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RESEARCH ARTICLE

Temporal and spatial evolution of agricultural carbon emissions in Fujian Province, China

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KEYWORDS

Agricultural carbon emissions, Fujian Province, logarithmic mean scale index, spatiotemporal characteristics, Tapio decoupling model

HIGHLIGHTS

- The total amount and intensity of agricultural carbon emissions (ACE) in Fujian Province from 2002–2022, had a fluctuating downward trend and this trend is predicted to continue.
- Agricultural material inputs were the largest source of ACE in Fujian Province.
- ACE in Fujian Province had a spatial pattern of higher levels in the west and lower in the east.
- Agricultural production efficiency was the most crucial factor in the reduction of ACE.
- Fujian Province has achieved a strong level of decoupling between ACE and agricultural economic development.

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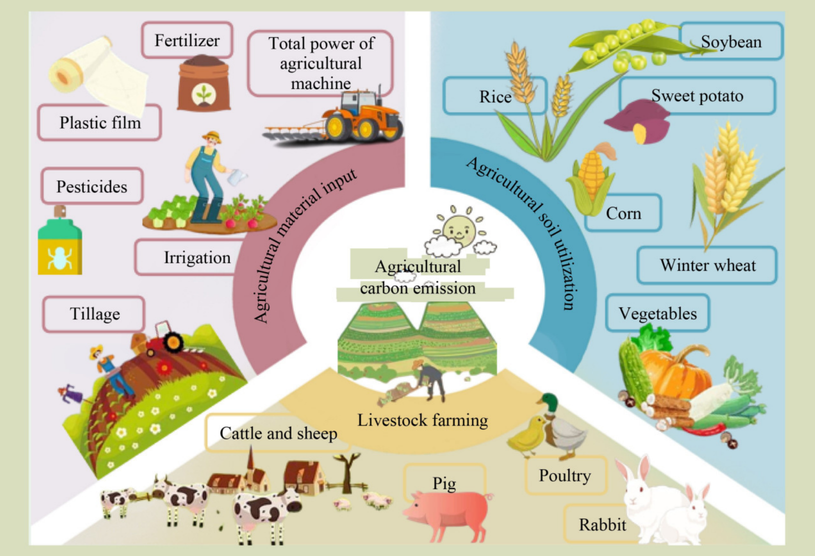
GRAPHICAL ABSTRACT



ABSTRACT

Analyzing the changes in agricultural carbon emissions (ACE) and their influencing factors can provide a sound basis for accurately estimating the carbon balance of agroecosystems. Such analyses can serve as a reference for developing policies to mitigate global climate change and promote sustainable agricultural development. Using the carbon emission calculation framework of the Intergovernmental Panel on Climate Change, this study examined the spatiotemporal characteristics of ACE, including total amount, intensity, structure and their influencing factors, in Fujian Province from 2002 to 2022. The logarithmic mean scale index model and Tapio decoupling model were used, with the GM (1,1) model to forecast carbon emissions from 2023 to 2040. The results indicate that both the total emissions and intensity of ACE had fluctuating downward trends and agricultural material inputs were the largest contributors to ACE. Additionally, total ACE was found to have a spatial pattern higher in the west and lower in the east and agricultural production efficiency was the primary factor in reducing ACE. ACE was clearly decoupled from economic development and is projected to continually decline after 2023.

1 Introduction

Global climate change, characterized by a sharp rise in temperatures and increasing frequency of extreme weather events, has profoundly impacted human life and social development. Human activities, particularly those affecting carbon cycle processes, are the primary drivers of the climate crisis[1,2]. Agricultural activities are a major source of global greenhouse gas emissions, accounting for about 9% to 14% of total emissions[3,4]. Therefore, controlling agricultural carbon emissions (ACE) and developing low-carbon agriculture are crucial strategies for mitigating climate change.

Research on ACE can be roughly divided into five categories. The first centers on directly measuring carbon emissions from agricultural activities. For example, Leite et al.[5] found that the transformation of farmland, natural pasture and planted in Brazil produced substantial greenhouse gases. Carbon sources, such as fertilizer[6], machinery[7] and irrigation[8], have been examined to measure ACE.

The second category involves temporal and spatial differences in ACE. For example, Borgen et al.[9] measured net greenhouse gas (GHG) emissions from Norwegian agriculture based on the IPCC calculation framework and Guo et al.[10] measured ACE for 14 different carbon sources in Jilin Province, China, to determine their spatiotemporal patterns.

The third category encompasses the factors influencing ACE. Koilakou et al.[11], for example, comprehensively analyzed regional ACE drivers across Germany and the USA. Wang et al.[12] analyzed the main contributors to ACE in Southwest China from 2000 to 2014.

The fourth category concerns the economic decoupling of ACE from the agricultural economy, including a study by Zhang and He[13] concerning the decoupling status of 31 provinces and regions in China from 1997 to 2018.

The final category involves the projection of trends in ACE. For example, Chang et al.[14] predicted that Henan Province could achieve carbon neutrality by 2029; Kuang and Hu[15] found that emissions in Guangxi Province are likely to continue increasing in the future.

Most studies have focused on large-scale areas, such as entire countries[16,17] or significant grain-producing regions[18,19], generally overlooking intra-provincial differences and the unique regional characteristics that may influence ACE. Fujian Province, a coastal region with a developed local economy and one of the strongest industrial provinces of China, has a uniquely mountainous terrain and limited arable land resources compared to neighboring regions. Agricultural production in Fujian heavily depends on material inputs, especially mineral fertilizers, which present significant challenges in reducing its carbon emissions. However, there have been few studies on ACE in Fujian and the underlying dynamics of ACE in the region merit deeper investigation. Foundational studies on carbon peaking and carbon neutrality in the region are similarly lacking.

To address these gaps, a comprehensive analysis of the spatiotemporal characteristics, driving factors, decoupling effects and future trends of ACE in Fujian Province was conducted in this study. By establishing a comprehensive ACE indicator estimation system, this study aimed to secure theoretical and data-driven insights for developing effective carbon emission reduction strategies in the agricultural sector.

2 Method and data

2.1 Method

2.1.1 Calculation of total agricultural carbon emissions

Based on the IPCC carbon emission factor method[20], combined with existing research results[18,21] and the characteristics of agricultural production in Fujian Province, indicators were selected to primarily reflect the carbon emissions directly and indirectly generated across agricultural material inputs, farmland utilization and livestock production (Fig. 1). For estimation purposes, CH_4 and N_2O produced by these activities were converted to CO_2 at 28 and 265 times the

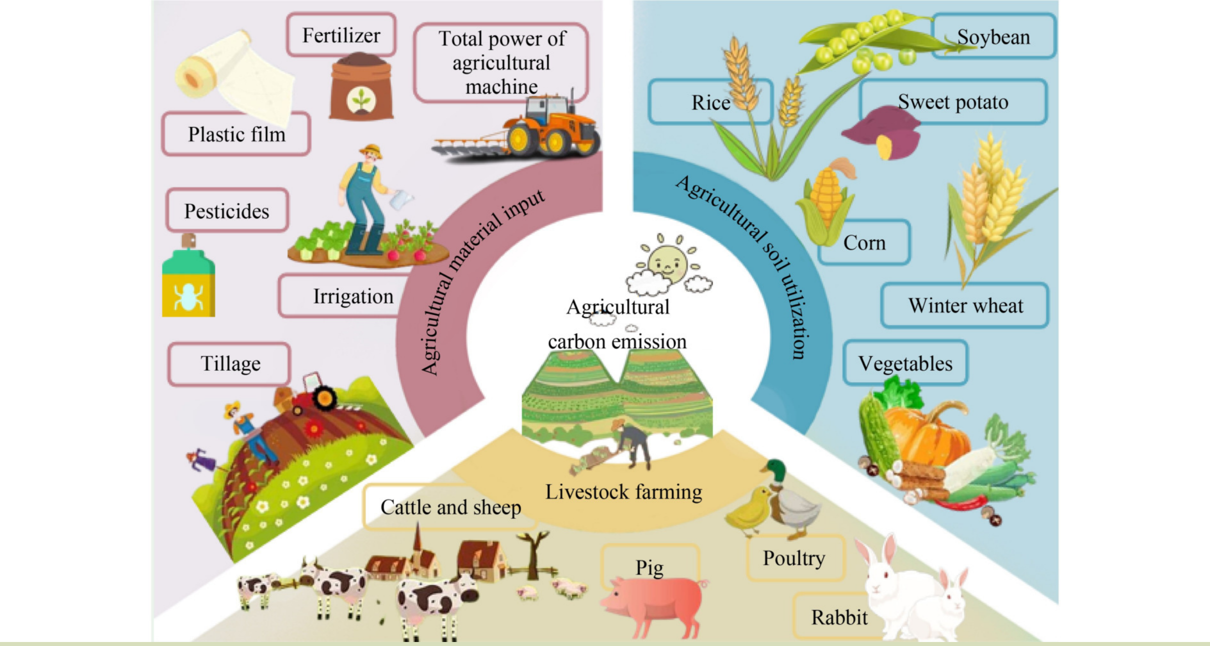


Fig. 1 Calculation of total agricultural carbon emissions.

100-year-scale CO_2 warming potential from the IPCC Fifth Assessment Report, respectively.

2.1.2 Carbon emission estimation for planting industry

Carbon emissions from planting were calculated as the sum of GHG emissions from agricultural material inputs and soil utilization expressed as:

$$C_1 = \sum C_{1i} = \sum (T_i \times \delta_i) \tag{1}$$

where, C_1 (10^4 t) is the total carbon emission of the planting industry, C_{1i} is the emissions of the i-th source of the planting industry, T_i (10^4 t) is the activity level of the i-th source and δ_i is the emission coefficient of the i-th source (Table 1).

2.1.3 Carbon emission estimation for livestock production

Carbon emissions from livestock production are a major source of CH_4 and N_2O[25,26], primarily originating from livestock enteric fermentation and fecal emissions. In Fujian Province, cattle, sheep, pigs, poultry and rabbits are the main species of livestock producing CH_4 and N_2O. Enteric fermentation in livestock leads to CH_4 emissions while fecal emissions are associated with both CH_4 and N_2O.

$$C_2 = \sum C_{2i} = \sum (N_i \times \gamma_i) \tag{2}$$

where, C_2 (10^4 t) is the total carbon emissions of livestock production, C_{2i} is the total carbon emissions of the i-th animal, N_i is the average feeding quantity of the i-th animal and γ_i is the emission coefficient of N_2O and CH_4 for the i-th animal (Table 2).

The length of livestock production periods varies, so the numbers of pigs, rabbits and poultry were adjusted as recommended by Min and Hu[24], with feeding cycles of 200, 105 and 55 d[27]. For cattle and sheep, which did not need adjustment, the number of head stocked at the end of the year was used as the estimates. The calculation was:

$$\mathrm{APP} = \begin{cases} \mathrm{Herds}_{\mathrm{end}}, \mathrm{Days} \geqslant 365 \\ \mathrm{Days} \times (N/365), \mathrm{Days} < 365 \end{cases} \tag{3}$$

where, APP (head) is the annual production, $\mathrm{Herds}_{\mathrm{end}}$ (head) is the year-end stocking level, Days is the feeding cycle and N (head) is the annual stock volume.

2.1.4 Carbon emission intensity

The term ACE intensity is used here to refer to the carbon consumed per unit of agricultural economic benefits[28], and was calculated as:

$$C_t = C/\mathrm{GDP}_t \tag{4}$$

where, C (10^4 t) is the total ACE of the t-period, as the sum of C_1 and C_2, and GDP_t (10^4 yuan) is the gross crop and livestock production in a certain period (comparable prices).

Table 1 Carbon emission sources and carbon emission coefficients for agricultural industry

Type	Carbon source	Carbon emission coefficient	Reference source
Agricultural material input	Fertilizer	0.8956 kg·kg^{-1} C	Oak Ridge National Laboratory
	Pesticides	4.934 kg·kg^{-1} C	Oak Ridge National Laboratory
	Plastic film	5.18 kg·kg^{-1} C	Institute of Resource, Ecosystem and Environment of Agriculture
	Total power of agricultural machinery	0.18 kg·kW^{-1} C	West and Marland[22]
	Irrigation	266.48 kg·ka^{-1} C	Duan et al.[23]
	Tillage	3.126 kg·ka^{-1} C	College of Agronomy and Biotechnology, China Agricultural University
Agricultural soil utilization	Early rice	0.24 kg·ka^{-1} N_2O	Min and Hu[24]
		77.4 kg·ka^{-1} CH_4	
	Late rice	0.24 kg·ka^{-1} N_2O	
		526 kg·ka^{-1} CH_4	
	Winter wheat	1.75 kg·ka^{-1} N_2O	
	Soybean	2.29 kg·ka^{-1} N_2O	
	Corn	2.532 kg·ka^{-1} N_2O	
	Sweet potato	0.95 kg·ka^{-1} N_2O	
	Vegetables	4.944 kg·ka^{-1} N_2O	

Table 2 Carbon emission sources and carbon emission coefficient for livestock production[26,27]

Carbon source	Intestinal fermentation per head (kg·yr^{-1} CH_4)	Fecal discharge per head	
		kg·yr^{-1} CH_4	kg·yr^{-1} N_2O
Cattle	47.8	1	1.39
Sheep	5	0.16	0.86
Pigs	1	3.50	0.53
Poultry	–	0.02	0.02
Rabbits	0.254	0.08	0.02

2.1.5 Kernel density estimation

The kernel density estimation method was applied to explore the dynamic changes in ACE across Fujian Province:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K[(X_i - x)/h] \tag{5}$$

where, n is the number of cities, h is the bandwidth; X_i is independent identically distributed observations, x is the sample mean, and K is the kernel function.

2.1.6 Decomposition of factors influencing carbon emissions

The LMDI (logarithmic mean divisia index) model is widely used for decomposition analyses due to its flexibility and straightforwardness. This model can be expressed as an extension of the Kaya constant equation[29,30]. Following the estimation of ACE, the effects of various factors on ACE were investigated based on existing research[31]. The extended Kaya identity was calculated as:

$$C = C_1 + C_2 = C_I \times A_I \times I_S \times E_{DL} \times U_{RB} \times P_R \tag{6}$$

$$C_I = C/CDP_P \tag{7}$$

$$A_I = CDP_P/CDP_A \tag{8}$$

$$I_S = CDP_A/GDP \tag{9}$$

$$E_{DL} = GDP/P_T \tag{10}$$

$$U_{RB} = P_T/P_R \tag{11}$$

where, C (10^4 t) is the total ACE, GDP_P (10^8 yuan) is the total output value for plantation and livestock, GDP_A (10^8 yuan) is the total agricultural output value, P_T (10^4 population) is the total regional population, P_R (10^4 population) is the total rural population, C_I defines agricultural production efficiency, A_I denotes the agricultural production structure, I_S is the regional industrial structure, E_{DL} is the regional economic development level and U_{RB} is the urbanization level.

The following LMDI model was used to decompose the above equation and quantify the magnitude of the impact of each factor on carbon emissions:

$$\Delta C_I = \sum[(C_t - C_0)/(\ln C_t - \ln C_0)] \times (\ln C_{It} - \ln C_{I0}) \quad (12)$$

$$\Delta A_I = \sum[(C_t - C_0)/(\ln C_t - \ln C_0)] \times (\ln A_{It} - \ln A_{I0}) \quad (13)$$

$$\Delta I_S = \sum[(C_t - C_0)/(\ln C_t - \ln C_0)] \times (\ln I_{St} - \ln I_{S0}) \quad (14)$$

$$\Delta E_{DL} = \sum[(C_t - C_0)/(\ln C_t - \ln C_0)] \times (\ln E_{DLt} - \ln E_{DL0}) \quad (15)$$

$$\Delta U_{RB} = \sum[(C_t - C_0)/(\ln C_t - \ln C_0)] \times (\ln U_{RBt} - \ln U_{RB0}) \quad (16)$$

$$\Delta P = \sum[(C_t - C_0)/(\ln C_t - \ln C_0)] \times (\ln P_{Rt} - \ln P_{R0}) \quad (17)$$

where, t is the period, 0 is the base period and ΔC_I, ΔA_I, ΔI_S, ΔE_{DL}, ΔU_{RB}, and ΔP is the contributions of agricultural production efficiency, agricultural industrial structure, regional industrial structure, level of regional economic development, level of urbanization, and rural population to the amount of change in ACE from the base period (2002) to the t-period, respectively.

2.1.7 Decoupling model

The Tapio decoupling model is widely used to analyze the relationship between carbon emissions and economic growth[32]. If the growth rate of ACE is negative or falls below the growth rate of agricultural economic development, then some level of decoupling has been achieved. Decoupling can be subdivided into connection, decoupling and negative decoupling based on its elasticity. This division depends on changes in ACE and the various growth rates of the agricultural economy. The specific categories are detailed in Table 3, based on the following formula for calculating decoupling elasticity:

$$e = (\Delta C/C)/(\Delta CG/CG) \quad (18)$$

where, e is decoupling elasticity, ΔC (10^4 t) is the change in ACE, C (10^4 t) is the total ACE for the base period, ΔCG (10^8 yuan) is the change in agricultural output, and CG (10^8 yuan) is the value of agricultural output in the base period.

2.1.8 Projections of ACE

The GM (1,1) gray prediction model can be used to predict time-series data based on historical samples, yielding a sequence with exponential growth. The core principle is creating an original sequence (0) from the raw data and then generating a new sequence (1) via cumulative transformation. This step reduces the randomness in the original data to make underlying patterns more readily evident. The transformed sequence (1) is used to establish a first-order differential equation model, the GM (1,1) model[33]. In this study, ACE data for Fujian Province for 20 years from 2002 to 2022, and the 10 years from 2012 to 2022, were taken as samples to predict the ACE of Fujian Province from 2023 to 2040.

The rank ratio of the original series was calculated using carbon emissions as the original series as:

$$\lambda^{(0)} = \frac{x^{(0)}(t-1)}{x^{(0)}(t)} \quad (19)$$

where, t is 1, 2, 3, ..., n.

Table 3 Tapio decoupling type classification

Category of decoupling	Decoupling state	Environmental pressure	Economic development	Decoupling elasticity
Negative decoupling	Expansion negative decoupling	+	+	$e > 1.2$
	Strong negative decoupling	+	–	$e < 0$
	Weak negative decoupling	–	–	$0 \leqslant e < 0.8$
Decoupling	Weak decoupling	+	+	$0 \leqslant e < 0.8$
	Strong decoupling	–	+	$e < 0$
	Recession decoupling	–	–	$e > 1.2$
Connection	Expansion connection	+	+	$0.8 \leqslant e \leqslant 1.2$
	Recession connection	–	–	$0.8 \leqslant e \leqslant 1.2$

If

$$\lambda^{(0)}(t) \in \left(\frac{-2}{\mathrm{e}^{n+1}}, \frac{2}{\mathrm{e}^{n+1}}\right) \tag{20}$$

then, the original series can be constructed as a GM (1,1) gray prediction model. The calculus equations for carbon emissions are:

$$\frac{\mathrm{d}(x)^{(1)}(t)}{\mathrm{d}t} + ax^{(1)}(t) = \mu \tag{21}$$

where, $(x)^{(1)}(t)$ is the cumulative sequence, and gray parameters a and μ can be solved using the least squares method:

$$\begin{bmatrix} a \\ \mu \end{bmatrix} = (\mathrm{B}^T \times \mathrm{B})^{-1} \times \mathrm{B}^T \times \gamma_n \tag{22}$$

where, $\begin{bmatrix} a \\ \mu \end{bmatrix}$ is a vector of proxy estimation parameters.

Substituting the parameters into the function gives:

$$x^{(1)}(t) = \left[x^{(0)}(1) - \frac{\mu}{a}\right] \tag{23}$$

The corresponding carbon emission projections are:

$$\hat{x}^{(0)}(t+1) = \hat{x}^{(1)}(t+1) - \hat{x}^{(1)}(t) \tag{24}$$

A residual test, post-residual test and correlation test were conducted to verify the accuracy of the model, followed by squared processing to predict the values of ACE in Fujian Province from 2023 to 2040.

2.2 Data sources

Data were sourced from the Fujian Statistical Yearbook and the Fujian Rural Statistical Yearbook covering the years 2002 to 2022, considering the availability and completeness of the data. We focused on three key areas: agricultural material inputs, agricultural soil utilization and livestock production. Agricultural materials were considered to include fertilizers, pesticides, plastic film, total power of machinery, irrigation and tillage; crops, included rice, winter wheat, soybeans, corn, sweet potatoes and vegetables; and livestock numbers were determined for cattle, goats, pigs, poultry and rabbits. We adjusted the data for inflation to enable vertical comparisons of agricultural economic outputs over time, standardizing to 2002 prices as a benchmark to ensure comparability across different years.

3 Results and discussion

3.1 Temporal characteristics of ACE

As shown in Fig. 2(a), the total ACE in Fujian Province had a fluctuating downward trend from 2002 to 2022. It reached just over 1460 × 10^4 t in 2022, marking a decrease of 322 × 10^4 t compared to 2002, with an average annual decrease of 0.9%. The ACE intensity in Fujian Province also decreased, from 2.68 t per 10^4 yuan in 2002 to 0.47 t per 10^4 yuan in 2022 (82.46%), at an average annual decline of 4.12%. This indicates that the “one control, two reductions and three basic” policy (where, *one control* refers to total agricultural water use and water pollution, *two reductions* to reducing the use of mineral fertilizers and pesticides, and *three basics* to the resourceful, reusable, and humane treatment of livestock and poultry manure, agricultural films, and crop residues) has been effective. Similarly, the promotion of eco-friendly agriculture at policy level appears to have optimized the agricultural production structure and enhanced productivity.

Regarding the carbon emission structure, the proportion of emissions from agricultural material inputs fluctuated downward, decreasing by 14.5% compared to the base period with an annual average share of 40.0%, which was the largest source of ACE in Fujian. The proportion of carbon emissions from agricultural soil utilization also had a fluctuating downward trend, decreasing by 23.8% compared to the base period and accounting for 34.1% annually. Carbon emissions from livestock production had a fluctuating downward trend but increases by 15.1% compared to the base period and accounts for 25.9% annually.

As shown in Fig. 2(b–d), fertilizers were the primary source of carbon emissions from agricultural material inputs, accounting for 56.3% of annual carbon emissions and 22.5% of total annual ACE. The predominantly mountainous terrain of Fujian is a significant factor in the extensive use of mineral fertilizers, which reduce the quantity needed per unit of farmland compared to organic fertilizers due to their higher nutrient content, making them easier to transport. Mineral fertilizers are also faster-acting, shortening the agricultural production cycle. Given the limited arable land resources in the province, fertilizer usage is crucial for boosting farmland productivity and ensuring sufficient food production.

However, carbon emissions from late rice cultivation were the largest contributor to emissions from agricultural land use, representing 76.9% of the average annual emissions in this category and 26.2% of total annual ACE. As the largest hybrid rice seed production base in China, Fujian is responsible for about 40% of the national hybrid rice seed output; rice is the most extensively planted crop in the province. In the livestock sector, pig production is the dominant source of emissions at an average of 60.6% per year and comprising 15.7% of total ACE.

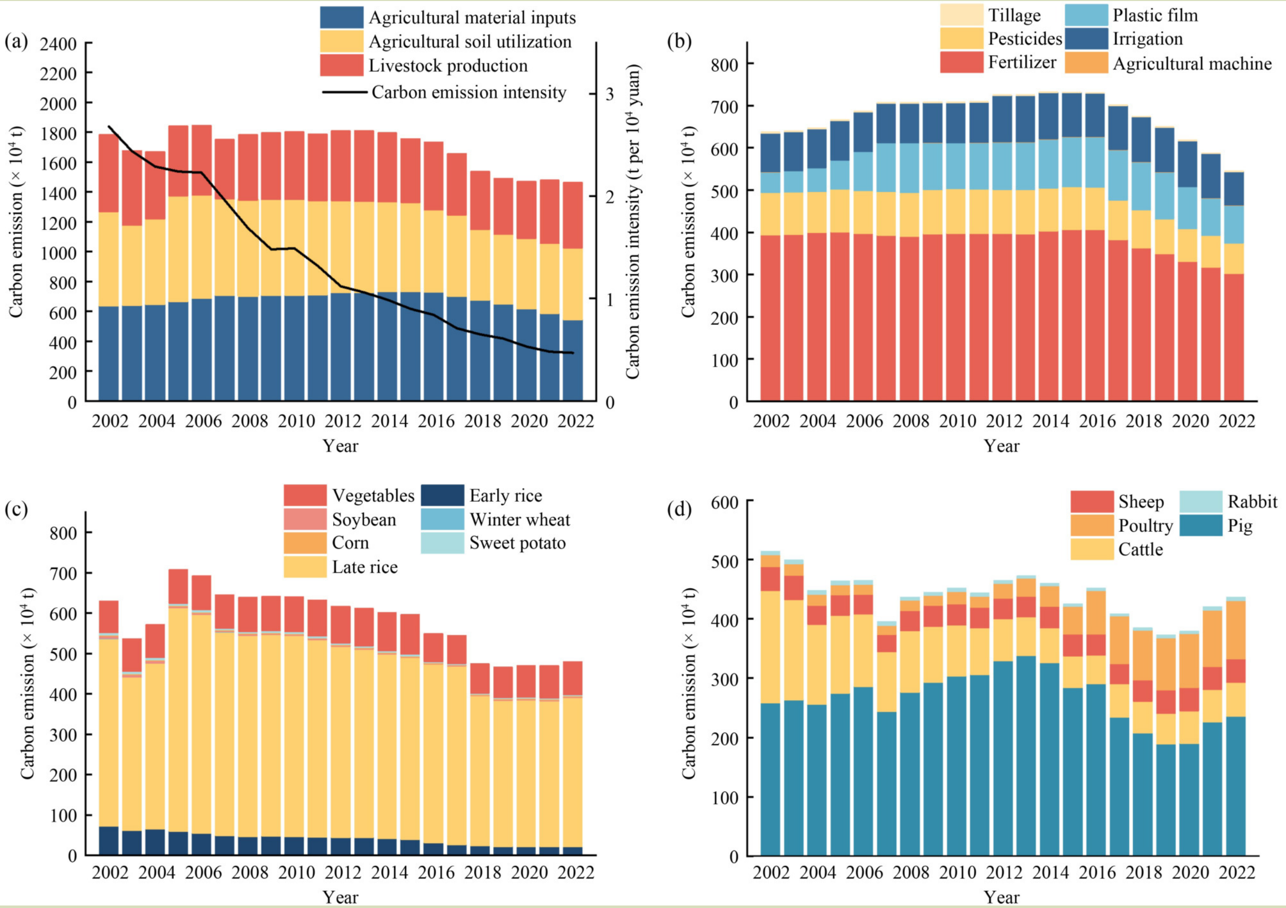


Fig. 2 Agricultural carbon emission trends in Fujian Province (2002–2022): (a) total volume, intensity, and structure; (b) structure of carbon emissions from agricultural material inputs; (c) structure of carbon emissions from agricultural soil utilization; and (d) structure of carbon emissions from livestock production

3.2 Spatial characteristics of agricultural carbon emissions

ACE in Fujian Province had a spatial pattern of higher levels in the west and lower in the east, though most areas show a decrease in ACE compared to the base period (Table 4).

Zhangzhou was the only high-carbon emission area in Fujian in 2002, with ACE totaling about 405 × 10^4 t, accounting for 22.7% of total provincial ACE. Zhangzhou, located in the southern tip of the province, has a subtropical monsoon humid climate and fertile land highly-suited for further agricultural development; it encompasses a vast area of crop cultivation and ranks highest in the provincial output of rice and vegetables. However, due to its distance from the core economic zone of Fujian Province, Zhangzhou lags in transportation infrastructure, has been slow to adopt modern agricultural

Table 4 Spatial distribution of agricultural carbon emissions (ACE) in Fujian Province (× 10^4 t)

Year	Cities of Fujian Province								
	Ningde	Fuzhou	Putian	Quanzhou	Xiamen	Zhangzhou	Longyan	Sanming	Nanping
2002	103.737	221.946	91.107	216.503	55.038	405.352	233.349	226.003	229.452
2012	108.121	177.557	96.306	209.892	35.983	312.647	278.827	280.509	307.538
2022	98.894	132.058	54.214	144.218	16.931	242.416	267.128	226.946	280.596

practices and lacks economic momentum. As a result, its consumption of agricultural inputs and carbon emissions remain relatively high.

By 2012, advancements in agricultural scale and modernization decreased the overall ACE in Fujian Province. Nanping, Sanming and Longyan transitioned from medium-carbon to high-carbon emission areas, with their combined ACE reaching 883 × 10^4 t, 8.1% higher than the 817 × 10^4 t level from 2002, and began to form a spatial distribution pattern of higher emissions in the west and lower in the east. The particularly mountainous terrain of western Fujian, its fragmented agricultural production and lack of scientific management practices have led to more intensive use of mineral fertilizers, agricultural films and other carbon-intensive materials, as well as a sharp increase in the number of pigs, cows, and sheep farmed in the region. These disparities in comparison to eastern Fujian contributed to the larger total amount of ACE in western Fujian.

The influence of innovative development concepts and the implementation of green agricultural policies caused the decline in total ACE across Fujian to become more pronounced by 2022, though the spatial distribution pattern remained largely unchanged. Eastern Fujian, which has a more developed economy and focuses on economic construction, has limited arable land and a growing tertiary sector; these qualities have resulted in a lower share of agricultural GDP as well as significantly lower ACE compared to the western areas of the province. Also, the economically advanced areas in the east benefit from more advanced agricultural production methods, a concentration of expertise in agriculture and modern technologies together contributed to the effective control of ACE.

The top four cities in terms of ACE, Nanping, Longyan, Zhangzhou and Sanming, had decreases of 11%, 5.2%, 24.6% and 19.0% in ACE, respectively, compared to 2012 levels. These high-emission agricultural areas account for 70.0% of the total provincial ACE. These cities have rich land resources, significant agricultural inputs, large-scale livestock production systems and substantial agricultural production capacity. They are expected to remain the primary agricultural production zones in Fujian Province in the future.

Kernel density curves illustrating the dynamic evolution of carbon emissions from 2002 to 2022 (Fig. 3) reveal several key trends. First, the position of the center of gravity in the curves had a general shift to the left over the study period, indicating a decline in ACE intensity. Second, the height of the central peak increased over time, indicating a reduction in the disparities among ACE intensity across regions.

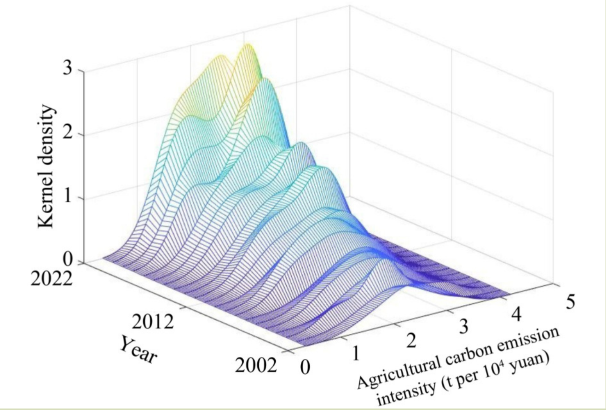


Fig. 3 Dynamic evolution trends of agricultural carbon emissions intensity in Fujian Province, 2002–2022

The earlier years had a single broad peak. However, a double-peak pattern emerged and persisted from 2012 onward. The secondary peak is primarily located in low-value ACE-intensity areas and the central peak in areas with medium-to-high ACE intensity. This indicates that the majority of cities have ACE-intensity levels ranging from medium to high, while a few cities (e.g., Fuzhou) had lower intensities.

3.3 Factor decomposition of agricultural carbon emissions

ACE in Fujian Province decreased by 320 × 10^4 t over the past 20 years (Fig. 4). Agricultural production efficiency (C_I), agricultural production structure (A_I), regional industrial structure (I_S) and total rural population (P) had negative effects on ACE.

A comparative analysis of A_I, I_S and P, where, C_I consistently has a positive and unique role, revealed that C_I was responsible for reducing ACE by 2980 × 10^4 t (56.3%) from 2002 to 2022. Thus, I_S is the most critical factor in ACE reduction. This significant impact can be attributed to continuous advancements in agricultural technology. As agricultural production becomes more mechanized and oriented toward green development, large-scale farming becomes more common, material input efficiency improves, waste is reduced and ultimately, ACE declines.

The impact of A_I on ACE was predominantly negative but its

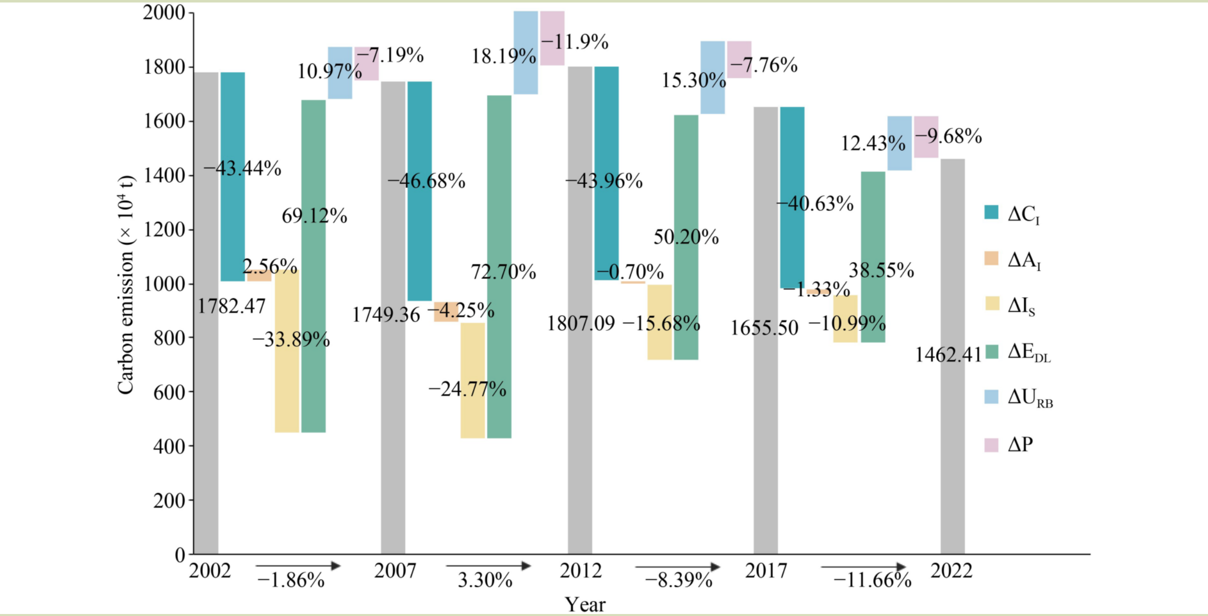


Fig. 4 Decomposition of factors influencing agricultural carbon emissions in Fujian Province (2002–2022).

effect was limited, contributing to a reduction of 62.3 × 10^4 t (1.18%) through structural adjustments. I_S and P also helped reduce ACE by 1550 × 10^4 t (29.3%) and 702 × 10^4 t (13.3%), respectively, when other influencing factors remained unchanged. The proportion of people living in rural areas in Fujian Province decreased from 54.3% in 2002 to 29.9% in 2022, and the proportion of agricultural output to gross regional product decreased from 25.2% in 2002 to 10.4% in 2022. These shifts indicate improvements in the provincial industrial structure over time having positively impacted ACE reduction.

However, E_{DL} and U_{RB} are dominant factors contributing to increased ACE. Regional economic growth increased ACE by 3950 × 10^4 t, comprising the main factor contributing to increased ACE. Urbanization has also exacerbated the aging and feminization of rural areas, where a lack of awareness among these groups has limited their ability to contribute more broadly to ACE reduction.

3.4 Decoupling of agricultural carbon emissions from agricultural economic growth

The agricultural economy in Fujian Province maintained a steady upward trend from 2002 to 2022, while ACE gradually declined. The decoupling status between these trends can be divided into three distinct stages (Table 5).

The first stage, from 2002 to 2004, had strong decoupling and a period of stabilization. During this time, ACE decreased at an annual rate of −2.7% while agricultural output grew by 3.8% per year, creating an inverse relationship. Despite the rapid economic growth of this time, agricultural development was relatively slow and dissemination of newer production technologies was limited. This led to a faster economic growth compared to the increase in ACE.

The second stage, from 2005 to 2013, was marked by mostly weak decoupling. The years 2007 and 2011 were notable exceptions featuring strong decoupling, and 2010 had expansion and negative decoupling. Overall, the decoupling during this period was relatively stable and favorable, marking a noteworthy transition. The annual growth rate of agricultural output was 10.1%, much higher than the annual growth rate of ACE at 1.0%. ACE grew slowly and even declined in particular years, however, agricultural output increased rapidly largely due to emission reduction policies and agriculture support programs introduced during the Eleventh and Twelfth Five-Year Plans.

The third stage, from 2014 to 2022, had stable and strong decoupling as the agricultural economy continued to grow while ACE decreased. Agricultural output increased at an annual rate of 7.0%, while ACE increased at a slower rate of 2.3%. Continuous adjustments to the agricultural industrial structure, the promotion of organic fertilizers, recycling of

Table 5 Decoupling of agricultural carbon emissions and economic growth in Fujian Province

Year	Total (10^4 t)	Environmental pressure	Value of agricultural output	Economic development	Decoupling elasticity	Decoupled state
2002	1782.47	−0.0161	666.27	0.0240	−0.67	Strong decoupling
2003	1676.19	−0.0557	685.74	0.0309	−1.80	Strong decoupling
2004	1667.92	−0.0043	726.90	0.0654	−0.07	Strong decoupling
2005	1838.71	0.0895	820.97	0.1495	0.60	Weak decoupling
2006	1844.76	0.0032	826.10	0.0082	0.39	Weak decoupling
2007	1749.36	−0.0500	893.94	0.1078	−0.46	Strong decoupling
2008	1783.69	0.0180	1054.97	0.2559	0.07	Weak decoupling
2009	1795.14	0.0060	1210.13	0.2466	0.02	Weak decoupling
2010	1801.24	0.0032	1210.56	0.0007	4.67	Expansion negative decoupling
2011	1786.34	−0.0078	1354.61	0.2290	−0.03	Strong decoupling
2012	1807.09	0.0109	1611.13	0.4077	0.03	Weak decoupling
2013	1810.23	0.0016	1704.22	0.1480	0.01	Weak decoupling
2014	1794.38	−0.0083	1818.45	0.1816	−0.05	Strong decoupling
2009	1795.14	0.0060	1210.13	0.2466	0.02	Weak decoupling
2010	1801.24	0.0032	1210.56	0.0007	4.67	Expansion negative decoupling
2011	1786.34	−0.0078	1354.61	0.2290	−0.03	Strong decoupling
2012	1807.09	0.0109	1611.13	0.4077	0.03	Weak decoupling
2013	1810.23	0.0016	1704.22	0.1480	0.01	Weak decoupling
2014	1794.38	−0.0083	1818.45	0.1816	−0.05	Strong decoupling
2015	1754.35	−0.0210	1942.46	0.1971	−0.11	Strong decoupling
2016	1732.28	−0.0116	2052.18	0.1744	−0.07	Strong decoupling
2017	1655.50	−0.0402	2325.57	0.4345	−0.09	Strong decoupling
2018	1534.97	−0.0632	2354.93	0.0467	−1.35	Strong decoupling
2019	1489.71	−0.0237	2454.89	0.1589	−0.15	Strong decoupling
2020	1468.86	−0.0109	2772.52	0.5048	−0.02	Strong decoupling
2021	1478.27	0.0049	3074.23	0.4795	0.01	Strong decoupling
2022	1462.41	−0.0083	3105.33	0.0494	−0.17	Strong decoupling

agricultural waste and other emission reduction measures allowed Fujian Province to effectively reduce pollution from its agricultural sector while achieving qualitative growth in output, thereby maintaining and stabilizing strong decoupling between the two.

3.5 Carbon emission projections

The ACE predictions for Fujian Province are given in Fig. 5. Projections based on data for 2002–2022 have an overall decrease in ACE from the peak in 2003 onward. ACE in 2030 is projected to be 7.1% lower than in 2022, and 15.2% lower by 2040, marking an average annual reduction of 13.1 × 10^4 t. Projections using ACE data for 2012–2022 have a rapidly decreasing trend in ACE after peaking in 2013. ACE in 2030 is projected in this case to be 20.5% lower than in 2022, and 40.5% lower by 2040, for an average annual reduction of 31.8 × 10^4 t.

These predictions indicate that ACE in Fujian Province will continue to decline if the contributing factors remain unchanged. The rapid development of green agriculture in recent years, coupled with the implementation of government policies related to ecological protection and green agricultural development, have contributed effectively to ACE reduction.

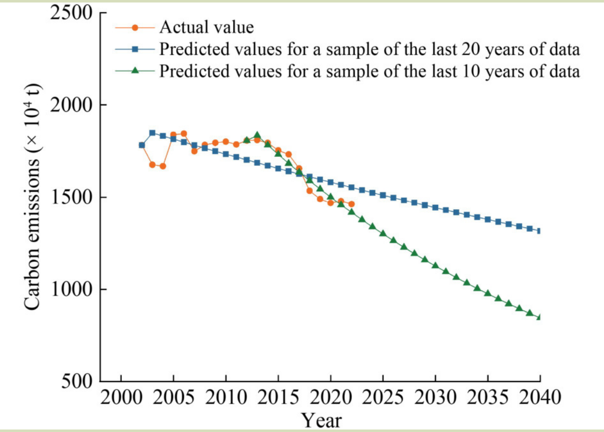


Fig. 5 Actual and predicted trends for agricultural carbon emissions in Fujian Province though to 2040.

4 Implication

The results of this study indicate that agricultural material inputs are the largest source of ACE in Fujian Province, consistent with the findings of Zheng et al.[34]. To address this, local governments should implement precise agricultural supply quota policies to reduce the use of fertilizers and pesticides in production. Agricultural subsidy policies should also be adjusted to encourage farmers to adopt organic farming and green production methods while prioritizing organic fertilizers and low-carbon pesticides and machinery. Recycling plastic films as much as possible can enhance resource efficiency and further reduce ACE as well.

Agricultural soil utilization is also a major source of ACE in Fujian Province, indicating significant potential for carbon sequestration and emission reduction from farmland soils. Transforming farmland from a carbon source into a carbon sink can be achieved through practices like conservation tillage, returning straw and manure to fields; this would enhance carbon sequestration and promote more sustainable soil management.

In the livestock sector, particularly pig production (the largest carbon source), relevant authorities should focus on production of high-yield and low-emission animals, improving manure treatment and promoting the integration of crop and livestock production to reduce emissions and increase carbon sequestration in the livestock sector of Fujian Province.

In terms of the spatial distribution of ACE, the results of this study align with previous research[35] showing regional differences between the south-eastern coastal areas and the north-western mountainous areas of Fujian. Based on the emission categories delineated in this study, tailored emission reduction targets and incentive programs can be formulated to promote synergistic regional development.

Regarding the drivers of ACE in Fujian Province, factors such as agricultural production efficiency, population size and industrial structure should be leveraged to inhibit ACE. Improving agricultural infrastructure and adopting modern technologies can enhance production efficiency, while encouraging a transition of agricultural labor to the secondary and tertiary sectors can streamline the agricultural workforce. Further optimizing the agricultural industry structure by adapting production to local conditions would contribute to reducing ACE as well.

Due to data limitations, we only considered primary sources of emissions in this study and did not quantify the impact of practices like straw and organic fertilizer return on soil GHG emissions. Additionally, this analysis did not account for carbon sequestration in farmland ecosystems. Future research should incorporate the carbon sequestration potential of farmland ecosystems, as well as conduct a more comprehensive analysis of regional carbon sequestration, carbon emissions and carbon footprints.

It is important to fully understand the management of crop straw and organic fertilizers in Fujian, and integrate these factors into the accounting system for ACE and carbon sequestration. Using diverse evaluation methods can improve the accuracy of such estimates. Also, additional evaluation indicators relevant to conditions specific to Fujian can be included to help identify and address issues more effectively. Additionally, the carbon emissions database for Fujian Province can be enhanced by conducting field surveys, allowing for more detailed regional differentiation studies. This would enable more targeted emission reduction strategies tailored to the local conditions.

5 Conclusions

The total amount and intensity of ACE in Fujian Province have trended downward in recent decades. Agricultural material inputs are the largest contributors to ACE; fertilizer application, rice cultivation and pig production are the three most significant sources of emissions. Spatially, ACE in Fujian generally follows a pattern of higher emissions in the west and lower emissions in the east. Agricultural production efficiency is the most critical factor in reducing emissions, while regional economic development is the primary driver of increasing ACE. Fujian Province has achieved a high degree of decoupling between ACE and agricultural economic development, and projections indicate that the provincial ACE will continue to decline.

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Compliance with ethics guidelines

Weiye Li, Zhiqiang Chen, Zhibiao Chen, Yuee Zeng, and Wenjing Hu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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