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Spatial-temporal characteristics and influencing factors of farmland carbon emissions in Guangdong Province, China

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Agricultural carbon emissions account for 17% of total greenhouse gas emissions in China. To effectively address the eco-environment changes in farmland, which serves as the foundation of agricultural activities, it is essential to estimate regional farmland carbon emissions. This study calculated the farmland carbon emissions in Guangdong from 2011 to 2021 using the classical IPCC carbon emission calculation methodology. The decoupling characteristics betweem farmland carbon emissions and agricultural output values were analyzed utilizing a decoupling model, and the influencing factors were examined through the Logarithmic Mean Divisia Index (LMDI). The results indicate that: 1) Farmland carbon emissions in Guangdong decreased by 13.21% from 2011 to 2021, with pesticide reductions contributing the most to emission decreases. Chemical fertilizers were the largest contributor to farmland carbon emissions, accounting for approximately 61.78% of the total. 2) The spatial distribution of farmland carbon emissions followed the pattern of "Western Guangdong > Northern Guangdong > Eastern Guangdong > Pearl River Delta". While emission intensity generally declined, regional disparities widened. 3) Most cities in Guangdong exhibited a strong decoupling relationship between farmland carbon emissions and agricultural output values, with decoupling coefficient ranging from −1.182 to −0.004. However, Heyuan and Shenzhen demonstrated a weak decoupling relationship. 4) The primary driver of increased farmland carbon emissions in Guangdong was the level of agricultural output, while improvements in agricultural production efficiency were the most significant inhibitory factor, followed by changes in the scale of agricultural labor force. This study offers policy recommendations to promote the reduction and sequestration of farmland carbon emissions in Guangdong.

KEYWORDS

farmland carbon emissions, spatial-temporal characteristics, influencing factors, decoupling model, LMDI

1 Introduction

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), agriculture is the second-largest source of greenhouse gases, accounting for approximately 13.5% of global anthropogenic greenhouse gas emissions and 58% of non-anthropogenic CO_2 emissions (Hao, 2021). In China, agricultural carbon emissions contribute 17% of the nation's total greenhouse gas emissions, with an average annual growth rate of 5% (Sun, 2018; Zhou, 2022). As a global leader in agriculture, China has achieved significant reductions in agricultural carbon emissions since the start of the 21st century. However, agricultural development continues to face critical challenges, including high resource consumption, farmland degradation, and ecological deterioration. This necessitates an urgent transition from high-carbon to low-carbon agriculture. Farmland, as the essential foundation of agricultural activities, represents China's most valuable natural resource and plays a pivotal role in ensuring national food security, ecological sustainability, and social stability. Within the policy framework of integrated farmland protection—encompassing quantity, quality, and ecology—it is particularly significant to estimate regional farmland carbon emissions to effectively address eco-environment changes impacting farmland.

Significant researches have been conducted on agricultural carbon emissions. However, relatively little attention has been given to carbon emissions originating specifically from farmland. Regarding research areas, existing studies have primarily concentrated on the identification of agricultural carbon sources, the measurement of agricultural carbon emissions, the spatial-temporal evolution of regional agricultural carbon emissions, and their influencing factors. In terms of agricultural carbon sources, scholars have mainly explored topics such as agricultural waste disposal (Johnson et al., 2007), the use of agricultural fossil fuels (Zhou, 2022), inputs of agricultural production factors (Liu Y. and Liu H. B., 2022), livestock breeding (Lesschen et al., 2011), rice cultivation (Ding et al., 2022), biomass combustion (Zeng et al., 2023), and land use changes (Tubiello, 2019). For instance, as early as 1986, Crutzen et al. (1986) studied methane emissions from livestock by combining animal feed intake with demographic data. West and Marland (2002) highlighted soil disturbance caused by agricultural cultivation methods as a significant contributor to increased agricultural carbon emissions. The United States Environmental Protection Agency (EPA) calculated the agricultural carbon emissions in the U.S., revealing that over half were associated with agricultural land use (Eggleston et al., 2006). In China, scholars have continuously advanced the study of agricultural carbon emission mechanisms. Over time, the scope of agricultural carbon emissions measurements has expanded to encompass the entire agricultural production process (Li et al., 2011; Peng et al., 2024).

From the perspective of agricultural carbon emissions measurement, several methods are commonly employed, including the IPCC carbon emission coefficient method (Ning et al., 2023), the Life Cycle Assessment (LCA) method (Zhang and Wang, 2014), the Input-Output Analysis (IOA) method (Wang, 2023), and the direct measurement method (Zhang and He, 2022). The LCA method requires extensive data and involves complex computations, making it highly susceptible to data uncertainties. The IOA method may overlook emissions from certain stages and is unable to accurately assess the carbon emissions of specific activities or products, resulting in lower precision. The IPCC carbon emission coefficient method, which categorizes emissions into distinct types and calculates them based on emission factors, is widely applied in agricultural carbon emissions research. For instance, Ding et al. (2022) employed this method to measure carbon emissions from the planting industry, utilizing statistical data on agricultural inputs and production values from 31 Chinese provinces from 2001 to 2018. Similarly, Li et al. (2022) applied the IPCC carbon emission coefficient method to calculate the intensity and efficiency of agricultural carbon emissions in Zhejiang Province from 2011 to 2020. Institutions such as the Oak Ridge National Laboratory (ORNL) in the U.S., the IPCC, and the Department of Climate Change of the National Development and Reform Commission in China have experimentally determined the emission coefficients for various agricultural carbon sources. These efforts have contributed to the development of comprehensive greenhouse gas emission inventories.

From the perspectives of spatial distribution and temporal changes, scholars have studied the composition, total amount, and intensity of agricultural carbon emissions (Chen et al., 2023), as well as conceptual indicators such as carbon footprint (Al-Mansour and Jejcic, 2017; Adewale et al., 2019) and agricultural carbon emissions performance (Liu and Gao, 2022). Given China's vast territory and significant regional differences in agricultural carbon emissions, scholars have conducted spatiotemporal analyses at various scales, including national, regional, provincial, and municipal levels, as well as from management perspectives. For instance, Su et al. (2023) calculated the agricultural carbon emissions of 31 Chinese provinces from 2005 to 2020, analyzing the temporal and spatial evolution, clustering characteristics, spatial correlations, and spillover effects. Xu et al. (2023) employed the emission coefficient method, parameter estimation method, and Gini coefficient method to examine the regional differences and the equity of farmland carbon budgets at the county level in Jiangsu Province from 2000 to 2020. Similarly, Hao (2022) investigated the changes in carbon sources and sinks of major grain crops and economic crops in the Heilongjiang Reclamation Area. Bai et al. (2023) explored the driving mechanisms of agricultural land management scale on agricultural carbon emissions, using the scale of agricultural land management as a starting point and agricultural product consumption intensity as an intermediary factor.

From the perspective of influencing factors, existing researches have investigated the influencing factors of agricultural carbon emissions using various models, such as the LMDI approach (Deng et al., 2023) and regression model (He et al., 2022). These studies reveal that improvements in production efficiency, agricultural production structure, rural population, agricultural industry structure, the level of agricultural economic development, rural education levels, agricultural mechanization, and agricultural service level can effectively reduce agricultural carbon emissions (Xia et al., 2019; Wu et al., 2020; Tong et al., 2024). Conversely, factors such as enhanced agricultural development levels, industrial clustering, urbanization, and large-scale farmland management tend to promote agricultural carbon emissions (Hu et al., 2020). For instance, Zhao et al. (2018) adopted the difference-in-difference model to evaluate the effects of pilot policies on agricultural carbon emission across various Chinese provinces. They found that low carbon pilot policies significantly reduced agricultural carbon emissions in Shaanxi, Hubei and Liaoning provinces, but showed no significant effects in Guangdong and Yunnan provinces. Similarly, Li and Zhou (2020) employed the SYS-GMM method to analyze the impact of agricultural technology progress on the intensity of agricultural carbon emissions. Their findings indicated that while technology progress overall contributed to emission reductions, its pathways varied: advancements in agricultural mechanization increased carbon intensity, whereas innovations in agricultural germplasm significantly reduced it. Hu et al. (2020) estimated agricultural carbon emissions across 31 Chinese provinces from 1997 to 2017, conducting peak-value analysis, LMDI decomposition, and EKC test. Their study identified production efficiency, agricultural industrial structure and rural population as key factors for reducing emissions, while industrial structure, regional economic development, and urbanization were associated with increased emissions.

The review of the existing literature reveals that while substantial progress has been made in the study of agricultural carbon emissions, several limitations persist: (1) Most researches focus on the agricultural production process, with insufficient attention given to its natural carrier—farmland itself. The absence of a robust measurement method for farmland carbon emissions hampers accurate analysis of carbon emissions originating directly from farmland. (2) Limited research has been conducted on farmland carbon emissions in Guangdong Province, and multi-scale analyses spanning from the provincial to municipal levels remain scarce. Guangdong, as both a major agricultural province and the region with the largest economic output in China, faces significant pressure to reduce farmland carbon emissions. There is an urgent need for studies that examine farmland carbon emissions at the prefectural level within Guangdong Province. (3) Many existing studies overlook the spatial heterogeneity of factors influencing agricultural carbon emissions. This gap prevents the precise identification of region-specific factors affecting farmland carbon emissions and hinders the development and implementation of targeted, effective policies.

To explore the spatiotemporal evolution of farmland carbon emissions and their driving factors in Guangdong Province, this study focuses on 21 prefectural-level cities as the research subjects. The classical IPCC carbon emission calculation theory is applied to measure the total amount and intensity of farmland carbon emissions. A decoupling model is employed to examine the decoupling characteristics of farmland carbon emissions from agricultural outputs. Additionally, the LMDI model is utilized to analyze the factors influencing farmland carbon emissions. The spatiotemporal characteristics and influencing factors are investigated at both provincial and prefectural levels in Guangdong Province from 2011 to 2021. Based on these findings, policy implications are proposed to enhance carbon sequestration and reduce emissions in farmland of Guangdong. This study aims to provide a valuable reference for the development of regional and differentiated farmland carbon emission reduction policies in the province.

2 Materials and methods

2.1 Study area

Guangdong Province, located in the southernmost part of mainland China, spans from 20°09′N to 25°31′N latitude and 109°45′E to 117°20′E longitude, covering a land area of approximately 179,800 km^2 and encompassing 21 prefecture-level cities. The province benefits from exceptionally favorable natural conditions for agricultural development, being situated in tropical and subtropical climate zones with abundant light, heat, and water resources. The rainy and hot seasons coincide, with average annual temperatures ranging from 18°C to 26°C. These conditions support the cultivation of double-season rice along with a winter crop, allowing for up to three harvests annually. Guangdong produces a wide variety of crops, including rice, wheat, soybeans, and tubers (Guangdong Provincial Conditions Website, 2024). As of early 2020, Guangdong's total farmland area was approximately 1.90 million hectares, and by 2021, its total output value had reached 830.58 billion yuan. However, with the continuous development of agriculture in Guangdong, the input of production materials for farmland has increased, necessitating an urgent assessment of farmland carbon emissions. This evaluation is critical for promoting the sustainable development of farmland in the region.

2.2 Data sources

The data used in this study, including the amount of agricultural chemical fertilizer, agricultural plastic film and pesticides applied, the area of crop cultivation, the agriculture output value, the number of people engaged in the primary industry, the total power of agricultural machinery, the area of irrigation, the area of farmland, as well as the sown area of crops such as rice, wheat, soybeans, tubers, and vegetables, were all sourced from the *Guangdong Rural Statistical Yearbook* (2012-2022) (https://stats.gd.gov.cn/gdnctjnj/).

2.3 Research methods

2.3.1 Measurement method of farmland carbon emissions

Agricultural carbon emissions are generally considered to originate from both crop cultivation and livestock breeding. Emissions from crop cultivation can be further divided into two components: agricultural material inputs and soil utilization in farmlands (Liu and Liu, 2022). Drawing on production practices, relevant research findings, and expert consultations, this study identifies the primary sources of farmland carbon emissions as

TABLE 1 Farmland carbon sources, carbon emission coefficients, and sources.

Production material inputs			Crop growth emissions		
Carbon Sources	Coefficients	References Sources	Carbon Sources	Coefficients	References Sources
Chemical fertilizer	0.89 kg/kg	ORNL	Early rice	150.5 kg/ha (CH_4)	Min and Hu (2012)
				0.24 kg/ha (N_2O)	
Pesticides	4.93 kg/kg		Late rice	516 kg/ha (CH^4)	
				0.24 kg/ha (N_2O)	
Agricultural film	5.18 kg/kg	IREEA	Wheat	1.75 kg/ha (N_2O)	
Total power of agricultural machinery	0.18 kg/kw	West and Marland (2002)	Soybeans	2.29 kg/ha (N_2O)	
Agricultural Irrigation	266.48 kg/ha	Duan et al. (2011)	Tubers	0.95 kg/ha (N_2O)	
Agricultural Plowing	3.126 kg/ha	CAB	Vegetables	4.944 kg/ha (N_2O)	
			Corn	2.532 kg/ha (N_2O)	

ORNL, oak ridge national laboratory; USA IREEA, institute of resource, Ecosystem and Environment of Agriculture, Nanjing Agricultural University; CAB, college of agronomy and biotechnology, China Agricultural University.

agricultural activities conducted on farmlands. These emissions mainly comprise the following two aspects:

(1) Carbon emissions, directly or indirectly caused by carbon sources during the input of production materials, include the following: emissions from the production and use of agricultural materials such as chemical fertilizers, pesticides, and agricultural films; emissions resulting from the consumption of fossil fuels (e.g., diesel and electricity) during the operation of agricultural machinery; emissions from electricity consumption for agricultural irrigation; and organic carbon loss due to soil tillage.
(2) Greenhouse gas emissions, such as CH_4 and N_2O, during crops growth. Emission coefficients for these gases vary by crop type. Considering the crop planting conditions in Guangdong, this study identifies rice, wheat, corn, soybeans, tubers, and vegetables as primary sources of CH_4 and N_2O emissions. According to the Fourth IPCC Assessment Report, the carbon conversion coefficients for CH_4 and N_2O are 6.8182 and 81.2727, respectively. The carbon sources and their corresponding emission coefficients for farmland are presented in Table 1.

This study utilizes carbon emission coefficients published by the IPCC of the United Nations to calculate the farmland carbon emissions in Guangdong. The formula is shown in Equation 1:

$$E = \sum E_i = \sum T_i \cdot \varepsilon_i \tag{1}$$

Where, E is the total farmland carbon emissions, E_i is the carbon released by the ith carbon source, ε_i is the carbon emission coefficient for the ith carbon source, and T_i is the input amount of the ith carbon source.

The formula for farmland carbon emission intensity is shown in Equation 2 and Equation 3:

$$I_{area} = \frac{E}{S} \tag{2}$$

$$I_{GDP} = \frac{E}{GDP} \tag{3}$$

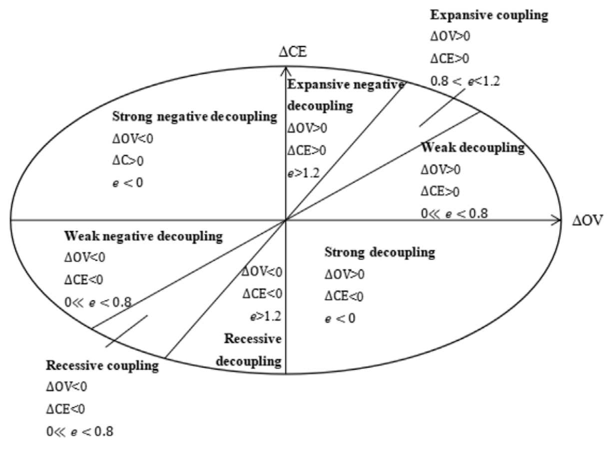

FIGURE 1
The degrees of coupling and decoupling of farmland carbon emissions (ΔCE) from agricultural output value (ΔOV) (modified from Vehmas et al., 2003).

Where, I_{area} represents the carbon emission intensity per unit area of farmland, I_{GDP} represents the carbon emission intensity per unit of agricultural GDP. E represents the total farmland carbon emissions, S represents the total farmland area, and GDP represents the total output value of agricultural production.

2.3.2 Decoupling model

When analyzing the relationships between GDP, traffic volumes and CO_2 emissions from transport in the EU15 countries, Tapio redefined the concept of decoupling, modifying it from the framework proposed by Vehmas et al. (2003). Based on variables and elasticity values, Tapio identified eight logical possibilities: decoupling (weak decoupling, strong decoupling, and recession decoupling), negative decoupling (expansion negative decoupling, strong negative decoupling, and weak negative decoupling), and coupling (expansive coupling and recessive coupling) (Tapio, 2005).

This paper employs the decoupling model to analyze the decoupling characteristics of farmland carbon emissions from agricultural outputs. The measurement formula is shown in Equation 4:

$$e = \frac{\%\Delta EP}{\%\Delta EG} = \frac{\Delta CE/CE}{\Delta OV/OV} = \frac{(CE_{t+1} - CE_t)/CE_t}{(OV_{t+1} - OV_t)/OV_t} \quad (4)$$

Where, e is the elasticity value. EP and EG are environmental pressure and economic growth, respectively, which are represented by farmland carbon emissions (CE) and agricultural output value (OV). The elasticity is calculated as the ratio of the percentage change in environmental pressure ($\%\Delta EP$) to the percentage change in economic growth ($\%\Delta EG$) over the period from t to $t+1$. Figure 1 illustrates the degrees of coupling and decoupling of farmland carbon emissions (ΔCE) from agricultural output value (ΔOV).

2.3.3 Influencing factor decomposition model of carbon emission

To examine the impact of various factors on carbon emissions from farmland in Guangdong Province, this study incorporates the Kaya identity (Kaya, 1989) into the analysis. By transforming the formula, it establishes the relationships among agricultural production efficiency, agricultural production structure, agricultural output level, labor force scale, and farmland carbon emission. The formula is shown in Equations 5–9:

$$E = \frac{C}{G} \times \frac{G}{G_w} \times \frac{G_w}{P} \times P \quad (5)$$

$$\alpha_e = \frac{E}{G} \quad (6)$$

$$\alpha_s = \frac{G}{G_w} \quad (7)$$

$$\alpha_p = \frac{G_w}{P} \quad (8)$$

$$E = \alpha_e \times \alpha_s \times \alpha_p \times P \quad (9)$$

Where, E is farmland carbon emissions. G is agricultural output value, G_w is the total output value of agriculture, forestry, animal husbandry, and fishery, and P is agricultural labor force scale. α_e is agricultural production efficiency, α_s is agricultural production structure, and α_p is the agricultural output level.

The LMDI approach (Ang, 2005) is applied to decompose Equation (9) to quantify the impact of each influencing factor on the farmland carbon emissions. The formula is shown in Equations 10–14:

$$\Delta\alpha_e = \frac{C^T - C^0}{\ln C^T - \ln C^0} \times \left(\ln \alpha_e^T - \ln \alpha_e^0\right) \quad (10)$$

$$\Delta\alpha_s = \frac{C^T - C^0}{\ln C^T - \ln C^0} \times \left(\ln \alpha_s^T - \ln \alpha_s^0\right) \quad (11)$$

$$\Delta\alpha_p = \frac{C^T - C^0}{\ln C^T - \ln C^0} \times \left(\ln \alpha_p^T - \ln \alpha_p^0\right) \quad (12)$$

$$\Delta P = \frac{C^T - C^0}{\ln C^T - \ln C^0} \times \left(\ln P^T - \ln P^0\right) \quad (13)$$

$$\Delta C = \Delta\alpha_e + \Delta\alpha_s + \Delta\alpha_p + \Delta P \quad (14)$$

Where, 0 is the base period, and T is the target period. $\Delta\alpha_e$、$\Delta\alpha_s$、 $\Delta\alpha_p$ and ΔP are the contribution values of agricultural production efficiency, agricultural production structure, agricultural output level, and agricultural labor force scale, respectively, to the change in farmland carbon emissions from the base period to period T. ΔC is the total effect of farmland carbon emissions caused by all influencing factors.

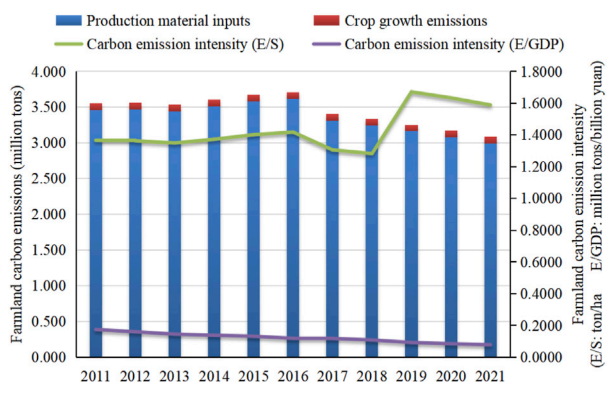

FIGURE 2
The total amount, intensity, and structure of farmland carbon emissions in Guangdong Province from 2011 to 2021.

3 Results

3.1 Spatial-temporal characteristics of farmland carbon emissions in Guangdong

3.1.1 Temporal changes of farmland carbon emissions at the provincial scale

Based on the measurement method for farmland carbon emissions, the temporal variation characteristics of farmland carbon emissions in Guangdong from 2011 to 2021 were calculated (Figure 2). As shown in Figure 2, total farmland carbon emissions in Guangdong exhibited an initial increase followed by a subsequent decline, rising from 3.55 million tons in 2011 to a peak of 3.71 million tons in 2016, before decreasing to 3.08 million tons in 2021. The peak in 2016 was followed by a sharp decline in 2017, characterized by significant reductions across multiple indicators of the carbon emission structure. This change may be attributed to a combination of policy interventions and adjustments in statistical methodologies. Overall, farmland carbon emissions in Guangdong decreased by approximately 13.21% over the study period, with an average annual reduction of 46,900 tons, corresponding to an average annual reduction rate of about 1.41%.

There is a significant difference between the two methods for estimating farmland carbon emission intensity in Guangdong. The intensity curve based on carbon emissions per unit area of farmland, exhibits fluctuations without a clear trend. Since 2019, changes in the statistical scope of farmland area have caused an abnormal, rapid increase in carbon emission intensity per unit area. In contrast, The intensity curve based on carbon emissions per unit of GDP shows a consistent downward trend, declining from 0.174 in 2011 to 0.078 in 2021. This represents a reduction of approximately 55.17% over 11 years, highlighting Guangdong's significant progres in promoting green and low-carbon farmland development. Compared to carbon

TABLE 2 Carbon emissions from various farmland carbon sources in Guangdong Province from 2011 to 2021.

Year	Fertilizer	Agricultural film	Pesticides	Irrigation	Tillage	Agricultural machinery	Rice	Other crops
2011	214.76	22.81	56.24	49.92	1.43	0.42	9.72	0.0084
2012	218.38	22.81	56.24	47.18	1.45	0.43	9.74	0.0086
2013	217.08	23.71	54.27	47.19	1.47	0.45	9.59	0.0091
2014	222.13	23.93	55.54	47.19	1.48	0.47	9.54	0.0094
2015	228.25	24.24	56.09	47.20	1.50	0.49	9.52	0.0096
2016	232.30	23.57	56.13	47.21	1.51	0.43	9.51	0.0098
2017	211.76	23.76	46.65	47.29	1.32	0.43	9.09	0.0082
2018	205.87	23.21	46.19	47.31	1.34	0.44	9.03	0.0084
2019	200.95	22.71	43.13	47.26	1.49	0.44	9.10	0.0087
2020	195.62	22.05	41.03	47.34	1.39	0.45	9.22	0.0090
2021	189.46	22.29	38.18	47.34	1.41	0.45	9.23	0.0092

Unit: ten thousand tons.

emissions per unit area of farmland, the metric of carbon emissions per unit of GDP better reflects changes driven by technological advancements and economic growth. Furthermore, the consistent statistical definition of GDP over time enhances the comparability of this indicator, making it more suitable for the municipal-scale analysis conducted in this study.

From the perspective of carbon emission structure, the carbon sources of farmland in Guangdong are mainly divided into two categories: production material inputs and crop growth emissions, totaling 12 subcategories. As shown in Figure 2, production material inputs account for approximately 97.27% of the total carbon emissions on Guangdong's farmland. Over the past of 11 years, the proportion of carbon emissions from production material inputs has slightly decreased, from 97.27% in 2011 to 97% in 2021. Table 2 presents the proportion of carbon emissions from various farmland carbon sources from 2011 to 2021, ranked from highest to lowest as follows: fertilizer > pesticides > irrigation > agricultural film > rice > tillage > agricultural machinery > other crops. Among these, carbon emissions from fertilizer, agricultural film, pesticides, irrigation, tillage, and rice planting have all decreased to varying extents. Notably, pesticides and fertilizer emissions showed the most significant reductions, with average annual growth rates of −3.80% and −1.25%, respectively. While carbon emissions from agricultural machinery and other crops have increased, the growth has been relatively modest. Over the last 11 years, the simultaneous decline in the use of chemical fertilizers, pesticides, and agricultural films in Guangdong, alongside sustained growth of agricultural output value, highlights the province's significant success in promoting technology that reduce agricultural material inputs while enhancing efficiency. This has led to continuous improvement in the green development of agriculture. The rise in carbon emissions from agricultural machinery, however, reflects the increasing mechanization of agriculture and the ongoing improvement of agricultural infrastructure in Guangdong.

In recent years, although the proportion of carbon emissions from fertilizer has decreased, it still accounted for a significant 61.44% of total emissions as of 2021. The fertilizer application intensity in Guangdong is 1096.29 kg/ha, much higher than the internationally recognized safe upper limit of 225 kg/ha. If fertilizer application in Guangdong were reduced to the safe threshold, it could lead to a carbon emission reduction of 1.5 million tons for the farmland. As the most significant source of carbon emissions reduction, pesticides, which account for 12.38% of total emissions, have experienced a significant decrease in carbon emissions. In contrast, carbon emissions from agricultural irrigation have remained stable, with a slight increase in recent years. By 2017, irrigation surpassed pesticides as the second-largest source of farmland carbon emissions in Guangdong, accounting for approximately 15.35% of the total. In 2021, carbon emissions from rice planting reached their highest level in recent years, making up 2.99% of the total, which is significantly higher than emissions from other crops. As one of China's major rice-producing provinces, Guangdong has a long history of extensive rice cultivation, with a planted area of 1.8274 million ha in 2021. Compared to other crops, rice contributes more greenhouse gas emissions.

3.1.2 Spatial-temporal characteristics of farmland carbon emissions at the municipal scale

3.1.2.1 Characteristics of carbon emissions and carbon emission intensities

There are significant variations in farmland carbon emissions across different cities in Guangdong. As shown in Table 3, in 2021, Zhanjiang, the city with the highest farmland carbon emissions, had carbon emissions approximately 64 times higher than Shenzhen, the city with the lowest emissions. Zhanjiang ranks first in Guangdong in terms of farmland carbon emissions, with a total of 527,600 tons. Maoming ranks second, with a total of 381,200 tons. Qingyuan, Zhaoqing, Jiangmen, and Meizhou are ranked third to sixth, with total farmland carbon emissions in these four cities exceeding 200,000 tons. The combined emissions from the top six cities account for 57.61% of the province's total emissions. The cities with the lowest rankings—Shenzhen, Dongguan, Zhuhai, Zhongshan, and Foshan—all have farmland carbon emissions below 50,000 tons. Among them, Shenzhen, with the smallest

TABLE 3 Carbon emissions, intensity, and their changes of farmland in Guangdong by city from 2011 to 2021.

Regions	Farmland carbon emissions			Farmland carbon emission intensity		
	2011	2021	2011–2021	2011	2021	2011–2021
Guangzhou	15.764	13.259	−2.505	0.088	0.045	−0.043
Shenzhen	0.705	0.825	0.120	0.152	0.054	−0.098
Zhuhai	5.234	1.789	−3.445	0.521	0.114	−0.407
Shantou	7.938	6.709	−1.228	0.122	0.057	−0.065
Foshan	7.900	4.316	−3.585	0.115	0.032	−0.083
Shaoguan	18.621	15.997	−2.625	0.154	0.083	−0.071
Heyuan	11.282	16.024	4.742	0.172	0.120	−0.052
Meizhou	21.902	20.875	−1.027	0.157	0.083	−0.074
Huizhou	15.676	13.956	−1.720	0.132	0.055	−0.077
Shanwei	10.440	9.318	−1.122	0.172	0.086	−0.086
Dongguan	2.091	1.093	−0.998	0.131	0.028	−0.103
Zhongshan	5.033	2.401	−2.632	0.176	0.051	−0.125
Jiangmen	21.053	20.947	−0.106	0.275	0.127	−0.148
Yangjiang	16.132	13.553	−2.579	0.188	0.122	−0.066
Zhanjiang	55.520	52.763	−2.756	0.195	0.095	−0.100
Maoming	41.880	38.125	−3.756	0.173	0.073	−0.100
Zhaoqing	25.734	22.085	−3.649	0.162	0.069	−0.093
Qingyuan	27.788	22.844	−4.944	0.239	0.092	−0.147
Chaozhou	11.356	6.353	−5.003	0.355	0.056	−0.299
Jieyang	17.227	14.445	−2.782	0.146	0.076	−0.070
Yunfu	15.990	10.659	−5.332	0.211	0.092	−0.119

Units: Farmland carbon emissions (ten thousand tons), farmland carbon emission intensity (million tons/billion yuan).

emissions, recorded less than 10,000 tons, at only 8,251.42 tons. The sum of these five cities accounts for only 3.38% of the total farmland carbon emissions in the province. Except for Heyuan and Shenzhen, farmland carbon emissions in all other cities in Guangdong have decreased compared to 2011. Heyuan has experienced a significant increase in emissions, rising by 47,400 tons, a growth of 42.03% compared to 2011. Among the cities with decreasing emissions, Zhuhai, Zhongshan, and Dongguan had the largest percentage reductions, with rates of 65.82%, 52.30%, and 47.73%, respectively. Yunfu, Chaozhou, and Qingyuan had the largest absolute reductions, with decreases of 53,300 tons, 50,000 tons, and 49,400 tons, respectively.

In terms of farmland carbon emission intensity, although there were some differences among cities in Guangdong from 2011 to 2021, the gaps between cities were relatively stable, with the ratio of highest to lowest increasing only slightly, from 4.55 times in 2011 to 4.57 times in 2021. Farmland carbon emission intensities in all cities across Guangdong have decreased to varying extents. Zhuhai and Chaozhou saw the most significant reductions, with intensity values decreasing by 0.407 and 0.299, respectively. Guangzhou experienced the smallest decrease, with its intensity value falling by just 0.043. As of 2021, the cities with the lowest farmland carbon emission intensities in Guangdong—Foshan, Dongguan, Guangzhou, Shenzhen, and Zhongshan—are all core cities in the Pearl River Delta, while the highest intensities are found in Jiangmen, Yangjiang, and Heyuan.

Utilizing the natural breaks method, the total amount and intensity of farmland carbon emissions in various cities of Guangdong were reclassified into five categories: "high, sub-high, medium, sub-low, and low," to further explore the spatial-temporal characteristics of farmland carbon emissions in Guangdong from 2011 to 2021. As shown in Figure 3, although there was a general decrease in farmland carbon emissions across cities in Guangdong from 2011 to 2021, the spatial distribution remained largely unchanged. Overall, the total farmland carbon emissions in Guangdong exhibited a spatial distribution pattern of "Western Guangdong > Northern Guangdong > Eastern Guangdong > Pearl River Delta". The areas with the lowest emissions are Shenzhen, Dongguan, Zhuhai, Zhongshan, and Foshan, all of which are core cities in the Pearl River Delta. There is a significant correlation between farmland carbon emissions and both the area of farmland and the scale of agricultural development. According to statistics for the first half of 2022, the share of the primary industry in the GDP of these five cities is less than 2.5%, with Shenzhen and Dongguan at

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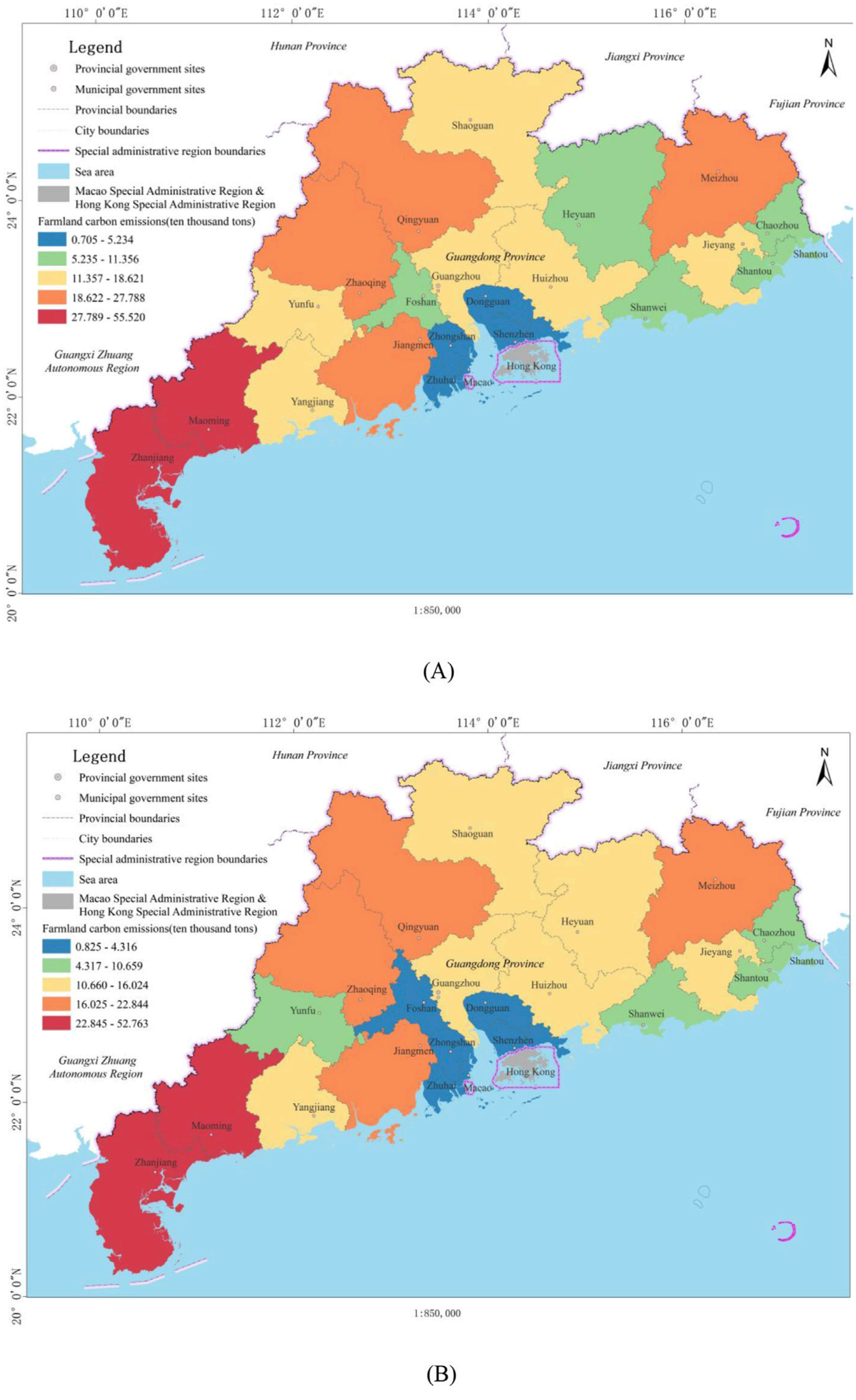

FIGURE 3
Spatial distribution of farmland carbon emissions in Guangdong by city: **(A)** 2011; **(B)** 2021.

just 0.1% and 0.3%, respectively. The sub-low emission areas are concentrated in the Chaoshan region in eastern Guangdong. With the exception of Jieyang, the farmland carbon emissions in Chaozhou, Shantou, and Shanwei rank among the six to eight lowest in the province. Small-scale farmers account for a relatively high proportion of the production entities in the Chaoshan region, characterized by a dense population, limited land, fragmented farmland, small production scales, and low levels of organization, which results in lower farmland carbon emissions. Zhanjiang and Maoming in western Guangdong have the highest emissions, with farmland carbon emissions of 5276000 tons and 3812000 tons in 2021, ranking first and second

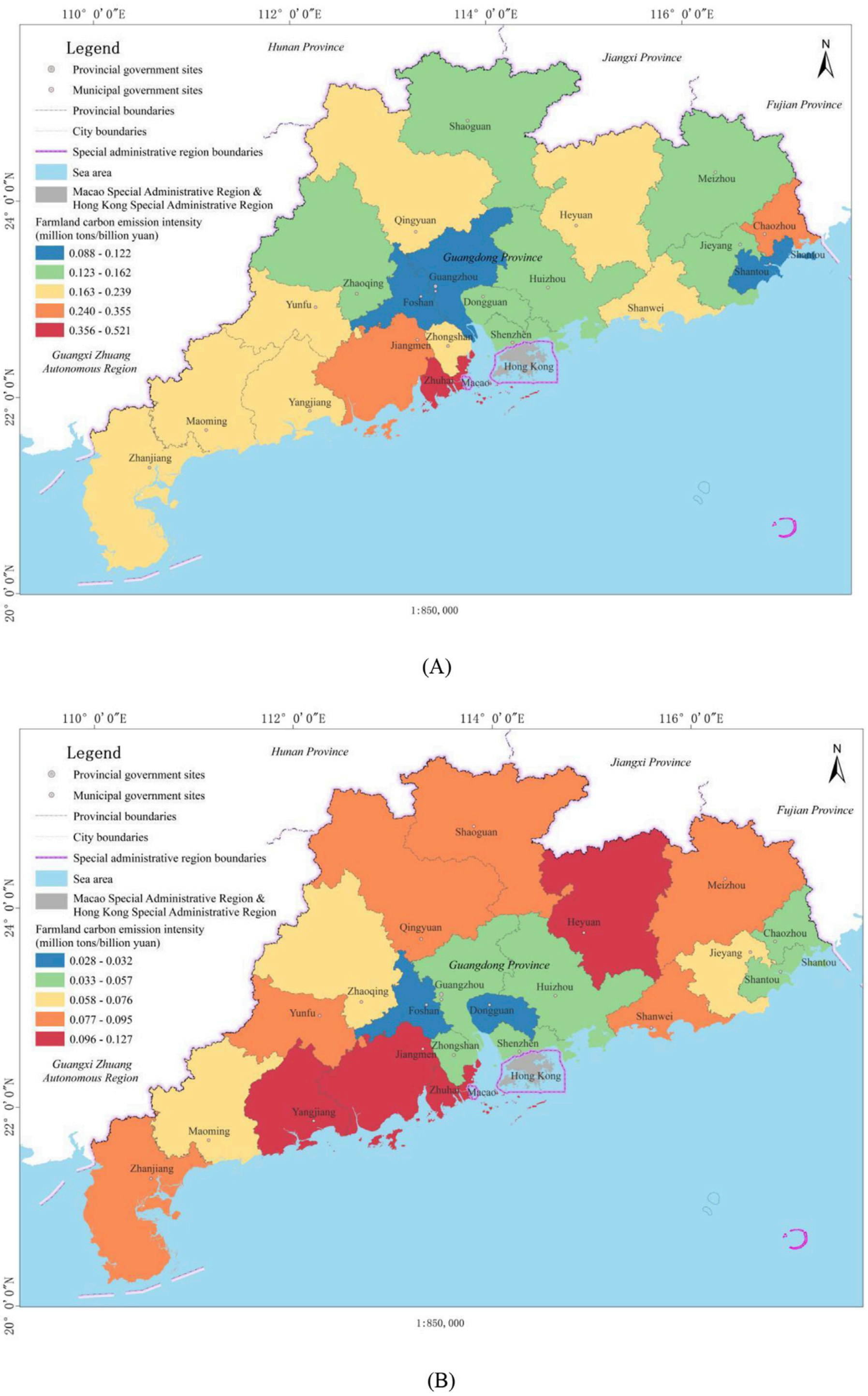

FIGURE 4
Spatial distribution of farmland carbon emission intensities in Guangdong by city: **(A)** 2011; **(B)** 2021.

in the province, far exceeding Qingyuan in third place, with 228,400 tons. Both Zhanjiang and Maoming are located in the transitional zone between tropical and subtropical regions, featuring high temperatures, abundant moisture, ample sunlight, and significant rainfall. They also have large areas of land suitable for agricultural development. By 2021, the farmland area in Zhanjiang and Maoming reached 413,600 ha and 166,100 ha, respectively, ranking first and third in Guangdong. According to the *Main Data Bulletin of the Third National Land Survey in Guangdong Province*, the proportion of farmland on slopes of 2° or less accounts for 82.99% and 73.33% of the total farmland in Zhanjiang and Maoming, respectively. The rich red soil, abundant in trace elements, makes these areas ideal for agricultural development, supporting a variety of crops with high yields. The favorable

TABLE 4 Decoupling characteristics of farmland carbon emissions from in Guangdong by city.

Regions	2011–2017		2017–2021		2011–2021	
	Coefficient	Decoupling state	Coefficient	Decoupling state	Coefficient	Decoupling state
Guangzhou	−0.574	SD	−0.014	SD	−0.240	SD
Shenzhen	0.727	WD	−2.005	SD	0.075	WD
Zhuhai	−5.176	SD	−0.343	SD	−1.182	SD
Shantou	0.087	WD	−0.692	SD	−0.196	SD
Foshan	−2.493	SD	−0.078	SD	−0.467	SD
Shaoguan	−0.292	SD	−0.267	SD	−0.237	SD
Heyuan	1.186	EC	−0.105	SD	0.407	WD
Meizhou	0.001	WD	−0.162	SD	−0.058	SD
Huizhou	−0.041	SD	−0.231	SD	−0.095	SD
Shanwei	0.004	WD	−0.315	SD	−0.138	SD
Dongguan	−0.640	SD	−0.230	SD	−0.328	SD
Zhongshan	4.708	RD	−0.144	SD	−0.833	SD
Jiangmen	0.032	WD	−0.052	SD	−0.004	SD
Yangjiang	−1.416	SD	−0.354	SD	−0.557	SD
Zhanjiang	0.120	WD	−0.295	SD	−0.053	SD
Maoming	0.091	WD	−0.385	SD	−0.077	SD
Zhaoqing	0.050	WD	−0.421	SD	−0.138	SD
Qingyuan	−0.182	SD	−0.226	SD	−0.156	SD
Chaozhou	−0.314	SD	−0.247	SD	−0.172	SD
Jieyang	−0.722	SD	−0.061	SD	−0.270	SD
Yunfu	−2.012	SD	−0.304	SD	−0.631	SD

SD, strong decoupling; WD, weak decoupling; EC, expansive coupling; RD, recession decoupling.

natural conditions, combined with large-scale agriculture and significantly higher material inputs compared to other regions, result in the highest farmland carbon emissions in the province. Over the 11 years period, Foshan and Yunfu achieved better emission reduction effects than the provincial average, with their total emissions decreasing by one level. As the only city with a significant increase in farmland carbon emissions, Heyuan's emissions rose from sub-low to the medium level in Guangdong.

Figure 4 shows that, although the intensity of farmland carbon emissions in various cities of Guangdong has decreased, the spatial pattern of the intensity has changed significantly. According to the intensity levels classified using the natural breaks method, in 2011, most cities had low to medium levels of farmland carbon emission intensity, with Guangzhou, Foshan, and Shantou having the lowest intensity. In contrast, Zhuhai, Chaozhou, and Jiangmen exhibited significantly higher intensity levels compared to other cities. There were notable regional variations in spatial characteristics. The Pearl River Delta and eastern Guangdong displayed substantial internal differentiation, encompassing all five intensity levels, while the western region exhibited spatial consistency with a medium level of farmland carbon emission intensity. From 2011 to 2021, the number of cities with low and sub-low levels of farmland carbon emission intensity has decreased, now primarily limited to parts of the Pearl River Delta and the Chaoshan region. Jiangmen has become the city with the highest intensity of farmland carbon emissions in Guangdong and, along with Yangjiang and Zhuhai, has formed a high-intensity cluster of farmland carbon emissions along the western coast of the Pearl River Delta.

3.1.2.2 Decoupling characteristics of farmland carbon emissions

Based on the decoupling model, the decoupling characteristics of farmland carbon emissions in various cities of Guangdong were calculated for two periods: 2011-2017 and 2017-2021 (Table 4). From 2011 to 2017, among the 21 prefecture-level cities in Guangdong, 11 cities exhibited strong decoupling, eight cities exhibited aweak decoupling, one city showed expansive coupling, and one city showed recessive decoupling. The 11 cities with strong decoupling, represented by Guangzhou, saw a reduction in farmland carbon emissions while agricultural output value increased, reflecting the most ideal state. The eight cities with weak decoupling, represented by Shenzhen, experienced an increase in farmland carbon emissions, but the growth rate of agricultural output value outpaced the increase in emissions, making it a

FIGURE 5
Influencing factors on farmland carbon emissions in Guangdong by city: **(A)** 2011-2017; **(B)** 2017-2021.

relatively favorable state. The decoupling characteristics of Heyuan and Zhongshan were more unique. Heyuan's expansive coupling state suggests that the growth in agricultural output value is proportional to the increase in farmland carbon emissions, while Zhongshan's recessive decoupling state indicates that both agricultural output value and farmland carbon emissions have decreased, with the latter declining at a faster rate. Among the 21 cities, Zhuhai exhibited the highest degree of decoupling, with a decoupling coefficient of −5.176, while Zhongshan exhibited the lowest degree of decoupling, with an elasticity coefficient of 4.708.

From 2017 to 2021, the decoupling characteristics in various cities of Guangdong remained stable, with all 21 cities exhibiting a strong decoupling state. This indicates that the output value of crop production based on farmland maintained positive growth, while farmland carbon emissions showed a downward trend. The strong decoupling state between farmland carbon emissions and economic growth in Guangdong suggests that low-carbon policies have been highly effective in reducing farmland carbon emissions. This marks the gradual decoupling of overall farmland carbon emissions and agricultural economic development in Guangdong, indicating that the conditions for achieving carbon peak at the level of farmland crop production have basically been met. Shenzhen, which transitioned from a weak decoupling state in the previous period, achieved the highest degree of decoupling with a coefficient of −2.005.

Throughout the entire research period, only Heyuan and Shenzhen exhibited a weak decoupling state, while all other cities showed a strong decoupling state. Zhuhai had the highest degree of decoupling, with a coefficient of −1.181, while Heyuan had the lowest degree, with a coefficient of 0.407. Compared to other cities in Guangdong, Heyuan lagged behind in reducing farmland carbon emissions, indicating significant potential for further emission reduction.

3.2 Influencing factors of farmland carbon emissions in Guangdong

Using the influencing factor decomposition model of carbon emission, the factors affecting farmland carbon emissions in various cities of Guangdong were analyzed for two periods: 2011-2017 and 2017-2021 (Figure 5). Over the 11 years, agricultural production efficiency has consistently been the primary driver of farmland carbon emission reductions in Guangdong. From 2011 to 2017, the cumulative carbon emission reduction due to agricultural production efficiency reached 1.34 million tons, with an average annual reduction of approximately 191,368.72 tons, accounting for 48.77% of the total reduction. In all cities except Shenzhen, Heyuan, Jiangmen, Yangjiang, Zhanjiang, Zhaoqing, and Yunfu, improvements in production efficiency were the main drivers of carbon emission reductions. Only Heyuan experienced an increase in farmland carbon emissions due to a decline in production efficiency. From 2017 to 2021, the cumulative carbon emission reduction due to agricultural production efficiency reached 1.32 million tons, with an average annual reduction of approximately 263,539.48 tons, accounting for 59.58% of the total reduction. Except for Shenzhen and Dongguan, agricultural production efficiency contributed the most to carbon emission reductions in the other cities. This indicates that improvements in agricultural production efficiency have significantly curbed the growth of farmland carbon emissions in Guangdong. Therefore, further enhancing agricultural production efficiency will be a key strategy to promote low-carbon farming in Guangdong. In cities like Chaozhou, Zhongshan, Foshan, and Jieyang, the contribution rate of agricultural production efficiency to carbon emission reductions exceeded 95%, with Chaozhou nearly reaching 100%. While the high contribution rate of agricultural production efficiency in these cities is notable, it also highlights the insufficient contribution of structural, economic, and labor factors to the overall carbon emission reduction.

Agricultural production structure is one of the factors contributing to the reduction of farmland carbon emissions in Guangdong, though its impact is not significant. From 2011 to 2017, the agricultural production structure factor resulted in aan increase of 71,268.41 tons in carbon emissions, with an average annual increase of approximately 10,181.20 tons. Among the 21 cities, nine cities saw a reduction in carbon emission due to changes in agricultural production structure. From 2017 to 2021, the cumulative carbon emission reduction effect of the agricultural production structure factor was only 78,825.12 tons, with an average annual reduction of about 15,765.02 tons. The carbon emission reduction effect of the agricultural production structure increased to 12 cities, indicating that, from the perspective of carbon emission reduction, the agricultural production structure in more cities began to trend towards rationality. Overall, the impact of the agricultural production structure on carbon emissions reduction in Guangdong remains limited, with a low contribution rate to either carbon emission increase or reduction. This suggests that the agricultural production structure is not a primary driver of carbon emissions reductions in most cities. By 2021, only Zhuhai, Zhongshan, and Foshan had experienced a significant increase in carbon emissions due to adjustments in their agricultural production structures.

The level of agricultural output is the primary driver of the increase in farmland carbon emissions in Guangdong and is the only factor among the four that results in an overall rise in carbon emissions. From 2011 to 2017, the cumulative carbon emission increase due to the agricultural output level was 1.50 million tons, with an average annual increase of approximately 214,164.65 tons. From 2017 to 2021, this cumulative increase amounted to 1.45 million tons, with an average annual increase of around 289,813.71 tons. Over the 11 years, the average annual increase in carbon emissions from agricultural output grew, and the number of cities experiencing this increase rose from 16 to all 21, with the contribution rate in most cities increase approaching nearly 100%. The increase in agricultural output level is largely driven by the chemicalization and mechanization of agricultural, relying heavily on the extensive use of high-carbon inputs such as chemical fertilizers, agricultural films, pesticides, and diesel. Consequently, the agricultural output level remains the primary cause of high farmland carbon emissions. Guided by green agricultural development, all regions should prioritize addressing the carbon emission effects of agricultural output levels. In light of the slight increase in emissions from agricultural output levels in recent years, efforts should be focused on maximizing the efficiency of farmland carbon emission reduction.

The scale of agricultural labor force is an important driving factor for the reduction of farmland carbon emissions in Guangdong. From 2011 to 2017, the cumulative carbon emission reduction due to the agricultural labor force scale factor was 380,746.01 tons, with an average annual reduction of approximately 54,392.29 tons. From 2017 to 2021, the cumulative reduction effect was 371,971.17 tons, with an average annual reduction of about 74,394.23 tons. At the prefecture level, the number of cities with increased carbon emissions decreased from five to 4, with only Shaoguan, Chaozhou, Jieyang, and Yunfu experiencing an increase in emissions due to the agricultural labor force scale. Over the 5 years, there was a synchronous decline in both the agricultural workforce and farmland carbon emissions in Guangdong. This indicates that, with the development of agricultural mechanization and modernization, Guangdong is increasingly moving away from the influence of small-scale and household farming, resulting in a reduced dependence of farmland on labor.

4 Discussion

4.1 Policy implications

Based on the research findings of this paper and the current status of farmland carbon emission reduction in Guangdong, we propose the following policy implications for the carbon sequestration and emission reduction in farmland in Guangdong.

4.1.1 Form a regional differentiated governance mode

The differences in geographical location, economic development levels, and functional orientations cross various regions in Guangdong create distinct requirements for carbon sequestration and emission reduction in farmland systems. As a result, enhancing the carbon sequestration and emission reduction capabilities of the farmland cannot be approached with a one-size-fits-all solution. Instead, a regionally differentiated strategy should be developed for farmland carbon sequestration and emission reduction. This study indicates that the factors influencing farmland carbon emissions in certain cities in Guangdong exhibit a high degree of similarity. For cities where farmland carbon emissions are driven by similar mechanisms, differentiated governance modes can be adopted within the Pearl River Delta, as well as in the eastern, western, and northern regions of Guangdong, or even at smaller administrative scales. Macro policies should be designed from multiple perspectives, including efficiency, structure, economy, and labor force, to align with the specific needs of each region's economic development, resource endowment, and ecological environment.

4.1.2 Improve agricultural production efficiency

This study demonstrates that agricultural production efficiency is the primary driver for reducing cultivated land carbon emissions in Guangdong Province. Compared to methods from the Green Revolution, such as increasing the use of fertilizers and pesticides, enhancing irrigation and management, and employing agricultural machinery, Guangdong Province should prioritize the development of resource-efficient and environmentally friendly agricultural practices, including circular agriculture, ecological agriculture, and intensive farming. Through the development of resource-efficient and environmentally friendly agriculture in Guangdong Province, the efficiency of agricultural resource utilization can be improved, the consumption of agricultural production factors can be reduced, and the long-term stability and risk-resilience of the agricultural system can be strengthened. Therefore, technologies such as precision agriculture should be promoted to ensure efficient resource utilization. For example, remote sensing technology can accurately monitor and assess crop growth, optimizing the quantity and spatial distribution of agrochemical usage. Furthermore, the development of intelligent agricultural machinery, leveraging GPS and drone technologies, can enable precise fertilization and efficient pesticide application, ensuring accurate input of production factors. Additionally, irrigation techniques such as sprinkler and drip irrigation should be widely adopted. Combined with sensor technology and data analysis, irrigation volume and timing can be optimized.

4.1.3 Optimize the structure and layout of agricultural production

This study reveals significant potential for reducing farmland carbon emissions in Guangdong Province by adjusting agricultural production structures. Therefore, diversified cultivation of grains, economic crops, and feed crops can be promoted within Guangdong Province, along with the implementation of water-dryland crop rotation, to reduce greenhouse gas emissions caused by prolonged rice planting. The planting structure and density of grain and economic crops should be scientifically optimized to effectively enhance the overall ecological capacity of the region and improve the carbon sequestration efficiency of agricultural production systems. The cultivation of low-carbon crops, such as low-emission rice varieties and Guangdong-specific crops, should be actively encouraged to balance food production and ecological goals as effectively as possible. Additionally, agricultural functional zones should be planned according to local conditions. For instance, priority should be given to establishing grain production zones in western Guangdong to cultivate high-yield, low-carbon staple crops, and develop large-scale and intensive agricultural production, ensuring food security and relatively lower agricultural carbon emissions. In the Pearl River Delta, efforts should focus on developing modern agriculture, facility-based farming, and the cultivation of high-efficiency economic crops. In the mountainous regions of eastern and northern Guangdong, emphasis should be placed on forestry-fruit economies and ecological agriculture, particularly the cultivation of high-carbon-sequestration fruit trees and tea tree, to maximize the economic benefits per unit of land.

4.1.4 Strengthen farmland conservation and management

Promote conservation tillage and cover crop cultivation through reduced-tillage/no-tillage practices, permanent soil cover, diversified cropping systems, and integrated nutrient management systems to decrease carbon emissions from soil tillage and enhance cropland carbon sequestration capacity. Promote the construction of well-facilitated farmland in various regions. By consolidating fragmented farmland and developing supporting facilities, achieve economies of scale in mechanized agricultural production, significantly improving the resource utilization efficiency of fertilizers, pesticides, and irrigation water, reducing farmland carbon emissions due to irrigation, tillage, and agricultural machinery. By increasing the organic matter content of cultivated soil, enhance soil fertility and strengthen the carbon sequestration capacity of farmland.

Promote the adoption of green manure crops to improve soil quality and reduce the reliance on chemical fertilizers.

4.1.5 Plan for a carbon trading market that coordinates adaptation for carbon emission reduction and sink enhancement in farmland

Given the significant disparities in funds, technology, land resources, and other factors between the Pearl River Delta and the eastern, western, and northern regions of Guangdong, as well as the distinction between major grain-producing areas and major grain-consuming areas, establishing a provincial agricultural carbon trading platform presents a feasible strategy. Enterprises, factories, and even cities could offset the carbon emissions generated by their production and operation activities by purchasing carbon sink products from areas with high ecological capacity. Funds from high-carbon source areas can be used to compensate for the ecology of high-carbon sink areas. By offering integrated services such as measurement, trading, registration, and supervision, the conversion of agricultural production into carbon trading products can be facilitated, effectively alleviating the regional carbon imbalances within the province.

4.2 Discoveries and innovations

This paper employs multidisciplinary approaches to investigate the spatial-temporal characteristics and influencing factors of farmland carbon emissions in Guangdong Province. It identifies the weaknesses in the province's farmland carbon emission reduction efforts. From the perspective of carbon sources, it is found that the production material inputs, such as chemical fertilizers and pesticides, are the main sources of carbon emissions. From the perspective of carbon emission measurement, it reveals that Zhanjiang and Maoming in western Guangdong are the areas with the highest farmland carbon emissions in Guangdong. From the perspective of decoupling characteristics, it shows that the decoupling status between farmland carbon emissions and economic growth is relatively weak in Heyuan and Shenzhen. The paper also clarifies the main driving factors affecting the farmland carbon emissions in Guangdong and provides policy recommendations for carbon sequestration and emission reduction in the farmland.

This study introduces multidisciplinary research methods in the field of farmland carbon emission research, fills the gap in multi-scale study on farmland carbon emissions in Guangdong, and enriches the knowledge system. The findings of this study are generally consistent with those of Liu and Gao (2022), Zhou (2022) and Ding et al. (2022), regarding the agricultural carbon emissions in various provinces and regions of China. Focusing on Guangdong Province, this study slightly differs from Ren et al. (2023)'s study in terms of the proportion of carbon emissions from various carbon sources. Ren et al. (2023) argue that the carbon emissions from late rice cultivation have the highest proportion. However, this study finds that the carbon emissions from production material inputs are much higher than those from crop growth, with the proportion of carbon emissions from chemical fertilizers, pesticides, irrigation, and agricultural films far exceeding that from rice. This discrepancy may be related to the selection of carbon conversion coefficients for CH_4 and N_2O.

5 Conclusion

This paper measures the farmland carbon emissions in Guangdong from 2011 to 2021 using the classical IPCC carbon emission calculation theory, explores the decoupling characteristics between farmland carbon emissions from agricultural outputs through the decoupling model, and analyzes the influencing factors based on LMDI method. The conclusions are as follows.

(1) From 2011 to 2021, the total farmland carbon emissions in Guangdong first increased and then decreased, with 2016 marking the peak year at 3.71 million tons. The average annual reduction rate of farmland carbon emissions across the province was approximately 1.41%. The primary source of farmland carbon emissions in Guangdong was production material inputs, accounting for approximately 97.27% of the total emissions. Among these, pesticides and chemical fertilizers had the most significant reduction effects.
(2) The spatial distribution of farmland carbon emissions in Guangdong followed a pattern of "Western Guangdong > Northern Guangdong > Eastern Guangdong > Pearl River Delta". While the intensity of farmland carbon emissions in all cities showed a decreasing trend, the range of cities with low emission intensity has contracted, now mainly limited to parts of the Pearl River Delta and Chaozhou-Shantou area. Jiangmen, Yangjiang, and Zhuhai have formed high-intensity clusters of farmland carbon emissions along the coast to the west of the Pearl River Delta.
(3) From 2011 to 2021, most cities in Guangdong exhibited a strong decoupling state between farmland carbon emissions and economic growth. This suggests that farmland carbon emissions in Guangdong have gradually decoupled from agricultural economic development, and conditions for reaching the carbon peak at the level of farmland planting industry have essentially been met.
(4) Overall, the increase in the level of agricultural output has contributed to higher farmland carbon emissions in Guangdong, while improvements in agricultural production efficiency have played the most significant role in reducing these emissions.

This study has yielded valuable insights into the quantitative study of farmland carbon emissions in Guangdong, but there are still several limitations. First, the carbon emission coefficients used in this study are primarily sourced from existing results conducted by various institutions in different regions, which may not fully capture the regional characteristics and variations of farmland carbon sources in Guangdong. Additionally, due to data availability issues, factors such as straw and organic fertilizers were not included in the carbon sources. Second, the study covers a period of only 11 years, making it challenging to provide high-precision predictions for farmland carbon emissions over the next decade or longer. Therefore, future research should focus on enriching the farmland carbon sources, obtaining localized carbon emission coefficients, extending the research period, considering the impact of policy implementation, and developing accurate predictive models for farmland carbon emissions based on these improvements.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZC: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. ZZ: Conceptualization, Funding acquisition, Project administration, Resources, Writing–review and editing. YL: Conceptualization, Data curation, Supervision, Validation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

Adewale, C., Reganold, J. P., Higgins, S., Evans, R. D., and Carpenter-Boggs, L. (2019). Agricultural carbon footprint is farm specific: case study of two organic farms. *J. Clean. Prod.* 229, 795–805. doi:10.1016/j.jclepro.2019.04.253

Al-Mansour, F., and Jejcic, V. (2017). A model calculation of the carbon footprint of agricultural products: thecase of Slovenia. *Energy* 136, 7–15. doi:10.1016/j.energy.2016.10.099

Ang, B. W. (2005). The LMDI approach to decomposition analysis: a practical guide. *Energy Policy* 33, 867–871. doi:10.1016/j.enpol.2003.10.010

Bai, J., Liu, J., Ma, L., and Zhang, W. (2023). The impact of farmland management scale on carbon emissions. *Land* 12, 1760. doi:10.3390/land12091760

Chen, Q., Mao, Y., and Cheng, J. (2023). Temporal and spatial evolution of agricultural carbon emissions and their impact on functional zoning: evidence from Hubei Province. *Front. Sustain. Food Syst.* 7, 1286567. doi:10.3389/fsufs.2023.1286567

Crutzen, P. J., Aselmann, I., and Seiler, W. (1986). Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans. *Tellus B* 38B (3-4), 271–284. doi:10.3402/tellusb.v38i3-4.15135

Deng, R. R., Xiao, X. T., and Liu, F. F. (2023). Agricultural carbon emissions in major grain-producing areas of China from the perspectives of fairness and efficiency. *World Surv. Res.* (6), 14–25. doi:10.13778/j.cnki.11-3705/c.2023.06.002

Ding, B. G., Zhao, Y., and Deng, J. H. (2022). Calculation, decoupling effects and driving factors of carbon emission from planting industry in China. *Chin. J. Agric. Resour. Reg. Plan.* 43, 1–11. doi:10.7621/cjarrp.1005-9121.20220501

Duan, H. P., Zhang, Y., Zhao, J. B., and Bian, X. M. (2011). Carbon footprint analysis of farmland ecosystem in China. *J. Soil Water Conserv.* 25, 203–208. doi:10.13870/j.cnki.stbcxb.2011.05.020

Eggleston, S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. Hayama, Japan: Institute for Global Environmental Strategies (IGES) for the IPCC.

Guangdong Provincial Conditions Website (2024). Guangdong province gazetteer: volume on resources and environment. Available at: https://dfz.gd.gov.cn/dfz/html/gdsqsj/sxnj/pc/page1.shtml#/?id=69dcef909a4b49b3a86fc6729aa4f764 (Accessed May 20, 2024).

Hao, X. Y. (2021). Changes of carbon source/sink intensity and carbon footprint of farmland ecosystem in Heilongjiang Province. *Heilongjiang Agric.Sci.* 8, 97–104. doi:10.11942/j.issnl002-2767.2021.08.0097

Hao, X. Y. (2022). Spatiotemporal variation of carbon source/sink in agricultural ecosystem based on carbon footprint in Heilongjiang land reclamation areas. *Chin. J. Agric. Resour. Regional Plan.* 43, 64–73. doi:10.7621/cjarrp.1005-9121.20220807

He, Y. Q., Wang, H. C., and Liu, Y. Q. (2022). Spatial effects of agricultural carbon emissions from the perspective of industrial agglomeration. *Resour. Sci.* 44 (12), 2428–2439. doi:10.18402/resci.2022.12.04

Hu, W. L., Zhang, J. X., and Wang, H. L. (2020). Characteristics and influencing factors of agricultural carbon emission in China. *Stat. Decis.* 36 (05), 56–62. doi:10.13546/j.cnki.tjyjc.2020.05.012

Johnson, M. F., Franzluebbers, A. J., Weyers, S. L., and Reicosky, D. C. (2007). Agricultural opportunities to mitigate greenhouse gas emissions. *Environ. Pollut.* 150, 107–124. doi:10.1016/j.envpol.2007.06.030

Kaya, Y. (1989). *Impact of carbon dioxide emission on GNP growth: interpretation of proposed scenarios*. Paris: Presentation to the Energy and Industry Subgroup, Response Strategies Working Group, IPCC.

Lesschen, J. P., van den Berg, M., Westhoek, H. J., Witzke, H. J., and Oenema, O. (2011). Greenhouse gas emission on profiles of European livestock sectors. *Anim. Feed. Sci. Tech.* 166, 16–28. doi:10.1016/j.anifeedsci.2011.04.058

Li, B., Zhang, J. B., and Li, H. P. (2011). Research on spatial-temporal characteristics and affecting factors decomposition of agricultural carbon emission in China. *China Popul. Resour. Environ.* 21(8), 80–86. doi:10.3969/j.issn.1002-2104.2011.08.013

Li, C. L., and Zhou, H. (2020). Relationship between agricultural technology progress and carbon emission intensity: an empirical analysis under different influence paths. *J. China Agri. Univ.* 25 (11), 162–171. doi:10.11841/j.issn.1007-4333.2020.11.17

Li, J., Li, S., Liu, Q., and Ding, J. (2022). Agricultural carbon emission efficiency evaluation and influencing factors in Zhejiang province, China. *China. Front. Environ. Sci.* 10, 1005251. doi:10.3389/fenvs.2022.1005251

Liu, Y., and Liu, H. B. (2022). Characteristics, influence factors, and prediction of agricultural carbon emissions in Shandong Province. *Chin. J. Eco-Agric.* 30, 558–569. doi:10.12357/cjea.20210582

Liu, Y. Q., and Gao, Y. (2022). Measurement and impactor analysis of agricultural carbon emission performance in Changjiang economic corridor. *Alex. Eng. J.* 61, 873–881. doi:10.1016/j.aej.2021.04.083

Min, J. S., and Hu, H. (2012). Calculation of greenhouse gases emission from agricultural production in China. *Chin. J. Popul. Resour.* 22 (7), 21–27. doi:10.3969/j.issn.1002-2104.2012.07.004

Ning, J., Wang, Z., Du, G. M., and Li, Y. J. (2023). Analysis of decoupling between agricultural carbon emission characteristics and agricultural economy in Northeast China. *Econ. Geogr.* 43 (11), 173–180. doi:10.15957/j.cnki.jjdl.2023.11.018

Peng, C., Jia, J. S., Yu, Q. X., and Zhu, C. M. (2024). Analysis of Spatio-temporal evolution and influencing factors of agricultural carbon emission in China. *Res. Environ. Sci.* 37 (6), 1181–1192. doi:10.13198/j.issn.1001-6929.2024.04.18

Ren, H. J., Li, H. S., and Feng, Y. Y. (2023). Study on the dynamic evolution characteristics and development trend of agricultural carbon emissions in Guangdong Province based on spatial and temporal perspective. *Chin. J. Eco-Agric.* 31, 1287–1300. doi:10.12357/cjea.20230168

Su, L. J., Wang, Y. T., and Yu, F. F. (2023). Analysis of regional differences and spatial spillover effects of agricultural carbon emissions in China. *Heliyon* 9, e16752. doi:10.1016/j.heliyon.2023.e16752

Sun, Y. (2018). *Spatial and temporal characteristics of agricultural carbon emission and its influencing factors in Shandong Province. master's thesis.* Lanzhou: Lanzhou University.

Tapio, P. (2005). Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. *Transp. Policy* 12, 137–151. doi:10.1016/j.tranpol.2005.01.001

Tong, W. W., Li, Y. L., and Zhang, D. M. (2024). Study on the influence of agriculture servitization on China's agricultural carbon emissions intensity. *Chin. J. Agric. Resour. Regional Plan.* 45 (06), 23–36. doi:10.7621/cjarrp.1005-9121.20240603

Tubiello, F. N. (2019). "Greenhouse gas emissions due to agriculture," in *Encyclopedia of food security and sustainability*. Editors P. Ferranti, E. M. Berry, and J. R. Anderson (Amsterdam, NLD: Elsevier), 196–205.

Vehmas, J., Malaska, P., Luukkanen, J., Kaivo-oja, J., Hietanen, O., Vinnari, M., et al. (2003). *Europe in the global battle of sustainability: rebound strikes back? advanced Sustainability Analysis*. Turku, Finland: Series discussion and working papers 7, publications of the turku school of economics and business administration.

Wang, B. (2023). The impact of the digital economy on China's carbon emissions from the perspective of global value chains. *Resour. Sci.* 45 (9), 1899–1911. doi:10.18402/resci.2023.09.15

West, T. O., and Marland, G. (2002). A synthesis of carbon sequestration, carbon emissions, and netcarbon flux in agriculture:comparing tillage practices in the United States. *Agr Ecosyst. Environ.* 91, 217–232. doi:10.1016/s0167-8809(01)00233-x

Wu, G. Y., Sun, X. J., Yu, F. B., and Yang, Y. S. (2020). Spatial correlation pattern and influencing factors of China's crop production carbon productivity. *Chin. J. Popul. Resour.* 30 (5), 46–57. doi:10.12062/cpre.20200106

Xia, S. Y., Zhao, Y., Xu, X., Wen, Q., Song, Y. Y., and Cui, P. P. (2019). Spatiotemporal dynamics and driving factor analysis of agricultural carbon emissions rate in China from 1997 to 2016. *Acta Ecol. Sin.* 39 (21), 7854–7865. doi:10.5846/stxb201806041258

Xu, Y., Wang, H., and Han, Q. F. (2023). Regional differences and equity of cultivated land carbon budget at county scale: taking Jiangsu province as an example. *J.Agric.Univ.Hebei Soc. Sci.* 25, 62–73. doi:10.13320./j.cnki.jauhe.2023.0007

Zeng, X. G., Yu, C., and Sun, Y. Q. (2023). Carbon emission structure and carbon peak of agriculture and rural areas in China. *China Environ. Sci.* 43 (4), 1906–1918. doi:10.19674/j.cnki.issn1000-6923.20221207.006

Zhang, G. S., and Wang, S. S. (2014). Structure, efficiency and deterministic mechanism of agricultural carbon emissions in China. *Issues Agric. Econ.* 35 (7), 18–26. doi:10.13246/j.cnki.iae.2014.07.003

Zhang, J. B., and He, K. (2022). Current Situation,Misunderstandings and prospects of agricultural low-carbon development under the targets of carbon peak and carbon neutrality. *Issues Agric. Econ.* 09, 35–46. doi:10.13246/j.cnki.iae.20220914.001

Zhao, S., Chen, R., and Jiang, Z. D. (2018). Empirical analysis of the low-carbon pilot policies' impact on agricultural carbon emissions based on DID model. *Ecol. Econ.* 34 (12), 22–28.

Zhou, Y. F. (2022). *Spatiotemporal evolution and spatial effects of agricultural carbon emissions in Hebei province at the county scale. master's thesis. Baoding*. Badoding (Hebei): Hebei Agricultural University.