, 23.20%.

The growth process of rice produces a large amount of methane emissions, and there are abundant methane-producing substrates and methanogenic bacteria in the paddy soil. The methane formed through the oxidation of the paddy soil is emitted to the atmosphere through the rice plants.

Calculations based on the growth cycle of single-season, late-season and mid-season rice yielded the methane emission coefficients during the rice growth cycle in each province of China (see Table 1).

Carbon emissions from livestock management, however, originate from three main sources: firstly, methane is produced by methanogens during intestinal digestion after feed intake; secondly, organic matter in animal manure produces a large amount of methane through the action of methanogens; and lastly, nitrous oxide is produced by microorganisms during manure stockpiling. The carbon emission factor of livestock includes both enteric fermentation and manure management. The methane emission coefficients for cattle, mules, camels, donkeys, horses, hogs, and sheep were 47.8, 10, 46, 10, 18, 1, and 5, respectively, the methane emission coefficients for manure management were 1, 0.9, 1.92, 0.9, 1.64, 3.5, and 0.16, respectively, and the nitrous oxide emission coefficients were 1.39 and 0.53. The annual livestock holding was calculated by averaging the current year's and the previous year's stockpiles Calculated.

Carbon emissions in the land management process are a priority and are divided into two principal areas. First, carbon emissions caused by the release of organic carbon due to the tilling of the land, the carbon emission coefficient of tilling is 321.6 kg/km^2 the carbon emission coefficient of plowing is 321.6. Second, soil nitrogen emission caused by carbon and nitrogen cycle in farmland

ecosystem. Soil carbon and nitrogen cycle carbon emissions are divided into direct emissions and indirect emissions. Among them, the direct emission selects the carbon emission caused by nitrous oxide emitted from fertilizer use and straw return to the field in agricultural land; the indirect emission includes nitrous oxide emission caused by atmospheric nitrogen deposition and nitrous oxide emission caused by nitrogen leaching runoff loss. The specific calculation formula is as follows:

$$E_{N_2O} = \sum (N_2O_{\text{direct}} + N_2O_{\text{deposition}} + N_2O_{\text{leaching}}) \quad (4)$$

Eq: E_{N_2O} is the total nitrous oxide emissions from agricultural systems; N_2O_{direct} represents nitrous oxide emissions from agricultural land; $N_2O_{\text{deposition}}$ represents the indirect emission of nitrous oxide caused by atmospheric nitrogen deposition; and N_2O_{leaching} is the indirect emission of nitrous oxide caused by leaching runoff.

Table 1. Methane emission coefficients during the growing cycle of rice in various provinces (cities and autonomous regions) of China.

Province (City, Autonomous Region)	Rice at Transplanting or Still Unripe	Late Rice	Mid-Season Rice	Province (City, Autonomous Region)	Rice at Transplanting or Still Unripe	Late Rice	Mid-Season Rice
Beijing	0	0	13.23	Hubei	17.51	39.0	58.17
Tianjin	0	0	11.34	Hunan	14.71	34.1	56.28
Anhui	0	0	15.33	Guangxi	12.41	49.1	47.78
Shanxi	0	0	6.22	Hainan	13.43	49.4	52.29
Inner Mongolia	0	0	8.93	Sichuan	6.55	18.5	25.73
Liaoning	0	0	9.24	Chongqing	6.55	18.5	25.73
Jilin	0	0	5.57	Guizhou	5.10	21.0	22.05
Heilongjiang	0	0	8.31	Yunnan	2.38	7.6	7.25
Shanghai	12.41	27.5	53.87	Tibet	0	0	6.83
Jiangsu	16.07	27.6	53.55	Shaanxi	0	0	12.51
Zhejiang	14.37	34.5	57.96	Gansu	0	0	6.83
Anhui	16.75	27.6	51.24	Qinghai	0	0	0
Fujian	7.74	52.6	43.47	Ningxia	0	0	7.35
Jiangxi	15.47	45.8	65.42	Xinjiang	0	0	10.50
Shandong	0	0	21.00				

Direct nitrous oxide emissions from agricultural land:

$$N_2O_{\text{direct}} = (N_{\text{fertilizer}} + N_{\text{residue}}) \times EF_{\text{direct}} \quad (5)$$

Where N_2O_{direct} is the direct emission of nitrous oxide from agricultural land; $N_{\text{fertilizer}}$ is the amount of fertilizer applied to agricultural land (nitrogen fertilizer and compound fertilizer); N_{residue} is the direct emission factor of nitrous oxide on agricultural land (see Table 8); EF_{direct} is straw return nitrogen (above ground straw return nitrogen and underground root nitrogen), the calculation formula is as follows;

$$N_{\text{residue}} = \sum_{i=1}^n \left(\frac{M_i}{L_i} - M_i \right) \times \beta_i \times K_i + \frac{M_i}{L_i} \times \alpha_i \times K_i \quad (6)$$

Where: N_{residue} is the straw return nitrogen; M_i is the seed yield of the i th crop; L_i is the economic coefficient of the i th crop; β_i is the straw return rate of the i th crop; K_i is the nitrogen content of straw of the i th crop; α_i is the root-crown ratio of crop i (see Tables 2 and 3 for specific parameters).

Table 2. Direct emission factors for nitrous oxide from agricultural land.

Shore	Nitrous oxide direct emission factor (EF) (%)	Range (%)
Region I (Inner Mongolia, Xinjiang, Gansu, Qinghai, Tibet, Shaanxi, Shanxi, Ningxia)	0.56	0.15 ~ 0.85
Zone II (Heilongjiang, Jilin, Liaoning)	1.14	0.21 ~ 2.58
Region III (Beijing, Tianjin, Hebei, Henan, Shandong)	0.57	0.14 ~ 0.81
Region IV (Zhejiang, Shanghai, Jiangsu, Anhui, Jiangxi, Hunan, Hubei, Sichuan, Chongqing)	1.09	0.26 ~ 2.20
Region V (Guangdong, Guangxi, Hainan, Fujian)	1.78	0.46 ~ 2.28
Region VI (Yunnan, Guizhou)	1.06	0.25 ~ 2.18

Table 3. Parameters for several types of crops.

Crop parameters	Nitrogen content of seeds (%)	Nitrogen content of straw (K) (%)	Economic coefficient (L) (%)	Root-crown ratio (α) (%)	Straw return ratio (β) (%)
Maize	0.0100	0.00753	0.489	0.125	32.30
Corn	0.0170	0.00580	0.438	0.170	9.30
Maize	0.0140	0.00516	0.434	0.166	76.50
Common sorghum (Sorghum vulgare)	0.0170	0.00730	0.393	0.185	4.00
Soybeans	0.0600	0.01810	0.425	0.130	9.30
Vegetable	0.0080	0.00800	0.830	0.250	61.85
Bast fiber	0.0131	0.01310	0.830	0.200	9.30
Potatoes	0.0040	0.01100	0.667	0.050	39.92
Leaf tobacco	0.0410	0.01440	0.830	0.200	61.85
Oilseeds	0.0005	0.00550	0.271	0.150	61.85

Indirect emissions of nitrous oxide due to atmospheric nitrogen deposition:

$$N_2O_{\text{deposition}} = (N_{\text{input}} \times 10\%) \times 0.01 \quad (7)$$

Where $N_2O_{\text{deposition}}$ is the indirect emission of nitrous oxide due to atmospheric nitrogen deposition N_{input} is the nitrogen input from agricultural land. 10% is the N_{input} the recommended value of volatilization rate, and 0.01 is the recommended value of nitrous oxide emission factor caused by atmospheric nitrogen deposition.

Indirect emissions of nitrous oxide from leaching runoff:

$$N_2O_{\text{leaching}} = N_{\text{input}} \times 20\% \times 0.0075 \quad (8)$$

Where N_2O_{leaching} is the indirect emission of nitrous oxide caused by leachate runoff; and N_{input} Nitrogen input from agricultural land; Nitrogen loss from nitrogen leaching and runoff is estimated as 20% of the total nitrogen input from agricultural land. 0.0075 is the recommended value of the nitrous oxide emission factor caused by leaching and runoff.

2.3. control variable

Level of financial support for agriculture (FS): Financial support for agriculture can promote agricultural economic growth. Appropriate financial inputs can promote rational resource allocation, healthy and sustainable development of economic innovation, thus promoting green and high-quality development of agriculture. This paper adopts the ratio of expenditure on agriculture, forestry, and water affairs in fiscal expenditure to GDP to measure.

Impact rate (IR): Natural disasters can inhibit the increase of total factor productivity in agriculture in the short term. It also has long-term effects, such as the reconstruction and production work of agriculture after it has been damaged by natural disasters will also affect the development of

agricultural production. Therefore, this paper takes the disaster-affected rate as one of the control variables, which is measured by the proportion of disaster-affected area to the sown area of crops.

Input intensity of agrochemicals (IA): Some farmers use agrochemicals excessively in pursuit of high yields and incomes, thus impacting on the growth of agricultural carbon emissions. In this paper, we use the ratio of the discounted amount of fertilizer to the total sown area of crops to measure the input intensity of agrochemicals.

Level of urbanization (CY): With the gradual improvement of China's infrastructure level and economic development, the urbanization rate is also steadily increasing, a relatively high level of urbanization can increase the employment rate of people, thus playing a role in promoting the human inputs for the green and high-quality development of agriculture, this paper adopts the ratio of the urbanized population in each region of China to the total population in order to measure the level of urbanization in each region.

3. Model construction and regression analysis

3.1. model building

To examine the impact of regional digital economy development on agricultural carbon emissions, a double fixed-effects model was constructed as a benchmark regression model for empirical testing, as follows.

$$CE_{it} = a_0 + a_1 DE_{it} + a_2 Control_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (9)$$

Where i denotes the province, and t denotes year, and CE is the explanatory variable Agricultural Carbon Emission, DE is the core explanatory variable Digital Economy Index, $Control$ is the control variable, and μ_i is the province fixed effect, the ν_t is the time fixed effect, and ε_{it} is the random error term. a_i are the estimated coefficients of the core explanatory variables, whose positive, negative and size reflect the direction of the influence of the core explanatory variables on the explanatory variables as well as the strength of their effects, respectively.

3.2. return to baseline

After testing, column (1) in Table 4 shows the regression results of the random effect model without adding control variables, and the results show that the digital economy has a suppressing effect on agricultural carbon emissions, but it is not significant. The results show that the digital economy significantly suppresses the intensity of agricultural carbon emissions at the 1% level, and the p-value is less than 0.01 by Hausman's test, therefore, the fixed effect model is chosen, and the coefficient of influence is -3.992. The results show that the digital economy significantly suppresses the intensity of agricultural carbon emissions at the 1% level, and the p-value is less than 0.01 by Hausman's test. Economy significantly suppresses the intensity of agricultural carbon emissions at the level of 1%, and for every 1% increase in the degree of development of the digital economy, the intensity of agricultural carbon emissions decreases by 3.5522 percentage points. With the continuous development of the digital economy, empowering agricultural production, carbon emission source application is reduced, which promotes the possibility of upgrading agricultural technological means and green business production, and then reduces the intensity of agricultural carbon emissions. The urbanization rate and financial support policies for agriculture weaken the inhibiting effect of the digital economy on agricultural carbon emissions. The degree of agricultural disaster and the intensity of agricultural chemical inputs have a suppressing effect on agricultural carbon emission intensity from the regression coefficients.

Table 4. Results of the benchmark regression.

	(1) CE	(2) CE	(3) CE
DE	-1.012 (-0.3023)	-3.992*** (-4.5007)	-3.552*** (-3.6021)
FA			2637.605 (1.1222)
CY			1254.667 (0.7508)
IR			-70.118 (-0.3356)
IA			-9100 (-1.2955)
_cons	3593.691*** (2.7866)	1927.392*** (5.0356)	1111.452 (0.7515)
Time fee	No	Yes	Yes
Province	No	Yes	Yes
N	248	248	248

3.3. Robustness and Heterogeneity Tests

This study verifies the significant effect of digital economy in curbing agricultural carbon emissions through two-way fixed-effects modeling analysis. To further verify the robustness of the findings, a variety of methods such as replacing the core explanatory variables, adjusting the sample capacity, and adding or subtracting control variables were used for the test. When reconstructing the core explanatory variables, new indicators such as fixed investment in social digital industry, word frequency of government digital attention and rural inclusive finance index were added to measure the effect of social investment, policy support and financial support for digital agriculture construction. Specific regression results show that the impact coefficient of digital economy after replacing the core explanatory variables is -3.552 and holds at 1% significance level; the impact coefficient after randomly selecting 20 provinces in order to adjust the sample capacity is -1.998, which is significant at 5% significance level; the impact coefficient after adding or subtracting control variables is -3.430, which is also significant at 1% significance level. These results indicate that the significant inhibitory effect of digital economy on agricultural carbon emission reduction remains robust under different conditions, verifying the robustness of the model.

In addition, this study further analyzes the heterogeneous impact of the digital economy on agricultural carbon emissions. There are significant differences in economic level, policy support and agricultural production methods in different regions, which leads to regional differences in the impact of digital economy on agricultural carbon emissions. The group regression analysis using the Northeast, East, Central and West regions as samples shows that the impact coefficient of the digital economy on agricultural carbon emissions in the Northeast region is -5.049 and holds at a significance level of 5%, indicating that the region has made significant progress in industrial structural adjustment, policy support, and the promotion of digital technology, which has promoted the sustainable development of agriculture and carbon emission reduction. The impact coefficient of digital economy in the central region is 2.031, but it fails the significance test, probably due to the relatively backward digital infrastructure in the region, the bias of agricultural production methods toward tradition, and the limited application of digital technology, which in turn limits the positive effect of digital economy. The impact coefficient in the eastern region is -1.005, which fails to reach the significance level, probably due to the complex economic structure of the eastern region, where the contribution of other sectors (such as industry and services) to carbon emissions is more significant, weakening the effect of the digital economy on carbon emission reduction in agriculture, and also because agriculture accounts for a relatively small share of the overall economy, which could be one of the reasons. The impact coefficient in the western region is -0.568, which is not significant, reflecting the

weak digital infrastructure in the region and the fact that the penetration of the digital economy into agriculture needs more time and resource support.

In summary, the results of this study indicate that the impact of digital economy on agricultural carbon emissions in different regions is characterized by significant heterogeneity. These findings provide empirical evidence for the development of locally adapted carbon emission reduction policies in digital agriculture, and emphasize that interregional policymaking needs to consider the differences in economic foundations, the degree of application of digital technologies, and the strength of policy support in each region in order to achieve more effective carbon emission reduction goals.

4. Summary

Based on panel data from 31 provinces (autonomous regions and municipalities directly under the central government) in China from 2015 to 2022, this study analyzes the impact of the digital economy on the intensity of agricultural carbon emissions and explores its emission reduction mechanism to promote high-quality and sustainable development of agriculture using a fixed-effects model. The findings show that the digital economy has a significant effect in curbing the intensity of agricultural carbon emissions, and effectively promotes the reduction of agricultural carbon emissions by promoting the optimization of the agricultural industrial structure, the development of new industries such as e-commerce, and the improvement of the utilization rate of agricultural resources and technical efficiency. In addition, the digital economy can expand the coverage of economic services in the agricultural sector, especially the promotion and application in remote rural areas, so that agricultural carbon emission reduction can obtain more extensive financial support and policy inclination. Using big data analysis, artificial intelligence and other digital technology means, the digital economy also realizes accurate assessment and rapid approval of agricultural carbon emission reduction projects and improves the service efficiency of agricultural production and carbon management. Overall, the development of the digital economy not only plays a key role in enhancing agricultural production efficiency, but also promotes the advancement of agriculture in the direction of low-carbon environmental protection by supporting the green transformation of agriculture and realizing the efficient allocation of resources. Through further policy support and concerted efforts, the digital economy will continue to play a key role in agricultural carbon emission reduction and sustainable development, laying a solid foundation for the realization of the "double carbon" goal.

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