POPULATION URBANISATION, RURAL–URBAN INCOME GAP, AND AGRICULTURAL CARBON PRODUCTIVITY IN CHINA

WANG, Y. N. – WANG, H. N.*

Hunan Institute of Engineering, 411104 Xiangtan, China

**Corresponding author*
e-mail: 274502561@qq.com

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Abstract. Low-carbon development is crucial for global climate governance and for maintaining sustainable economic, social, and environmental development. Urbanization and agricultural production are two essential factors in low-carbon development. Exploring the impact of population urbanization on agricultural carbon productivity is crucial for low-carbon development. To this end, we use the data of 31 provinces in China (excluding Hong Kong, Macao, and Taiwan) from 2004 to 2021 to empirically test the impact and mechanism of population urbanization on agricultural carbon productivity. The results indicate that population urbanization significantly improves agricultural carbon productivity, with notable geographic and functional regional heterogeneity. In the mechanism test, the Theil index and the urban–rural income ratio were used to measure the urban–rural income gap, respectively. The results show that population urbanization can increase agricultural carbon productivity by narrowing the income gap between urban and rural areas. Reducing the rural–urban income gap is also an effective way to increase carbon productivity in agriculture.
Keywords: *low carbon, fixed effects model, Theil index, food production functional zone, intermediary effect*

Introduction

Frequent environmental problems, such as climate warming, have made reducing greenhouse gas emissions, particularly carbon dioxide, a global priority. Agriculture both absorbs and stores carbon dioxide, but is one of the main sources of greenhouse gas emissions. According to the Pathways to Carbon Neutral in Agricultural report released by The Boston Consulting Group and Polar Technologies in July 2022, greenhouse gases from agricultural activities and land use change account for about 17% of the total global greenhouse gas emissions, being the second largest source of emissions. China is a populous, agricultural, and developing nation. As a basic industry of China's economic development, agriculture not only provides a material basis for other departments, but also has social, cultural and ecological effects. To this end, China prioritizes developing ecological and low-carbon agriculture to strengthen its agricultural sector. With the rapid growth of agricultural economy, China will promote the goal of "double carbon" in agriculture and achieve the coordinated development of agricultural economic growth and carbon emission reduction. Agricultural carbon productivity balances economic growth with carbon emission reduction, making its improvement essential for green, low-carbon development (Liu et al., 2022a). Carbon productivity refers to the level of GDP output per unit of carbon dioxide, also known as "carbon average GDP", which is inversely related to "carbon emission intensity per unit of GDP". Agricultural carbon productivity is the ratio of the total value of agricultural production to the total amount of carbon emissions generated by its production process, that is, the economic benefits of agriculture per unit of agricultural carbon emissions.

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Urbanization is a historical process of transformation from a traditional agricultural society with a large proportion of agricultural population to a modern civilized society with a majority of non-agricultural population. It is an important symbol to measure the process of modernization. Statistics show that China's urbanization rate was 17.9% in 1978, and it has reached 64.72% by 2021, making it one of the countries with the fastest development speed of urbanization in the world. In China, with the continuous development and improvement of the level of urbanization, as well as the deepening of academic research, different forms of urbanization have emerged. Such as population urbanization (Zhou et al., 2020), land urbanization (Ji et al., 2020), economic urbanization (Liu et al., 2022b) and the social urbanization (Wang et al., 2019a). Population urbanization is the most commonly used indicator to measure the level of urbanization (Chen, 2024). Urbanization is an important and driving force of modern economic growth. The concentration of population in cities creates significant economies of scale, significantly reducing the average and marginal costs of private and public investment, creating a larger market and higher profits (Liu et al., 2024). Urbanization affects agricultural carbon emissions and agricultural carbon productivity (Ridzuan et al., 2020), at the same time, population urbanization will affect the income gap between rural residents' income and urban and rural residents (He and Du, 2022), and the income gap between urban and rural residents will affect agricultural carbon emissions (Wang et al., 2023b). But will population urbanization affect agricultural carbon productivity through the income gap between urban and rural residents? This remains to be investigated. Because there is no literature on these three studies in the same analytical framework.

To this end, we take China as an example, using data from 31 Chinese provinces (excluding Hong Kong, Macao and Taiwan) from 2004 to 2021. And we incorporate population urbanization, the urban–rural income gap, and agricultural carbon productivity into the same research framework. Three main questions are examined. First, what is the impact of population urbanization on agricultural carbon productivity? Is it positive or negative? Is there a heterogeneity characteristic? Second question, will population urbanization affect agricultural carbon productivity through the income gap between urban and rural areas? Third, will the income gap between urban and rural residents affect agricultural carbon productivity? The conclusions will provide useful inspiration for urbanization and low-carbon agricultural development in developing countries. Our marginal contribution lies in three aspects. The first aspect is the first to analyze the relationship between population urbanization, urban–rural income gap and agricultural carbon productivity for the first time. The second aspect is to re-examine the impact of population urbanization on agricultural carbon productivity in a new era, using new data, and to analyze the existing heterogeneity characteristics. The third aspect is to test for the first time the impact of urban–rural income gap on agricultural carbon productivity. And in the process of the impact of population urbanization on agricultural carbon productivity, to explore whether the urban–rural income gap has a mediating effect.

Literature review

Impact of urbanization on agricultural carbon emissions and agricultural carbon productivity

The urbanization process will inevitably have a profound impact on the ecological environment and agricultural development. However, the academic community has not reached a unified conclusion on the impact of urbanization development on carbon

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emissions. On the one hand, urbanization will increase carbon emissions. Urbanization increases the production processes (Prastiyo et al., 2020), transport services (Boateng, 2020), and other carbon-based energy sources, as well as increased energy demand driven by fossil fuel resources (Raihan, 2023; Raihan and Tuspekova, 2022), resulting in increased carbon dioxide emissions. On the other hand, urbanization can promote the reduction of carbon emissions. In the process of urbanization, as the urban built-up area expands and urban building density reaches the optimal level, the carbon emission intensity can be significantly reduced (Qiao et al., 2024). At the same time, in the process of urbanization, the implementation of CCMP is a powerful strategy to effectively curb urban carbon emissions (Yin and Miao, 2024). Similarly, there are different conclusions on the impact of urbanization on agricultural carbon emissions. In the long term, urbanization will increase agricultural carbon emissions (Li et al., 2023). From a spatial perspective, urbanization positively affects local agricultural carbon emissions and negatively affects agricultural carbon emissions in neighboring regions (Huang et al., 2022). From the perspective of different types of urbanization, population urbanization negatively affects agricultural carbon emissions, while land urbanization positively affects agricultural carbon emissions (Zeng and Han, 2021). The urbanization of employment and urban construction can significantly reduce the carbon emissions of agricultural, while the positive effect of population urbanization on the carbon emissions of agricultural is not obvious (Wu, 2015). From different regions, urbanization has a significant positive effect on the carbon output efficiency of agriculture in China's Yellow River basin (Song et al., 2024). From the perspective of the policy effect, China's new-type urbanization pilot policy is conducive to promoting the low-carbon development of agriculture (Zhou et al., 2024).

However, there is a lack of research on the impact of urbanization on agricultural carbon productivity, with only two relevant papers. These two papers were completed by Cheng et al. (2018, 2019), which took Chinese provinces as the study sample, with a time span from 1997 to 2014, and both used the spatial Dubin model method. Conclusion: from the perspective of multi-scale urbanization, urbanization has an inhibitory effect on agricultural carbon productivity. The agricultural carbon productivity in the province is not only affected by local urbanization, but also by the role of urbanization in the surrounding areas, and even the indirect spillover effect of the latter is much higher than the direct effect of the former. From the perspective of different types of urbanization, population urbanization and social urbanization are not conducive to the improvement of local agricultural carbon productivity, while land urbanization plays a positive role in promoting it. Population urbanization in neighboring areas has an indirect positive spill-over effect on agricultural carbon productivity in these areas, while other types of urbanization have no such effect.

Impact of population urbanization on the urban–rural income gap

In general, improving the level of population urbanization plays a significant role in alleviating the urban–rural income gap (Wang et al., 2019b), but this effect has different implementation paths. In terms of impact characteristics, there is an obvious non-linear relationship between population urbanization and the urban–rural income gap, with an inverted U-shaped structure that first expands and then contracts (Cheng et al., 2023). From the perspective of income sources, population urbanization is conducive to narrowing the gap between urban and rural wage income, and then narrowing the overall urban–rural income gap, but it also shows an inverted U-shaped characteristics (Pu and

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Zhu, 2018). Therefore, in the long run, population urbanization is conducive to narrowing the income gap between urban and rural areas (Na and Zhang, 2016). From the perspective of spatial spillover effects, improving the level of urbanization in local and surrounding areas is conducive to narrowing the gap between urban and rural income areas. In this process, the urbanization of the population can promote the flow of factors and improve the efficiency of production, which has a spatial spillover effect on the increase of rural residents' income (Zhao and Liu, 2022). In addition, the economic development and the improvement of human capital levels are also conducive to narrowing the urban–rural income gap in promoting the urbanization process (Zhang and Chai, 2018). From the perspective of the influence mechanism, both the scale of financial development (Liu and Zhu, 2017) and the upgrading of industrial structure (Hong and Zhang, 2021) affect the urban–rural income gap, among which population urbanization has a significant mediating effect.

The impact of the income inequality on carbon emissions

Much attention has been paid to the impact of income inequality on carbon emissions, both in China and elsewhere. The overall conclusion is that rising income inequality is detrimental to reducing carbon emissions, but there is significant regional heterogeneity and non-linearities. From a global perspective, income inequality has an inhibitory effect on increasing carbon emission efficiency (Wang et al., 2023a). And this effect is significant for both developed and developing countries (Gimba, et al., 2023), but the effect is more pronounced in developed countries (Che et al., 2023; Hou et al., 2024). From a regional perspective, there is a highly non-linear relationship between income inequality and CO_2 emissions in the G7 countries. Between 1870 and 1880, income inequality had a significant positive effect on CO_2 emissions, while between 1950 and 2000 it had a significant negative effect. Between 1881–1949 and 2000–2014, there was no apparent relationship between the two variables (Uddin et al., 2020). In the period 1971–2014, income inequality and carbon dioxide emissions were positive only in 1988–1997, and negative in the other periods (Ghazouani and Beldi, 2022). In China, the income inequality is positively associated with carbon abatement, but there is also clear regional heterogeneity and non-linearity. Income inequality has a significant negative impact on carbon productivity, and the widening income gap between urban and rural residents increases carbon emissions (Guo, 2017; Jia et al., 2023), which is more pronounced in western and central China (Du et al., 2022). The income gap between urban and rural residents increases carbon emission intensity by affecting urbanization, inhibiting innovative development and increasing resource mismatch (Yan et al., 2023). In terms of regional differences, the income gap is positively correlated with carbon intensity in poor areas of China, while it is negatively correlated in high-income areas (Huo and Chen, 2022). In addition, the uneven spatial distribution of income will also increase carbon dioxide emissions (Liu et al., 2019).

From the literature review, we can see that many documents have confirmed the significant impact of population urbanization on carbon emissions and agricultural carbon emissions. However, there is only one literature on the impact of population urbanization on agricultural carbon productivity, and the conclusion is that the two are negatively related. In addition, although much literature has confirmed that population urbanization can reduce the urban–rural income gap, while widening the urban–rural income gap increases carbon emissions. However, the impact of the urban–rural income gap on agricultural carbon productivity has not been studied. There is also no literature on

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population urbanization, urban–rural income gap and agricultural carbon productivity in the same framework. Therefore, our study is highly innovative and can be a good addition to the existing literature.

Theoretical analysis and research hypotheses

As for the influence mechanism of population urbanization on agricultural carbon production rate, we mainly analyze it from two aspects: direct effects and indirect effects. *Figure 1* shows this influence mechanism.

Population urbanization drives agricultural carbon productivity growth

Population urbanization plays a driving role in the improvement of agricultural carbon productivity, which is mainly influenced by the resource allocation effect and technological progress effect of urbanization. First of all, the non-agricultural relocation of population and industry is a prominent feature of urbanization (Luo and Hong, 2021). The increase of in the proportion of the secondary and tertiary industries drives the transfer and employment of surplus rural labor force. This increases the scarcity of agricultural production factors and promotes the development of agricultural specialization and the formation of agglomeration economies (Luo, 2017). Agricultural management tends to be intensive and large-scale, and the agricultural industrial structure and resource allocation efficiency are optimized. It creates favorable conditions for improving the efficiency of agricultural carbon emission and increasing the agricultural output per unit of agricultural carbon emission. Secondly, the urbanization of population will increase the demand of the whole society for the quantity and quality of green and low-carbon agricultural products, and then force agriculture to optimize its management means, innovate business models and improve the technical level. Technological progress and knowledge spillovers are the key to improving agricultural carbon productivity, and the process of urbanization is also a process of technological change. The accumulated human capital, innovative knowledge and the resulting technological progress effect will spill over and spread to the agricultural sector, which will be conducive to improving agricultural total factor productivity and carbon productivity (Zhang et al., 2016). Finally, the government will take a series of environmental protection measures to protect the urban and rural environment. Because of the close link between urban and rural areas, the governance benefits it brings will spill over into the agricultural sector. By promoting technological progress in agriculture and constraining production behavior, it can drive green emission reductions in agriculture, which is also beneficial for improving efficiency (Tao and Hu, 2011; Huang et al., 2021). To this end, we propose the first hypothesis.

Hypothesis 1: Population urbanization can improve agricultural carbon productivity.

Population urbanization promotes agricultural carbon productivity by reducing the income gap between urban and rural areas

Population urbanization Narrows the urban–rural income gap. Population urbanization has reconfigured urban and rural resources, especially human resources. In the process of population urbanization, surplus labor in the traditional agricultural sector will be heavily shifted to the modern industrial sector. In order to maximize family income, rural residents will adjust labor factors, capital factors and production strategies, leading to a

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change in rural income sources, which is conducive to improving the income of rural residents and narrowing the income gap between urban and rural areas. In terms of wage income, the urbanization of the population makes the rural labor resources transfer to non-agricultural industries in large quantities, which enriches the income sources of farmers, especially the rapid increase of farmers' wage income (Goodwin and Mishra, 2004). In terms of operating income, on the one hand, the urbanization of the population makes agricultural production more dependent on modern production factors such as capital and technology (Wang et al., 2017). The types of agricultural products, management technology, equipment resources and production technology have been upgraded and improved, improving the efficiency of agricultural production, and thus increasing the net income of farmers. On the other hand, the urbanization of the population can lead to the abandonment of farming by households with insufficient labor, creating the conditions for the development of large-scale land production. With the improvement of production efficiency, the operating income of land inflow to farmers has been increased (Chen and Fu, 2014). In terms of property income, with the increasing urbanization of the population, the demand and price of land has also gradually increased, and rural residents have more opportunities to get compensation for land expropriation. However, farmers who settle down in cities also tend to transfer their homesteads to gain profits (Wang et al., 2021), thus supporting the rapid growth of property income. In summary, the urbanization of the population may have an increasing impact on farmers' wages, business income and property income. Reducing the rural–urban income gap is conducive to increasing carbon productivity in agriculture. The rural–urban income gap can improve agricultural carbon productivity through technological progress and optimization of resource allocation. First, innovation and application of production technology is an important measure to achieve high quality economic growth and reduce carbon emission intensity (Coondoo and Dinda, 2008). The impact of the income gap between urban and rural residents on regional innovation and carbon emissions is mainly driven by the mechanisms of "demand-induced innovation" and "human capital supply" (Yang, 2020). From the perspective of "demand leads innovation", it can be seen from Keynesian consumption theory that the widening income gap between urban and rural residents leads to a decline in the average consumption propensity and total consumption scale (Lewis, 1954). From the perspective of "human capital supply", the widening of the income gap between urban and rural areas suppresses the enthusiasm of urban human capital investment to some extent, and also leads to the reduction of rural residents' opportunities to obtain quality education and the decline of the return to education. Therefore, from these two perspectives, the widening of the urban–rural income gap is not conducive to technological innovation. Second, the optimization of resource allocation can force production factors to gather industries with low energy consumption and high efficiency, thus improving the quality of development (Bian et al., 2019). The widening income gap between urban and rural residents affects the regional resource mismatch, which affects the efficiency of economic development and the environmental quality of the region (Boyce, 1994). On the one hand, due to the existence of the urban–rural gap, the non-agricultural sector has allocated relatively more capital and relatively less labor (Guo and Zhang, 2022), which reduces the efficiency of resource allocation and hinders the upgrading of industrial structure. On the other hand, the "cost-benefit" of environmental protection is not equal for urban and rural residents. The of "environment for development" mode turns rural areas into "shelters" for regional polluting industries, which increases the scale of regional pollution emissions and suppresses the force of

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industrial transformation and upgrading (Du et al., 2022). In addition, there is an obvious urban bias in the government's economic growth management, which leads to the expansion of resource mismatch and the increase of carbon emission intensity. Therefore, we propose Hypothesis 2.

Hypothesis 2: Population urbanization can improve agricultural carbon productivity by narrowing the income gap between urban and rural areas.

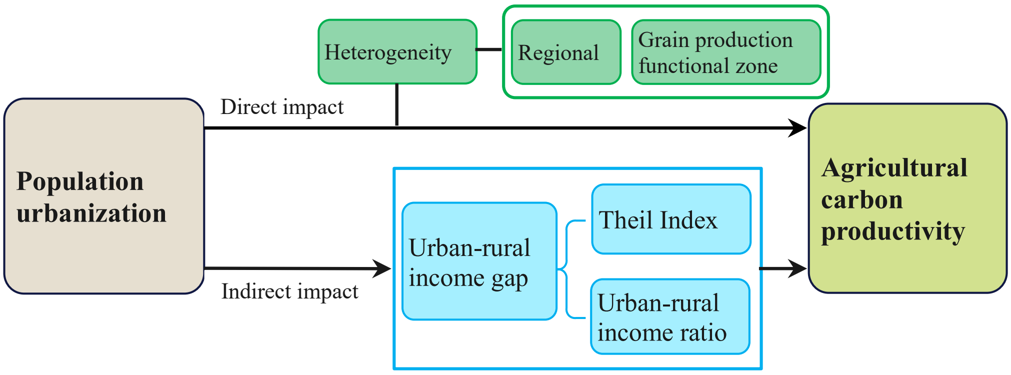

Figure 1. *Influence mechanism*

Methods and data

Model construction

Taking into account the unobservable individual differences between provinces and the confounding of empirical results by special years. Therefore, we examine the effect of population urbanization on agricultural carbon productivity by constructing a panel data regression model, where the baseline model is as follows:

$$ACP_{it} = \alpha_0 + \alpha_1 PU_{it} + \alpha_2 X_{it} + \eta_i + \psi_t + \varepsilon_{it} \quad \text{(Eq.1)}$$

where, *i* represents province and *t* represents year. The explained variable *ACP* represents agricultural carbon productivity. The *PU* denotes population urbanization, and *X* denotes the control variable. The α represents the parameter to be estimated. η_i and ψ_t represent the province fixed effect and the time fixed effect, respectively, and ε_{it} the random perturbation term.

Theoretical analysis shows that population urbanization is likely to affect agricultural carbon productivity by narrowing the urban–rural income gap. In order to test whether population urbanization can affect agricultural carbon productivity through the intermediary mechanism of the urban–rural income gap, we constructed the following mediation effect model to test:

$$gap_{it} = \gamma_0 + \gamma_1 PU_{it} + \gamma_3 X_{it} + \eta_i + \psi_t + v_{it} \quad \text{(Eq.2)}$$

$$ACP_{it} = \beta_0 + \beta_1 PU_{it} + \beta_2 gap_{it} + \beta_3 X_{it} + \eta_i + \psi_t + \pi_{it} \quad \text{(Eq.3)}$$

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In *Equations 2* and *3*, the intermediary variable is the urban–rural income gap (*gap*), γ and β represent the parameters to be estimated, v and π represent the random error terms, and the symbols and meanings of other variables are consistent with *Equation 1*. In order to effectively test the mediation effect, this paper uses the gradual regression method proposed by Baron and Kenny (1986) to verify whether population urbanization affects agricultural carbon productivity through the mediation effect of urban and rural income gap. Firstly, the significance of the coefficient α_1 in *Equation 1* is tested. If significant, then sequentially test whether the coefficient γ_1 in *Equation 2* and the coefficient β_2 in *Equation 3* are significant. If both are significant, this indicates the existence of a mediating effect. Finally, we test whether the coefficient β_1 in *Equation 3* is significant. If it is significant, it indicates the existence of a partial mediation effect. If it is not significant, there is a full mediation effect exists.

Variable selection

(1) The explained variables. Agricultural carbon productivity (ACP). There are currently two methods for measuring agricultural carbon productivity, including the total factor productivity measurement method and the single factor productivity measurement method. However, we have chosen to use the more common single-factor productivity measurement method as is used in the literature. Some international conventions reflect emission reduction responsibility arrangements under a single factor framework, which can directly reflect the degree of achievement of the dual goals of “reducing carbon and promoting economy”. Improvement in total factor carbon productivity may not necessarily mean improvement in emission reduction, and there is an error in measuring carbon emission efficiency by total factor productivity, which does not separate the inefficient parts of other factors (Wang and Gao, 2018). According to the Kaya and Yokobori (1999) definition of carbon productivity, agricultural carbon productivity is defined as the ratio of total agricultural output to total agricultural carbon dioxide emissions. Agriculture here is a narrow sense of agriculture (Xiaokaiti et al., 2024). Agricultural carbon productivity represents the output value of agricultural unit carbon emission, and meets the development requirements of green, low-carbon and sustainable agriculture. The calculation formula is:

$$\text{ACP} = \text{AGDP} / \text{ACE} \qquad \text{(Eq.4)}$$

In *Equation 4,* the gross agricultural product (*AGDP*) shall be subject to the gross agricultural output value issued by the National Bureau of Statistics. *ACE* says total agricultural carbon emissions. Meanwhile, following the approach of Liao et al. (2023), the specific calculation formula of the total agricultural carbon emission is as follows:

$$ACE = \sum_{i=1}^{k} T_i \times \theta_i \qquad \text{(Eq.5)}$$

In *Equation 5,* the T_i represents the agricultural carbon emission source, θ_i for agricultural carbon emissions coefficient, i for province. And to chemical fertilizers, pesticides, agricultural film, diesel oil, agricultural planting, agricultural irrigation as agricultural carbon emission sources. The emission coefficients of these agricultural emission sources are shown in *Table 1*.

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Table 1. *Carbon emission source, emission coefficient*

Agricultural carbon emission sources	Agricultural carbon emission coefficient	Reference source
Chemical fertilizer	0.89 kg/kg	Oak Ridge National Laboratory (Ma, 2011)
Pesticide	4.93 kg/kg	Oak Ridge National Laboratory (Ma, 2011)
Diesel oil	0.59 kg/kg	Stocker et al. (2013)
Agricultural film	5.18 kg/kg	The Institute of Agricultural Resources and Eco-Environment, Nanjing Agricultural University (Wang and Zhang, 2016)
Irrigate	266.48 kg/hm^2	Duan et al.(2011)
Turn over	312.60 kg/km^2	Li and Zhang (2012)

(2) Core explanatory variable: population urbanization (PU). The essence of the urbanization process is the process of transforming the rural population into the urban population. An important indicator reflecting the level of urbanization is the urbanization rate, that is, the proportion of the urban population living in a region to the total population of the region. Therefore, the proportion of urban population in the total population at the end of each year is used to measure the population urbanization rate of each province (Tian et al., 2024).

(3) Control variables. Referring to existing studies and combined with study subjects, we selected the following control variables. Foreign direct investment (*FDI*) is measured by the proportion of foreign direct investment in GDP in each province. Marketization level (*MI*) is measured by the Chinese provincial marketization index. The calculation method of market index in China refers to Fan et al. (2003) approach. The level of agricultural mechanization (*LFM*) is measured by the power of agricultural machinery (ten thousand kilowatts) used in each unit of the sown area of crops (one thousand hectares) in each province. Industrialization level (*IL*), the proportion of total industrial output value to GDP in each province. The level of financial development (*FD*) is measured by the ratio of the sum of deposits and loans in each province to GDP at the end of each year.

(4) Intermediation variables: urban–rural income gap. There are many ways to measure the urban–rural income gap, such as the Thiel index, the Gini coefficient and the disposable income gap between urban and rural residents. Compared to the Gini coefficient or the urban–rural income ratio, the advantage of the Theil index lies in its ability to reflect changes in income at both high and low ends, as well as the differences in population structure and migration flow between urban and rural areas. It can more objectively, truthfully, and comprehensively demonstrate the income gap between urban and rural residents (Wang and Ouyang, 2008). Therefore, we use the Theil index to measure the income gap between urban and rural areas. Simultaneously utilizing the income of urban and rural residents to enhance the robustness of research conclusions.

Theil index is a special form of entropy (GE) index system, which can decompose the overall income gap into the gap within groups and the gap between groups, and also fully take into account the change of disposable income of urban and rural residents and the change of the structure of urban and rural population ratio. Therefore, when measuring the urban–rural income gap, using the Theil index can well reflect this typical group gap change (Conceicao and Galbraith, 2000). Therefore, we first chose the Theil index to measure the income gap between urban and rural residents in China. In general, the lower

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the Theil index is, the more equal the income distribution is, and the smaller the gap is. Conversely, the higher the Theil index is, the more unequal the income distribution is, and the greater the gap is. Using the method of Luo and Hu (2024), construct the calculation formula is constructed as shown in *Equation 6*. In *Equation 6*, 1 means the town and 2 means the countryside. Y_{i1t} and Y_{i2t} respectively represent the income of urban and rural residents in region i during period t, Y_{it} represents the total income of the district residents. P_{i1t}, P_{i2t}, and P_{it} represent the population size.

$$\sum_{i=1}^{31}\sum_{t=2004}^{2021} theil_{it} = \sum_{j=1}^{2}\left(\frac{Y_{ijt}}{Y_{it}}\right)\times \ln\left(\frac{Y_{ijt}/P_{ijt}}{Y_{it}/P_{it}}\right) = \frac{Y_{i1t}}{Y_{it}}\times \ln\left(\frac{Y_{i1t}/P_{i1t}}{Y_{it}/P_{it}}\right)+\frac{Y_{i2t}}{Y_{it}}\times \ln\left(\frac{Y_{i2t}/P_{i2t}}{Y_{it}/P_{it}}\right) \quad \text{(Eq.6)}$$

However, the Theil index is very sensitive to high and low income, and the disposable income gap between urban and rural residents can more directly reflect the dynamic income changes of urban and rural residents, which is also used by numerous literature (Tu et al., 2024). Therefore, we choose the disposable income gap between urban and rural residents to measure the change of the income gap between urban and rural residents as the robustness verification. The urban–rural income ratio is used to measure the disposable income gap of urban and rural residents. The low ratio indicates that the urban–rural income gap is small; on the contrary, the larger the ratio is, the greater the income gap between urban and rural residents is. This index can better reflect the income difference between urban and rural residents, and it is easy to calculate. The calculation formula is shown in *Equation 7*. Among, Y_{i1t} and Y_{i2t} respectively represent the income of urban and rural residents in region i during period t.

$$IR_{it} = \frac{Y_{i1t}}{Y_{i2t}} \quad \text{(Eq.7)}$$

To more clearly show the names, abbreviations and measures of each variable, we use a tabular description. As shown in *Table 2*.

Table 2. *Main variables and measurement methods*

Type of variable	Variable name	Variable abbreviation	Measurement method
Explained variable	Agricultural carbon productivity	*ACP*	Agricultural carbon emissions/total output value of agriculture, forestry, animal husbandry, and fishery
Core explanatory variables	Population urbanization	*PU*	The proportion of the urban population in the total population
Controlled variable	Foreign direct investment	*FDI*	The proportion of foreign direct investment in GDP
	Marketization level	*MI*	Reference to Fan et al. (2003) approach
	Level of farming mechanization	*LFM*	The total power of agricultural machinery used in the total sown area of crops
	Industrialization level	*IL*	The proportion of the total industrial output value in GDP
	Financial development level	*FD*	The ratio of the combined deposits and loans to GDP
Mediating variables	Urban–rural income gap	*theil*	Theil index number
		RURI	The ratio of urban–rural income

The variable abbreviations in the table are mainly composed of the first letter of the variable name

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Data source

Given the availability and completeness of the data, panel data from 31 Chinese provinces (excluding Hong Kong, Macao and Taiwan) from 2004 to 2021. Relevant data are from the China Statistical Yearbook, China Rural Statistical Yearbook and the statistical yearbooks of the provinces, and some of the missing values are supplemented by the average method. The economic data in this article are adjusted to the 2004 constant prices to eliminate the influence of price factors. Descriptive statistics for each variable are shown in *Table 3*.

Table 3. *Descriptive statistics*

Variable	Mean	Standard deviation	Minimum value	Maximum value	Median	Sample capacity
ACP	0.4741	0.2535	0.1506	2.3502	0.4119	558
PU	0.5425	0.1496	0.2029	0.8958	0.5332	558
FDI	0.0215	0.0203	0.0001	0.1210	0.0171	558
MI	7.3857	2.1432	-0.1610	12.3900	7.4325	558
LFM	0.6446	0.3542	0.1697	2.6979	0.5565	558
IL	0.3468	0.0979	0.0705	0.5738	0.3569	558
FD	3.1420	1.1222	1.4447	7.5783	2.8823	558
theil	0.1055	0.05166	0.0180	0.3030	0.0990	558
RURI	2.7424	0.4962	1.8417	4.9494	2.6493	558

Analysis of direct impact results

Benchmark regression analysis

First, in order to study the impact of population urbanization on agricultural carbon productivity, the benchmark regression estimation is conducted based on *Equation 1*. Before regression estimation, conduct a Hausman test on the model to determine whether to use a fixed effect model or a random effect model. Based on the Hausman test results, it is suitable to estimate using a fixed-effect model. To examine the effect of population urbanization on agricultural carbon productivity under different conditions, stepwise regression was estimated here. *Table 4* reports the estimation results, with column (1) adding no control variables and column (2) adding control variables, and both columns with province fixed effect but no fixed time effect. Column (3) without control variables, column (4), and the bidirectional fixed effects of province and time were used in both columns. The results showed that under the four different conditions, the estimation coefficient of population urbanization on agricultural carbon productivity was significantly positive, confirming that population urbanization can promote the improvement of agricultural carbon productivity and verifying Hypothesis 1. In particular, in column (4), the estimated coefficient of agricultural carbon productivity by population urbanization is 1.8179, and it is significant at the 1% level. At the same time, comparing columns (3) and (4), it can be found that after controlling other factors that may affect agricultural carbon productivity, the estimated value of agricultural carbon productivity by population urbanization increases, indicating that agricultural carbon productivity will not only be affected by population urbanization, but also be affected by other factors.

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Table 4. *Benchmark regression results*

Variable	(1)	(2)	(3)	(4)
PU	2.7481*** (0.1104)	2.3137*** (0.1569)	1.6427*** (0.3279)	1.8179*** (0.3146)
FDI		−2.5355*** (0.4156)		−2.0418*** (0.3648)
MI		0.0292*** (0.0106)		0.0236** (0.0118)
LFM		0.1158*** (0.0338)		0.1304*** (0.0410)
IL		−0.7107*** (0.1162)		−0.5196*** (0.1493)
FD		−0.0701*** (0.0153)		−0.0800*** (0.0127)
Constant	−1.7789*** (0.0996)	−1.1185*** (0.1119)	−0.9075*** (0.2513)	−0.6603** (0.3015)
Time effect	No	No	Yes	Yes
Province effect	Yes	Yes	Yes	Yes
Sample size	558	558	558	558
R^2	0.7879	0.8216	0.8275	0.8480

(1) *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. Standard error is given in parentheses. (2) “Yes” and “No” indicate whether the model controls for the relevant variables

For the control variables, under a two-way fixed-effect model. The estimated coefficient of foreign direct investment is −2.0418, which is significantly negative, indicating that the larger the proportion of foreign direct investment in GDP is not conducive to the improvement of agricultural carbon productivity. The reason may be that the foreign funds introduced by China are mainly invested in the manufacturing and service industry, resulting in a large amount of capital and talent flowing into the manufacturing and service industry, which is not conducive to the improvement of agricultural carbon production efficiency. The estimated coefficient of marketization is 0.0236, and it is significant at the 5% level, indicating that marketization development is conducive to the improvement of agricultural carbon productivity. The higher the marketization level, it is conducive to the cross-regional flow of factors and resources, and has a positive effect on the upgrading of agricultural industry and technological innovation, so it is conducive to the improvement of agricultural carbon production efficiency. The estimated coefficient value for agricultural mechanization was 0.1304, which is significant at the 1% level. The higher the level of agricultural machinery replacing labor force, the agricultural production efficiency will be effectively improved. For the same carbon emissions, an increase in output will inevitably lead to an increase in carbon productivity. The estimated coefficient value for industrialization was −0.5196, significant at the 1% level. The improvement of industrialization level leads to agricultural over-dependence on chemical fertilizers and pesticides, which maximizes the carbon emissions of fossil energy inputs in agricultural carbon emissions, and thus restricts the improvement of agricultural carbon productivity. The parameter value for financial development is −0.0800, also significant at the 1% level. It shows that financial development is not conducive to the improvement of agricultural carbon productivity.

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Financial development provides a large amount of funds for the industry and promotes the development of chemical fertilizer and pesticide industries, so it also restricts the improvement of agricultural carbon productivity.

Robustness test

In order to test the reliability of the benchmark regression results, this paper conducts multiple robustness tests from the aspects of replacing explanatory variables, eliminating some samples, and adjusting sample duration. First, replace the explanatory variable method. Regression using the first-order lag term of population urbanization as the core explanatory variable. Second, some samples were removed. Considering the difference in population urbanization and agriculture. The four municipalities, Beijing, Shanghai, Tianjin and Chongqing, receive strong support from national policies, have a higher population urbanization level than that of other provinces, and the proportion of total agricultural output value is relatively lower. Therefore, the samples of four municipalities were excluded to further examine the impact of population urbanization on agricultural carbon productivity. Third, adjust the sample period and test it by shortening the sample period. In March 2014, China officially released the National New Urbanization Plan (2014-2020), and China’s urbanization has entered a new stage of development. Therefore, the sample period was adjusted to 2014–2021, and then the regression estimation was conducted. *Table 5* reports the results of the robustness test, which shows that the impact of population urbanization on agricultural carbon productivity under the three different methods is all positive, and it is significant at the 1% level. The direction and significance of the three estimated coefficient values are consistent with the benchmark regression results, indicating that the benchmark regression results have good robustness.

Table 5. *The robustness test*

Variable	(1)	(2)	(3)
PU	1.8503*** (0.3364)	2.7640*** (0.5878)	2.9239*** (1.0271)
Constant	−0.7451** (0.3347)	−0.7901*** (0.2648)	−0.8413 (1.0308)
Time effect	Yes	Yes	Yes
Province effect	Yes	Yes	Yes
Sample size	527	486	249
R^2	0.8461	0.8477	0.9235

(1) *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. Standard error is given in parentheses. (2) “Yes” and “No” indicate whether the model controls for the relevant variables

Heterogeneity analysis

Geographic-regional heterogeneity. There are obvious differences between the population urbanization level and agricultural carbon productivity in different regions of China. Therefore, the impact of population urbanization on agricultural carbon productivity in different regions is also different. We divided the study sample into eastern, central and western regions according to traditional geographic region classification methods (Zhao et al., 2020), aiming to explore whether there is geographic

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regional heterogeneity in the impact of population urbanization on agricultural carbon productivity in different regions. After the regression estimation, the results are shown in *Table 6*. The results show that in the three regions, the impact of population urbanization on agricultural carbon productivity is positive, and all have passed significant tests, indicating that population urbanization has significantly promoted the improvement of agricultural carbon productivity. Comparing the estimated coefficient values and significance level in the three regions reveals large differences. In terms of the influence coefficient, the western region is the largest, and the eastern region is the smallest. At the significance level, the eastern region only passed the 5% significance level test, while the central and western regions both passed the 1% significance level test. Compared with the central and western regions, eastern China's population urbanization started early, industrialization and service industry developed rapidly, and the proportion of total agricultural output value gradually decreased. However, due to the advantages of economic growth and technological innovation, the carbon emissions per unit of agricultural output value are relatively low. Although population urbanization has a significant impact on agricultural carbon productivity, its effect is significantly lower than that in the central and western regions. In the western region, due to the natural conditions, the land is barren, agricultural productivity has been low, and economic growth and technological progress also lag behind the eastern and central regions. Therefore, the impact of economic development and technological innovation on agricultural carbon productivity is much more significant in the process of population urbanization.

Table 6. *Test of geographic regional heterogeneity*

Variable	East (1)	Central (2)	Western (3)
PU	0.4670** (0.1963)	1.5493*** (0.2379)	10.0092*** (1.7072)
Constant	1.0743 (0.2686)	−0.2490* (0.1437)	−2.7431 (0.5621)
Time effect	Yes	Yes	Yes
Province effect	Yes	Yes	Yes
Sample size	198	144	216
R^2	0.9367	0.9479	0.8847

(1) *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. Standard error is given in parentheses. (2) "Yes" and "No" indicate whether the model controls for the relevant variables

Regional heterogeneity of food production function. Food security is a top priority related to the national economy and people's livelihood, and is the foundation of national security. The grain production capacity of different provinces in China is obviously different, and the resulting agricultural carbon productivity is also different. China divides 31 provinces (excluding Hong Kong, Macao, and Taiwan) into major grain production areas, grain production and sales balance areas, and major grain selling areas based on their grain production and sales situation. We draw on this classification method to examine the impact of population urbanization in different grain production functional areas on agricultural carbon productivity. The test results are shown in *Table 7*. The results showed that in the three functional areas of grain production, the regression

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coefficient values of population urbanization were all positive, and all were significantly positive at the 1% level. This shows that in different functional areas of grain production, population urbanization can significantly promote the improvement of agricultural carbon productivity. Among them, the influence of grain balance area is the largest, the main grain producing area is the second, and the main grain selling area is the smallest. The reasons for this result may be similar to the reasons for geographic regional heterogeneity. Because in the food balance area except Shanxi, other are western provinces. The main grain producing areas are mainly provinces in the central region, with a few provinces in the eastern and western regions. And the main grain sales area is the eastern region provinces.

Table 7. *Test of heterogeneity in functional areas of grain production*

Variable	(1) Major grain-producing areas	(2) Grain balance area	(3) Main grain marketing area
PU	1.6290*** (0.2600)	10.0057*** (1.7367)	1.2398*** (0.3947)
Constant	–0.1306 (0.1687)	−3.6300 (0.6706)	0.7711 (0.5049)
Time effect	Yes	Yes	Yes
Province effect	Yes	Yes	Yes
Sample size	234	198	126
R^2	0.9284	0.8816	0.9338

(1) *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. Standard error is given in parentheses. (2) “Yes” and “No” indicate whether the model controls for the relevant variables

Analysis of indirect impact results

In order to further explore the action mechanism of population towns on agricultural carbon productivity, based on the previous theoretical analysis, we took the urban–rural income gap as the mediation variable. *Equations 2* and *3* were adopted, and the Theil index and urban–rural income ratio were used as the measure of urban–rural income gap to verify the existence of intermediary effect. The test results are shown in *Table 8*. In column 1 of *Table 8*, the estimated coefficient value of population urbanization was 1.8179, which passed the 1% level test, which is consistent with the benchmark regression results. In the case of Theil index as the intermediary variable, the estimated coefficient value of population urbanization in column 2 is −0.3151, which has passed the 1% level test, and means that population urbanization has narrowed the income gap between urban and rural areas. In the third column, after the inclusion of the Theil index intermediary variable, the estimated coefficient values of the population urbanization and the Theil index were 1.0072 and −2.5732, respectively, and both passed the 1% significance level test. However, the estimated coefficient value of population urbanization shows a small decrease from 1.8179 to 1.0072, which suggests that Theil’s index is the action mechanism of population urbanization to promote the improvement of agricultural carbon productivity. It shows that there is mediation effect of urban–rural income gap and it is partial mediation effect. In the case of urban–rural income ratio as the intermediary variable, the results are shown in columns 4 and 5, which are consistent with column 2 and 3 in numerical direction and significance, which once again proves that urban–rural income gap is the mechanism of population urbanization to promote the improvement of agricultural carbon productivity.

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Table 8. *Test of the mediation effect*

Variable		*theil*		*gap*	
	(1) *ACP*	(2) *theil*	(3) *ACP*	(4) *RURI*	(5) *ACP*
PU	1.8179*** (0.3146)	−0.3151*** (0.0207)	1.0072*** (0.2586)	−1.8656*** (0.2636)	1.4523*** (0.2736)
theil			−2.5732*** (0.5910)		
gap					−0.1960*** (0.0432)
Constant	−0.6603** (0.3015)	0.3240*** (0.0231)	0.1735*** (0.2399)	4.7050*** (0.2916)	0.2619 (0.2533)
Time effect	Yes	Yes	Yes	Yes	Yes
Province effect	Yes	Yes	Yes	Yes	Yes
Sample size	558	558	558	558	558
R^2	0.8480	0.9668	0.8571	0.9424	0.8565

(1) *, **, and*** represent the 10%, 5%, and 1% significance levels, respectively. Standard error is given in parentheses. (2) "Yes" and "No" indicate whether the model controls for the relevant variables

Table 9 shows the results of the test for mediation effect Soble. The results show that in the case of the Theil index as the mediation variable, the *p*-value is less than 0.001, and the null hypothesis was rejected, indicating that the mediation effect holds. The indirect effect of population urbanization on improving agricultural carbon productivity by reducing the urban–rural income gap is 0.8107, the direct effect is 1.0072, and the mediating effect is 44.60%. The above analysis confirms that Hypothesis 2 holds. With the urban–rural income ratio as the intermediary variable, the intermediary effect was also established, but the intermediary effect accounted for 20.11%. The urbanization of the population has changed the original single agricultural economic form, continuously adjusted the industrial structure, developed the industry and service industry, and made the income sources of rural residents more diversified. On the one hand, it increases the income of rural residents, and on the other hand, it can narrow the income gap between urban and rural residents. With the increase of income level, it has promoted the upgrading of household consumption, so that it prefers green products and low-carbon environment. To provide realistic demand and development impetus for the low-carbon development and reform of agriculture, and to achieve the goal of improving agricultural carbon productivity.

Table 9. *Results of the Soble test*

Metavariable	Indigo effect	Direct effect	Total utility	Proportion of mediation effect
theil	0.8107*** (0.1530)	1.0072*** (0.2579)	1.8179*** (0.2211)	44.60%
RURI	0.3656*** (0.0850)	1.4523*** (0.2252)	1.8179*** (0.2211)	20.11%

*, **, and *** represent the 10%, 5%, and 1% significance levels, respectively. Standard error is given in parentheses

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Discussion

Few available literature addresses the impact of population urbanization on agricultural carbon productivity. Therefore, we conducted relevant studies and concluded that population urbanization can promote agricultural carbon productivity. However, this conclusion is contrary to the research conclusion of Cheng et al. (2019). Cheng et al. took the panel data of 31 provinces in China (excluding Hong Kong, Macao and Taiwan) from 1997 to 2014, but the agricultural carbon productivity was measured using the stochastic frontier method (SFA). Agricultural inputs, such as primary industry labor and agricultural capital stock, were also included in the calculation. Different measurement methods of agricultural carbon productivity may be the main reason for the inconsistent conclusions. However, many current studies have shown that urbanization has a stimulating effect on carbon emissions. According to the survey, for every 1% increase in urban population in ASEAN between 1989 and 2009, carbon emissions increased by 0.2% (Wang et al., 2016). But carbon productivity is a measure of the economic output generated per unit of carbon emissions. Even if carbon emissions do not decrease, but economic output increases, carbon productivity increases. In the process of China's urbanization, economies of scale, technological innovation, knowledge accumulation and factor allocation have emerged, which are changing the external environment and internal structure of agriculture (Henderson, 2010). And has a positive impact on the increase of agricultural total factor productivity (Yin, 2020), thus promoting the growth of agricultural economic output value. Therefore, based on theoretical analysis and empirical evidence, it shows that population urbanization can promote the improvement of agricultural carbon productivity.

In the process of population urbanization affecting agricultural carbon productivity, although there is no literature discussing the intermediary effect of the urban–rural income gap. The literature on the impact of population urbanization on the urban–rural income gap is even more extensive, but no consistent conclusions have been drawn on the relationship between the two. Barro and Sala-I-Martin (1992), based on the perspective of population migration, found that urbanization does not help to reduce the urban–rural income gap. Cheng and Li (2007) also believe that urbanization and urban bias are the reasons for the widening of the urban–rural income gap, and have a positive impact on the widening of the urban–rural gap. This is inconsistent with our conclusion, and this situation may occur for two reasons. The first is that the time period of the study is different; we use data from the last 20 years. Second, there are regional differences. The income gap between urban and rural areas due to urbanization exists only in some regions, such as the eastern region of China (Su et al., 2015). However, we verified the overall situation in 31 provinces in China (excluding Hong Kong, Macao and Taiwan) and conclude that urbanization can reduce the income gap between urban and rural areas, which is consistent with the conclusions of much of the current literature.

At the same time, no literature discusses the impact of the urban–rural income gap on agricultural carbon productivity. However, a small amount of literature analyzes the relationship between the income inequality and carbon productivity. Among them, the Sun et al. (2021) argue that the income gap between countries has increased the inequality in global carbon productivity, and that total factor productivity in high-income countries increases faster than in low-income countries. In general, the income inequality in high-income countries is relatively small (Grunewald et al., 2017), and thus narrowing the inequality gap could boost carbon productivity. In addition, regarding the impact of the income inequality on carbon emissions, Liu et al. (2019) found that income inequality in

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the United States, for example, increased carbon emissions in the short run and promoted carbon reduction in the long run. However, using China as an example, Wang and Zhang (2021), found that there were large regional differences in this impact. Across the whole country and in the central and western regions, narrowing the income gap between urban and rural areas is conducive to carbon emission reduction. In the eastern region, where the level of economic development is high, the narrowing of the income gap between urban and rural areas has increased carbon emissions. However, given China's overall development status, narrowing the urban–rural income gap is conducive to carbon reduction. Therefore, narrowing the urban–rural income gap can increase carbon productivity.

The most important measures to improve the carbon productivity of agriculture. First, we will promote the construction of a new type of urbanization, represented by population urbanization. The new urbanization emphasizes the basic characteristics of urban and rural integration, urban and rural integration, interaction between industry and city, economy and intensification, ecological livability and harmonious development. The core of the new urbanization is not at the cost of agriculture, food, ecology and the environment. Therefore, to increase agricultural input, improve agricultural production efficiency, on the one hand, to increase agricultural output value, to ensure agricultural and food security. On the other hand, we need to promote low-carbon agricultural development and reduce agricultural energy consumption and carbon emissions. Second, we will continue to raise the incomes of rural residents and narrow the income gap between urban and rural areas. To remove the barriers of urban and rural household registration migration system as the starting point, release the potential rural surplus labor force to invest in the urbanization construction, and promote the sustainable growth of farmers' income. We should take multiple measures to increase the income of rural residents in cities. We will ensure steady growth in the wage income of urban rural residents and expand flexible employment channels. We will further increase the property income of urban rural residents and stabilize their right to contract land, the right to use residential land, and the right to distribute collective income. We will expand the channels of business income for rural residents in cities and foster new types of agricultural business entities. Third, given China east, central and western population urbanization of agricultural carbon productivity, should be based on regional urbanization stage and agricultural carbon productivity difference, on the basis of respecting the objective law of urbanization development, overall coordination to promote urbanization and agricultural production, "adjust measures to local conditions" to promote agricultural carbon productivity, achieve higher quality of new urbanization and low carbon agricultural development.

This paper provides a good complement to the related research on urbanization and low-carbon agricultural development, but there are also some limitations. First, in terms of sample selection, due to the availability of data, only inter-provincial samples are currently used. However, the number of provincial samples in China is small and lacks sufficient universality. Second, in terms of the influence mechanism, we only selected one factor of the urban–rural income gap, but in fact there may be multiple factors. Therefore, in the future research, we will expand the study sample to the prefecture-level cities in China, the study sample will reach about 300, and the sample size will be greatly expanded. At the same time, we will analyze the impact mechanism of population urbanization on agricultural carbon productivity from more perspectives.

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Conclusion

Taking China as an example, we used 31 provinces in China (excluding Hong Kong, Macao and Taiwan) from 2004 to 2021 as samples to empirically test the impact of population urbanization on agricultural carbon productivity. And using the urban–rural income gap as the mediating variable. We draw the following three main conclusions. First, population urbanization can significantly promote the improvement of agricultural carbon productivity. According to the regression estimation using a two-way fixed effect model, the effect of population urbanization on agricultural carbon productivity is 1.8179, which is significant at the 1% level. However, there are significant geographical regional heterogeneity in this effect, and the influence in the western region is significantly greater than that in the eastern region and the central region. Moreover, there are obvious heterogeneity in the different grain production functional areas. Second, the mediation effect model was used for mechanism testing, and we found that population urbanization can affect agricultural carbon productivity through the intermediary variable of urban–rural income gap. The urban–rural income gap, measured by Theil index and urban–rural income ratio, respectively, has some intermediary effects. However, the intermediary effect of Theil index accounted for 44.60%, and that of urban–rural income ratio accounted for 20.11%. Third, population urbanization can narrow the urban–rural income gap, while narrowing the urban–rural income gap can improve agricultural carbon productivity. In particular, the impact of urban–rural income gap on agricultural carbon productivity, the estimated coefficient of Theil index is −2.5732, and the estimated coefficient of urban–rural income ratio is −0.1960, and both are significant at the 1% level.

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