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Original Research

Study on Low-Carbon Development of Agriculture in Ethnic Areas of Sichuan, China Under Dual-Carbon Target

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Abstract

Dual carbon target is the definition of carbon peak and carbon neutrality, on the one hand reducing fossil consumption in order to reduce carbon emissions, and on the other hand using afforestation to increase carbon absorption. In recent years, Sichuan ethnic areas actively implemented the "double carbon" strategy, committed to promoting the low-carbon development of agriculture. In this paper, the agricultural carbon emissions of Sichuan ethnic areas from 2006 to 2021 were measured, and then the efficiency was calculated by the super-efficiency SBM model and the influencing factors were calculated by the Tobit model. The results show that the agricultural carbon emissions in ethnic areas of Sichuan show an increasing trend, with the carbon emissions in Liangshan Prefecture being the largest, and its increase is also the largest. Agricultural carbon emission efficiency showed a fluctuating trend and gradually changed to the effective state, but the efficiency in Ganzi Prefecture was the lowest in 2021. Agricultural mechanization level, agricultural economic development level, and farmland irrigation rate can promote agricultural carbon emission efficiency, while fertilizer application rate has a negative effect on it. Based on this, the paper puts forward some suggestions on the scientific use of chemical fertilizers, the vigorous implementation of water-saving actions, the emphasis on improving farmers' environmental awareness, the transformation and upgrading of agriculture, and the optimization of agricultural industrial structures and agricultural products.

Keywords: low-carbon development, agricultural carbon emissions, Sichuan ethnic areas, super-efficiency SBM model

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Introduction

Today, global warming is a recognized and urgent global crisis. It is clear from the statistics of the authoritative International Panel on Climate Change (IPCC) that the carbon emissions of the agricultural sector are second only to fossil fuels, ranking second in global greenhouse gas emissions. As a big agricultural country in China, the issue of agricultural carbon emissions is closely related to realizing the "dual carbon" goal and needs to be solved urgently. In recent years, China's agricultural carbon emissions have shown a growing trend, and the carbon emissions of agricultural production should not be underestimated. According to public data, China's agricultural carbon emissions reached 828 million tons of carbon dioxide equivalent in 2014, accounting for 6.7% of the national carbon emissions and contributing 13.6% to the global total agricultural carbon emissions [1]. The agricultural carbon emissions in Sichuan Province in 2019 have slightly decreased compared to the interannual trend, with a value of 53.8367 million tons, a decrease of 12.51% compared to 2005 [2]. The Department of Agriculture and Rural Affairs of Sichuan Province and the Development and Reform Commission of Sichuan Province jointly issued the Implementation Plan for Carbon Reduction and Storage in Agriculture and Rural Areas of Sichuan Province in 2023 [3], which made arrangements for the target, key tasks, and major actions of carbon emission reduction and sequestration in rural areas of Sichuan Province in the next period and further promoted the low-carbon development of agriculture. Sichuan is not only a large agricultural province, but it is also a large multi-ethnic province. This paper focuses on the western Sichuan Plateau, a multi-ethnic settlement, including the Aba Tibetan and Qiang Autonomous Prefecture, Garze Tibetan Autonomous Prefecture, and Liangshan Yi Autonomous Prefecture (hereinafter referred to as Aba Prefecture, Ganzi Prefecture, and Liangshan Prefecture). The three prefectures are not only key ethnic minority areas in Sichuan Province, but also play an important role in the national ecological security barrier and rural revitalization. The research on agricultural carbon emissions is helpful in understanding the real situation of agricultural development in the region, provides a scientific basis for formulating agricultural development plans and rural revitalization strategies in line with local realities, promotes environmental improvement and rural development in ethnic areas, and builds "pure land Aba", "holy Ganzi", and "beautiful Daliang".

Related Research

The issue of agricultural carbon emissions has attracted much attention, and scholars at home and abroad have conducted in-depth research. In terms of carbon emissions, Chinese scholar Baogen Ding divided carbon emission sources into three parts: agricultural land utilization, methane in rice fields, and carbon emissions from livestock and poultry breeding [4]. There are currently three main methods for calculating agricultural carbon emissions. One is the widely used emission coefficient method [5], which mainly calculates the carbon emissions of agricultural production and livestock farming based on recommended values published by IPCC or other authoritative scholars or further adjusted and optimized data. Second, the model simulation method [6], based on biogeochemical processes combined with the core processes and impact factors of agricultural ecosystems, extends the limited field observation data to a wider regional scope, providing strong support for the measurement of agricultural carbon emissions. The third is the measurement method [7], which uses relevant instruments and equipment to obtain carbon emissions through experiments.

The key index to evaluate the effect of emission reduction is the agricultural carbon emission efficiency. It is closely related to the expected output of agricultural production activities; the higher the efficiency, the more expected output, and the higher the economic benefits brought by agricultural production. There are two main methods for measuring agricultural carbon emission efficiency. One type is the single-factor method, which has been widely applied in the specific practice of the international community and governments of various countries to fulfill their energy-saving and emission-reduction responsibilities. The calculation process is relatively simple and can be expressed by carbon emission intensity and carbon productivity. The other type is the multi-factor method, which is widely applicable, practical, and closer to reality, but the calculation process is more complex, including stochastic frontier analysis (SFA) [8] and data envelopment analysis (DEA) [9]. The SFA model incorporates agricultural carbon emissions into the frontier production function to calculate efficiency and considers it as one of the input factors [10], while the DEA model calculates agricultural carbon emissions as output. However, the traditional DEA model has limitations in dealing with unexpected output and relaxation. Later scholars have successively proposed SBM models containing expected output and non-expected output [11], DEA-Malmquist efficiency index [12], and super-efficiency SBM model [13].

Many factors can affect agricultural carbon emission efficiency, and their analysis methods are also diverse. Dong's team used the LMDI model to study the influencing factors of China's agricultural net carbon sink and pointed out that net carbon sink intensity, agricultural structure, and rural population size inhibited carbon sink, while the level of agricultural economic development promoted carbon sink capacity [14]. Subsequently, Hossain and Chen used the Tapio decoupling and LMDI methods to reveal that the main driving factors of agricultural carbon emissions in Bangladesh are population growth, agricultural energy intensity, and agricultural economic activities. Agricultural economy, agricultural emissions, and energy structure factors are responsible for reducing carbon emissions [15]. Wei et al. used the Tobit model to analyze the factors of agricultural carbon emission efficiency in 14 prefectural regions of Xinjiang from 2011 to 2020. They found that urbanization, cultivated land scale, and water-saving irrigation promoted efficiency, while per capita GDP and public budget revenue and expenditure ratio restrained efficiency [16].

According to comprehensive literature, many scholars use the emission coefficient method to calculate carbon emissions when studying agricultural carbon emissions and use data envelopment analysis to construct various evaluation indicators to measure carbon emission efficiency. The calculation models of influencing factors are very diverse. Therefore, this article intends to choose the IPCC method to calculate the agricultural carbon emissions in the ethnic areas of Sichuan from 2006 to 2021 and, on this basis, use the super-efficiency SBM model to evaluate the efficiency of agricultural carbon emissions. Finally, the Tobit model will be used to further analyze the influencing factors of agricultural carbon emission efficiency.

Overview and Data of the Study Area

Overview of the Study Area

In the western part of Sichuan, China, there are three autonomous prefectures with a large concentration of ethnic minorities, namely Aba, Ganzi, and Liangshan. The overall outline of the surface of these three prefectures is a typical plateau with high terrain, with a total land area of 298,100 square kilometers, accounting for 61.3% of the land area of Sichuan Province. By the end of 2021, the rural population of Aba Prefecture is about 654,000, Ganzi Prefecture is about 876,000, and Liangshan Prefecture is as high as 4.155 million. The climate in this region is characterized by dry and warm valleys and cold and wet mountains. Light is abundant, but precipitation is low. Aba Prefecture and Ganzi Prefecture are important production areas of high-quality potatoes in the plateau. The main crops also include corn, highland barley, soybeans, edible fungi, and so on. Liangshan Prefecture is rich in cultivated land resources, ranking first in the province and fourth in grain production, with the world's largest Tartary buckwheat base, the national green food raw material vegetable standardized production base, an important strategic quality tobacco leaf base, and the largest green food raw material potato standardized production base. However, most of these locations are in sensitive areas such as mountains, plateaus, and canyons, and the ecological environment is fragile. Agricultural production activities have a direct impact on the ecological environment in these areas, so the study of agricultural carbon emissions in these areas is helpful in assessing the potential impact of agricultural production activities on the ecological environment.

Data Sources

This study takes 16 years (2006-2021) as the research period, and all the basic data involved in this paper come from the Statistical Yearbook of Sichuan Province (2007-2022), the Yearbook of Aba Prefecture, the Statistical Yearbook of Ganzi Prefecture, and the Statistical Yearbook of Liangshan Prefecture (2007-2022).

Experimental

Calculation Methods of Agricultural Carbon Emissions

Based on the current situation of Aba Prefecture, Ganzi Prefecture, and Liangshan Prefecture, the scientific method recommended by IPCC was used to estimate the total agricultural carbon emission in Sichuan ethnic areas. The formula is as follows:

$$C = \Sigma C_i = \Sigma E_i \times \delta_i$$

Where C is the total agricultural carbon emission, C_i is the carbon emission of the i carbon emission source, E_i is the application amount, power, and area corresponding to the i carbon emission source, and δ_i is the carbon emission coefficient corresponding to the i carbon emission source (Table 1). Given that the statistical definition and indicator coefficients of carbon emissions from standard livestock and poultry farming are not yet clear, existing accounting methods need to be optimized. Therefore, this article will

Table 1. Table of agricultural carbon emission coefficients.

Sources of agricultural carbon emissions	Carbon emission coefficient	Reference source
Chemical fertilizer	895.6kg/t	Oak Ridge National Laboratory
Mechanical power	0.18kg/kW	Huaping Duan et al. [17]
Cultivated land area	312.6kg/km^2	College of Biology and Technology, China Agricultural University
Irrigation area	266.48kg/km^2	Institute of Agricultural Resources and Ecology, Nanjing Agricultural University

focus on the planting part of agricultural carbon emission sources, specifically agriculture in a narrow sense, which mainly includes four carbon sources: fertilizers, mechanical power, cultivated land area, and irrigation area.

Agricultural Carbon Emission Efficiency Index

This article is based on the principles of measurability, accessibility, and relevance. Drawing on the research of Yun and Zijuan [18] and combining it with the actual situation of agricultural development in ethnic regions of Sichuan, an indicator system for evaluating the carbon emission efficiency of agriculture in ethnic regions of Sichuan was constructed. Among them, the input index mainly includes the fertilizer application amount, the total power of agricultural machinery, the actual cultivated land area at the end of the year, the irrigated land area, and the primary industry employees, while the output index is subdivided into the expected total agricultural output value and the unexpected agricultural carbon emissions. Finally, 5 input indicators and 2 output indicators were selected to form the evaluation index system of agricultural carbon emission efficiency. The specific indicators were selected, as shown in Table 2.

Super-efficiency SBM Model

At present, there are a variety of methods to measure agricultural carbon emission efficiency, among which the DEA method proposed by Charnes and Cooper [19] has been widely used in efficiency evaluation. Comparing the super-efficiency SBM with the early DEA-CCR model, it can be found that the super-efficiency SBM model is more comprehensive in evaluating unexpected outputs. It accurately measures the inadequacy or excess of input and output by introducing slack variables, thus deeply analyzing the root causes of inefficiency. Therefore, this paper adopts the super-efficiency SBM model to measure the agricultural carbon emission efficiency in ethnic areas of Sichuan Province from 2006 to 2021. The formula is as follows:

$$min\,\rho = \frac{1+\frac{1}{m}\sum_{m=1}^{M}\left(\frac{S_x^m}{x_t^m}\right)}{1-\frac{1}{q+h}\left(\sum_{q=1}^{Q}\left(\frac{S_q^y}{y_{jq}^t}\right)+\sum_{h=1}^{H}\left(\frac{S_n^b}{b_{jh}^t}\right)\right)}$$

$$s.t.$$

$$\sum_{j=1,j\neq 0}^{n} x_{jm}^t\lambda_j^t + S_m^x \le x_{jm}^t$$

$$\sum_{j=1,j\neq k}^{n} y_{jq}^t\lambda_j^t - S_q^y \le y_{jq}^t$$

$$\sum_{j=1,j\neq k}^{n} b_{jh}^t\lambda_j^t - S_h^b \le b_{jh}^t$$

$$\lambda_j \ge 0, S_m^x \ge 0, S_q^y \ge 0, j = 1,2,\dots,n$$

Among them, ρ is the agricultural carbon emission efficiency, n is the number of decision units, λ is the weight vector, m, q, h are the number of input, expected output, and non-expected output factors, respectively. S_m^x, S_q^y, S_h^b are the relaxation variables of input, expected output, and non-expected output, respectively. x_j^t, y_j^t, b_j^t are the input, expected output, and non-expected output values of DMU in the t period, respectively. DMU is effective if $\rho \ge 1$. However, if $\rho < 1$, DMU is invalid and needs to be improved in terms of input and output. If the relaxation value of the input is greater than zero, it means that the input needs to be reduced. If the relaxation value of the output item is greater than zero, the output needs to be increased. If the relaxation value of the undesired output term is greater than zero, it means that the undesired output needs to be reduced.

Results and Discussion

Analysis of Calculation Results of Agricultural Carbon Emissions

Based on the data of various agricultural carbon emission sources and corresponding carbon emission

Table 2. Selection of agricultural carbon emission efficiency indicators in ethnic areas of Sichuan.

Index class		Index name	Unit
Input		Fertilizer application rate	Ten thousand tons
		Total power of agricultural machinery	Megawatt
		Actual cultivated land area at the end of the year	Ten thousand hectares
		Irrigated area of cultivated land	Ten thousand hectares
		People working in the primary industry	Thousands of people
Output	Expected output	Gross agricultural output value	Ten thousand yuan
	Undesirable output	Agricultural carbon emissions	Ten thousand tons

coefficients in Table 1, calculate the total agricultural carbon emissions in Sichuan ethnic areas from 2006 to 2021 (see Table 3). From Table 3, it can be seen that the agricultural carbon emissions in these three states are generally on the rise, but have slightly decreased from 2016 to 2021. Specifically, the total carbon emissions from agriculture increased from 111549 tons in 2006 to 124583 tons in 2021, an increase of 13034 tons. However, from 2006 to 2016, the total agricultural carbon emissions in ethnic minority areas of Sichuan continued to increase. However, since 2017, this trend has reversed, and the total carbon emissions from agriculture have begun to decline sharply, showing negative growth for several consecutive years. This means that carbon emissions are steadily decreasing. Moreover, we can also observe that from 2019 to 2020, the growth rate experienced a significant decline once again. The reason may be that agricultural development has stagnated due to the impact of the COVID-19 epidemic. Between 2006 and 2016, the total carbon emissions from agriculture slightly increased. According to the previously collected data on agricultural carbon emissions sources, the use of fertilizers has significantly increased during this period. During this period, the widespread use of fertilizers greatly affected the increase in agricultural carbon emissions. Since 2017, the total carbon emissions from agriculture in ethnic minority areas of Sichuan have been decreasing year by year. This indicates that under the guidance of a series of policies such as fertilizer reduction and efficiency improvement technology, soil pollution prevention and control action plan, green development technology support, and environmental inspection action, agriculture is gradually shifting towards low-carbon mode, and the effect of agricultural carbon emission control is beginning to emerge. It is worth mentioning that the total carbon emissions from agriculture suddenly decreased significantly in 2013. This significant change is mainly influenced by the proactive actions of Liangshan Prefecture.

From the perspective of regional distribution, the agricultural carbon emission of Liangshan Prefecture is much higher than that of Aba Prefecture and Ganzi Prefecture. The total agricultural carbon emissions of Aba Prefecture and Ganzi Prefecture are relatively close, but Aba Prefecture is slightly higher than Ganzi Prefecture. Liangshan Prefecture, which has the largest total agricultural carbon emissions, also saw the largest increase, increasing by 10,833 tons. Liangshan Prefecture, the fourth largest grain production city in Sichuan Province, consumes a lot of fertilizer, irrigation area, and machinery in agricultural production activities, so its agricultural carbon emission is high. Agricultural carbon emissions in the Liangshan Prefecture showed a trend of first rising and then decreasing. In recent years, the Liangshan Prefecture has been committed to high-quality development and has achieved remarkable results in agricultural green development, with an obvious carbon reduction effect. In contrast, the agricultural carbon emissions of Aba and Ganzi prefectures are low. As the regions with the lowest grain output in ethnic areas of Sichuan, these two places have less resource input and consumption

Table 3. Total agricultural carbon emissions per 10,000 tons in Sichuan ethnic areas from 2006 to 2021.

Year	Aba Prefecture	Ganzi Prefecture	Liangshan Prefecture	Total	Sequential growth
2006	0.7743	0.2510	10.1296	11.1549	7.3847
2007	0.8306	0.2610	10.9056	11.9972	7.5513
2008	0.8303	0.2798	11.7201	12.8302	6.9435
2009	0.9841	0.2899	12.2928	13.5668	5.7406
2010	0.8771	0.3087	12.5682	13.7540	1.3801
2011	0.9589	0.3189	12.9340	14.2118	3.3285
2012	1.0648	0.3237	13.3128	14.7013	3.4444
2013	1.1187	0.3420	12.1400	13.6007	-7.4866
2014	1.2085	0.3449	12.3975	13.9510	2.5758
2015	1.2094	0.3504	12.5338	14.0936	1.0221
2016	1.2104	0.3658	12.6460	14.2222	0.9126
2017	1.1212	0.3867	12.5865	14.0944	-0.8987
2018	1.0402	0.3356	12.5552	13.9310	-1.1593
2019	0.9866	0.3206	11.8775	13.1846	-5.3577
2020	0.9526	0.3145	11.2528	12.5199	-5.0415
2021	0.9307	0.3146	11.2130	12.4583	-0.4923

in agricultural production and relatively low agricultural carbon emissions. However, due to more fertilizer input, Aba Prefecture's total agricultural carbon emissions are slightly higher than Ganzi Prefecture.

From the perspective of the structure of carbon emission sources, the proportion of carbon emission sources in ethnic areas of Sichuan in the past 16 years has been chemical fertilizer, cultivated land, irrigation, and machinery, from high to low. The use of chemical fertilizer plays a dominant role in the carbon emissions in ethnic areas of Sichuan, and its annual average carbon emissions account for about 90% of the total annual average carbon emissions. This suggests that the overuse or improper use of fertilizers in agricultural production may be one of the main causes of high carbon emissions. This data not only highlights the central role of fertilizer use in carbon emissions in ethnic areas of Sichuan, but also reveals the severe challenges and emission reduction potential faced by the region in the agricultural production process, especially in the use of fertilizer. Therefore, the optimal management of fertilizer use will undoubtedly become a key part of achieving carbon emission reduction targets in Sichuan ethnic areas. At the same time, the carbon emission contribution of machinery, cultivated land, and irrigated areas in agricultural production cannot be ignored, although their proportion is relatively low. They also need to take effective measures to reduce their carbon emissions.

Analysis of Calculation Results for Agricultural Carbon Emission Efficiency

Based on the super-efficiency SBM model, the agricultural carbon emission efficiency level of ethnic areas in Sichuan was calculated with the help of SBMRUN software (https://www.dearun.net), and the results were shown in Fig. 1. From 2006 to 2021, the agricultural carbon emission efficiency of Sichuan ethnic areas showed a steady increase, gradually moving from a state of inefficiency to a state of efficiency, indicating that agriculture is moving toward low-carbon development. Although the average efficiency value continued to rise from 2006-2020, it never broke the threshold of 1. This means there is still room for improvement in agricultural carbon emission control in the region, especially in terms of inputs such as fertilizers and carbon emissions output. However, by 2021, the average efficiency of agricultural carbon emissions in Sichuan's ethnic areas jumped to more than 1, reaching a historical high. This indicates that the agricultural carbon emission efficiency of Sichuan ethnic areas has entered an effective state, the efficiency gap between regions is gradually narrowing, and the overall efficiency level is performing well. In addition, further analysis of the average value of each input-output relaxation from 2006 to 2021 shows that, except for 2021, the relaxation values of input items and non-expected output items are generally greater than zero. This means that in the input indicators such as fertilizer, total power of agricultural machinery, irrigated area of cultivated land, and labor force, the input amount should be appropriately reduced according to the size of the relaxation amount, and efforts should be made to reduce the agricultural carbon emission, which is an undesirable output. It can be seen that Sichuan minority areas still need to make unremitting efforts to improve agricultural carbon emissions.

From the perspective of regional distribution, the agricultural carbon emission efficiency of Aba Prefecture increased most significantly, with a range of 0.8472. This shows that the region has achieved remarkable results in controlling agricultural carbon emissions. In contrast, Ganzi Prefecture's efficiency performance

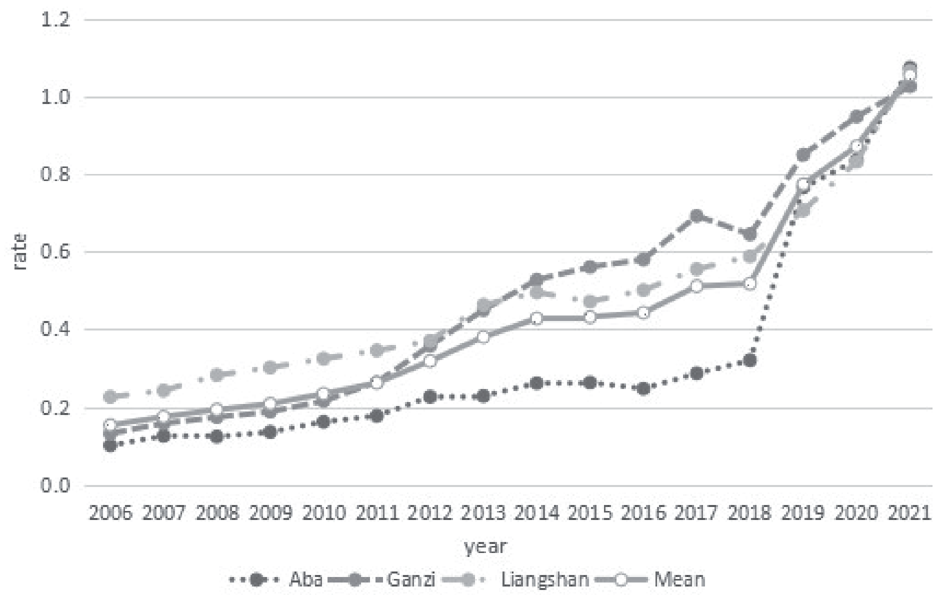

Fig. 1. Agricultural carbon emission efficiency in Sichuan ethnic areas from 2006 to 2021.

in 2021 lagged. Although Ganzi Prefecture has made some achievements in carbon emission reduction, due to its relatively backward economy, science and technology, and society, further efforts are needed to improve its carbon emission efficiency. It is worth noting that between 2017 and 2018, the agricultural carbon emission efficiency of Ganzi Prefecture once showed a downward trend. Through in-depth analysis of the data during this period, it is found that this is mainly due to the excessive pursuit of economic growth in the process of agricultural development in the state, which has led to a series of problems. In particular, the dramatic increase in fertilizer use and the significant expansion of irrigation areas have undoubtedly contributed to the rise in carbon emissions. At the same time, compared with the growth of agricultural output, the growth rate of carbon emissions is more significant, which leads to the decline of agricultural carbon emission efficiency. However, Ganzi Prefecture also realized this problem in time and took positive adjustment measures to continue to promote the low-carbon development of agriculture.

Analysis of Influencing Factors of Agricultural Low-carbon Development in Ethnic Areas of Sichuan

Tobit Model

In order to further explore the changes in agricultural carbon emission efficiency, this paper draws on the research results of Yun et al. [20] and Jing et al. [21] and intends to consider the following six influencing factors:

(1) Fertilizer application rate (FAR), the ratio of fertilizer application to cultivated land area;

(2) Agricultural mechanization level (AML), which is the ratio of the total power of agricultural machinery to the cultivated land area;

(3) Irrigation rate of cultivated land (ARCD), which is the proportion of irrigated area in the total area of cultivated land;

(4) Agricultural economic development level (AEDL), which is the proportion of the total agricultural output value to the total rural population;

(5) Industrial structure (IS), which refers to the proportion of total agricultural output value to total agricultural, forestry, animal husbandry, and fishery output value;

(6) Urbanization rate (UR) is the ratio of the urban population to the total local population.

In this paper, combined with the panel data on agricultural carbon emission efficiency in Sichuan ethnic areas from 2006 to 2021, the main factors affecting agricultural carbon emission efficiency were further discussed through the Tobit model. The formula is as follows:

$$Y_{it} = \beta_0 + \beta_1 FAL_{it} + \beta_2 AML_{it} + \beta_3 AL_{it} + \beta_4 AEDL_{it} + \beta_5 IS_{it} + \beta_6 UR_{it} + \varepsilon_{it}$$

Among them, i and t are regions and years, respectively; Y_{it} is the explained variable, namely agricultural carbon emission efficiency; β_0 is a constant term; β_1, β_2, β_3, β_4, β_5, β_6 are the estimated coefficients of each explanatory variable. ε_{it} is a random error term.

Analysis of Influencing Factors

STATA software (Version 15) (https://soft.wxqilinz.cn/) was used for the regression analysis of the above equation, and the results are shown in Table 4. According to the data in the table:

(1) The application rate of chemical fertilizers is inversely proportional to the efficiency of agricultural carbon emissions (-0.7154) and passes the significance test at the 1% level. This indicates that the higher the amount of fertilizer applied, the lower the efficiency of agricultural carbon emissions, which poses a significant obstacle to improving agricultural carbon emission efficiency. Although fertilizers can replenish nutrients in the soil and increase crop yields, they produce greenhouse gases such as methane and nitrous oxide, which are important sources of agricultural carbon emissions. Therefore, the greater the amount of fertilizer applied, the greater agricultural carbon emissions will also increase, and the carbon emission efficiency will gradually decline.

(2) The level of agricultural mechanization is positively proportional to the agricultural carbon emission efficiency (0.0276) and has passed the significance test of 1% level, indicating that the level of agricultural mechanization has a positive promoting effect on the improvement of agricultural carbon emission efficiency. Improving the level of agricultural mechanization can greatly improve the efficiency of agricultural production, reduce human input, and reduce production costs. At the same time, agricultural mechanization can also promote the specialization and scale of agricultural production, optimize resource allocation, and improve resource utilization efficiency. Therefore, these factors contribute to reducing the carbon intensity of agricultural production and improving the efficiency of agricultural carbon emissions. Moreover, in recent years, with the rapid development of science and technology, agricultural machinery has gradually transitioned towards lightweight and low-carbon directions, and the carbon reduction effect in agricultural production has become increasingly significant.

(3) The cultivated land irrigation rate is inversely proportional to agricultural carbon emission efficiency (0.8785) and passes the significance test at the 1% level, which means that the higher the irrigation rate, the lower the agricultural carbon emission efficiency. Sichuan ethnic areas are located in the west Sichuan Plateau, with more dry seasons and less precipitation throughout the year, and the arable land is mainly dry land. The demand for agricultural irrigation increases due to the frequency of dry seasons and the lack of precipitation, which in turn increases agricultural

Table 4. Tobit regression results of factors affecting agricultural carbon emission efficiency in ethnic areas of Sichuan Province.

Y	Coef.	Std. Err.	z	P>|z|
Cons_	-0.2396	0.1969	-1.22	0.244
FAR	-0.7154*	0.1729	-4.14	0.000
AML	0.0276*	0.0093	2.97	0.003
ARCD	0.8785*	0.2734	3.21	0.001
AEDL	0.0001*	0.0000	5.75	0.000
IS	0.2395	0.3150	0.76	0.447
UR	-0.0066	0.0056	-1.16	0.244

Note: * and ** are significant at 10% and 1% levels, respectively.

carbon emissions and gradually reduces agricultural carbon emission efficiency.

(4) The level of agricultural economic development is significantly positively correlated with agricultural carbon emission efficiency (0.0001) and passes the test at a confidence level of 1%. The improvement of the level of agricultural economic development can promote the improvement of agricultural production efficiency, which, to some extent, helps to reduce agricultural carbon emissions. This is because the improvement of the agricultural economic level means an increase in the income level of farmers, and more funds are invested in agricultural production. For example, using advanced agricultural technology and equipment can not only improve agricultural production efficiency, but also reduce the negative impact of agriculture on the environment, thereby improving agricultural carbon emission efficiency.

(5) Industrial structure and agricultural carbon emission efficiency were positively proportional (0.2395), but did not pass the significance test. The ethnic areas of Sichuan are rich in herbivorous livestock such as yak and Tibetan sheep, and animal husbandry is very prosperous, and the carbon dioxide emissions generated by livestock far exceed those of agriculture. In comparison, agriculture produces fewer carbon emissions. In theory, an increase in agricultural output value could lead to an increase in agricultural carbon efficiency, as a higher output value could mean an increase in agricultural production efficiency and a more rational use of resources. However, in the actual production process, agriculture in the region is highly dependent on production materials such as fertilizers, which often leads to relatively large carbon emissions. This dependence makes the effect of industrial structure on agricultural carbon emission efficiency less significant, reflecting that carbon emission in agricultural production is not only affected by output value, but also restricted by many other factors.

(6) The urbanization rate is inversely proportional to agricultural carbon emission efficiency (-0.018), which also fails the significance test. In the process of urbanization, the rural population in ethnic areas continues to decrease. In order to make up for the shortage of agricultural labor force, agricultural production has to rely on more agricultural materials and mechanized inputs to maintain or even improve the stability of production. However, while this strategy has increased agricultural productivity, it has also quietly increased carbon emissions. On the other hand, with the further improvement of the level of urbanization, urban residents' demand for agricultural products is increasingly strong, which promotes the expansion of agricultural production scale and the innovation of agricultural production methods. Although this meets the needs of the market, it also has a negative impact on the efficiency of agricultural carbon emissions to a certain extent. However, the development of urbanization has also imperceptibly promoted people's awareness of low-carbon environmental protection. With the popularity of this awareness, more advanced, low-carbon agricultural tools and farming methods are gradually promoted and applied, which not only help reduce carbon emissions, but also improve efficiency to a certain extent. Therefore, although there is an inverse relationship between the two, its effect is not significant.

Conclusions

This paper selects 16 years of agricultural carbon emission-related index data from 2006 to 2021 in three prefectural regions of Sichuan Province as the data source, uses the IPCC method to calculate the total agricultural carbon emission, and applies the super-efficiency SBM model and Tobit model to calculate the agricultural carbon emission efficiency and its influencing factors in this region. The conclusions are as follows:

Firstly, agricultural carbon emissions in ethnic areas of Sichuan showed an overall upward trend from 2006 to 2021, but decreased from 2016. The agricultural carbon emissions in Liangshan Prefecture were the largest, with the largest decline.

Secondly, the agricultural carbon emission efficiency of Sichuan ethnic areas in 2006-2021 showed a general fluctuation trend, gradually changing from the state of inefficiency to the state of efficiency. The efficiency of Aba Prefecture increased the most, but Ganzi Prefecture had a greater fluctuation and the lowest efficiency in 2021.

Thirdly, the improvement of the agricultural mechanization level, irrigation efficiency, and agricultural economic development level in ethnic areas of Sichuan can promote the improvement of agricultural carbon emission efficiency, and fertilizer is a restricting factor for agricultural carbon emission efficiency in this region.

Suggestions

According to the above calculation results of carbon emissions in Sichuan ethnic areas, the following measures are proposed in order to reduce carbon emissions, improve efficiency, and promote the low-carbon development of agriculture:

First, scientific use of chemical fertilizers, comprehensive use of cultivation, biological control, and physical technologies to achieve fertilizer reduction and efficiency and reduce agricultural pollution; and gradually build a circular agricultural system of "land cultivation and cultivation combination" aimed at enhancing soil fertility and ensuring long-term sustainable use of land resources.

Second, vigorously implement water-saving actions to reduce irrigation water consumption, use water-saving measures such as drip irrigation and channel lining, agronomic water-saving measures such as intercropping and straw returning to the field, management water-saving measures such as ladder water price and irrigation system, and domestic water recycling and other measures to improve water resource utilization efficiency.

Third, while promoting the growth of farmers' income, pay attention to the improvement of farmers' environmental awareness and the transformation and upgrading of agriculture, use more reasonable, more efficient, and environmentally friendly agricultural technology to develop green agriculture, and reduce the negative impact of agriculture on carbon emission efficiency.

Fourth, optimize the agricultural industrial structure and varieties of agricultural products, reduce the planting of high-carbon emission crops, and actively develop special industrial demonstration areas such as corn, highland barley, and potatoes. At the same time, strengthen the construction of key counties in agriculture, forestry, and animal husbandry, actively promote the combination of agriculture and tourism, and realize the double optimization of economic benefits and carbon emissions.

Fifth, in the process of urbanization, sustainable, green, and low-carbon development of rural and agricultural areas cannot be ignored, and we cannot simply give up on low-carbon agricultural development to solve labor and consumer demand issues.

Deficiency and Prospect

The problem of agricultural carbon emissions is complicated. The total amount and efficiency of agricultural carbon emissions in ethnic areas of Sichuan are preliminarily discussed in this study, but the research is still shallow. When estimating carbon emission sources, only four emission sources from the planting industry were considered, while other emission sources such as forestry, animal husbandry, and fishing were ignored. As a result, there may be errors in the accounting results of total carbon emissions. In the future, agricultural carbon emissions should be calculated more comprehensively and accurately. In addition, this study mainly focuses on the estimation of total carbon emissions and efficiency and the analysis of influencing factors. However, agriculture can both produce and absorb carbon, so comprehensive studies on the agricultural carbon budget should be strengthened to more accurately assess its carbon emissions and help the low-carbon development of agriculture and the realization of the "dual carbon" target.

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Conflict of Interest

The authors declare no conflict of interest.

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