TEMPORAL-SPATIAL EVOLUTION AND INFLUENCING FACTORS OF AGRICULTURAL CARBON EMISSIONS IN ANHUI PROVINCE, CHINA

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Abstract. Agricultural carbon emissions are crucial for achieving carbon peaking and carbon neutrality in China. Based on the emission factor method, ecological pressure coefficient and grey correlation model, the temporal and spatial evolution of agricultural carbon emissions in Anhui province and their influencing factors are explored. The following results are obtained: From 2001 to 2022, the agricultural carbon emissions in Anhui province showed a trend of decreasing - increasing - declining- increasing, especially from 2001 to 2007, with an average annual decline of 4.58%. The agricultural carbon emission intensity showed a trend of fluctuating decline; the agricultural carbon absorption was also increasing year by year. The total agricultural carbon emissions in Anhui province basically decreased from north to south, and the carbon emission intensity of traditional agricultural areas was higher than that of areas with good industrial base. The spatial distribution of ecological pressure coefficients of carbon emissions was basically consistent with the distribution trend of total carbon emissions, and the pressure coefficients were between 0.7 and 1.8. Grey correlation analysis showed that the core affecting factors of agricultural carbon emissions were agricultural industrial structure, agricultural production scale, scientific and technological factors, economic development and agricultural employees.
Keywords: *carbon emission, spatio-temporal characteristics, driving factors, grey correlation analysis, Anhui Province*

Introduction

Global warming caused by greenhouse gas emissions poses a serious threat to human survival and development. Carbon emissions have become a crucial concern for most countries worldwide, with energy conservation and emission reduction being prioritized in their environmental protection. China has surpassed the United States to become the world’s largest carbon emitter, which requires a daunting task of reducing emissions (Tian and Lin, 2021). In September 2020, during the general debate of the 75th session of the United Nations General Assembly, the Chinese President solemnly pledged that China will strive to achieve peak carbon dioxide emissions before 2030 and carbon neutrality before 2060. In addition, the “14th Five-Year Plan” for National Economic and Social Development in 2021 clearly proposed to formulate a plan to achieve peak carbon emissions before 2030. However, agricultural production ranks as the second-largest source of carbon emissions globally, followed by the industry. According to the statistics from the Food and Agriculture Organization of the United Nations (FAO), global agricultural production and land utilization account for about 30% of the total greenhouse gas emissions, equivalent to producing 15 billion tons of carbon dioxide annually (Li et al., 2023a). The agricultural sector accounts for about 14% of anthropogenic greenhouse gas emissions and 58% of global non-anthropogenic CO_2 emissions (Lang et al., 2019). In China, the agricultural carbon emissions account for

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17% of the total greenhouse gas carbon emissions, with an annual average growth rate of 5% (Huang and Sun, 2022; Liu and Liu, 2022). In the course of promoting the transformation of agricultural development, it is necessary to mitigate carbon emissions while maintaining steady progress in the agricultural economy and keeping pace with industrial emission reductions. It is evident that in China, agricultural carbon emissions are the core issue of carbon emissions. In recent years, the “No. 1 Document” released by the CPC Central Committee has repeatedly stressed the importance of achieving high-quality agricultural development and pursuing green and ecological development, which is consistent with our advocacy for a low-carbon transformation path in agricultural production.

In recent years, the study of agricultural carbon emissions is largely focused. These studies mainly encompass four key areas: the measurement of agricultural carbon emissions (Liu and Liu, 2022; Shang et al., 2022), the analysis of the impact of agricultural science and technology as well as driving factors of agricultural carbon emissions (Tian and Wang, 2020; Ali et al., 2022), the interaction between agricultural carbon emissions and economic growth (Tian and Lin, 2021; Xia et al., 2023), and the spatiotemporal characteristics of agricultural carbon emissions (Wen et al., 2022). The calculation of agricultural carbon emissions mainly includes planting, animal husbandry, soil respiration and decomposition, and artificial agricultural inputs. During the planting and production process, there are six major sources of carbon emissions: fertilizers, pesticides, agricultural films, diesel fuel usage, ploughing activities, and agricultural irrigation. For example, Chen et al. (2023) measured agricultural carbon emissions and their impact on functional areas in Hubei. Liu et al. (2022) analyzed the evolution and trend of agricultural carbon emission intensity and agricultural economic development taking Jiangxi Province as an example. The No.1 Central document of 2022 emphasized the importance of agricultural technology in promoting energy conservation and emission reduction. The document emphasizes the need to develop and implement carbon-reducing and sink-enhancing agricultural technologies at the strategic planning. Yan et al. (2023) analyzed the impact of agricultural technical efficiency on agricultural carbon emissions, considering spatial spillover effects and threshold effects. Han and Zhong (2023) conducted a case study on the three major grain functional zones in China to examine the influence of agricultural scientific and technological innovation on carbon emissions in food production. Due to regional differences in natural and socio-economic factors, there is significant spatial correlation and heterogeneity in agricultural carbon emissions. The study covers a range of regional scales such as national, provincial, and county levels. Gan et al. (2023) examined the spatial correlation characteristics of agricultural carbon emissions in China using the stochastic environmental impact assessment model (STIRPAT), constructing five weight matrices that included economic and geographical factors. Tian and Chen (2021) quantified the carbon emissions of inter-provincial agriculture and evaluated their low-carbon level based on derived indices and the TOPSIS method. Wang et al. (2023) studied the spatiotemporal characteristics of agricultural carbon emissions in Shanxi province from 2000 to 2020. Zhou et al. (2022) examined the spatiotemporal evolution and influencing factors of agricultural carbon emissions in counties of Hebei province.

Anhui province is a prominent agricultural province and an important agricultural production base in China. Its cultivated land area accounts for 4.3% of the total national

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cultivated land, ranking the eighth. The rapid development of agriculture and the advancement of agricultural modernization have led to a continuous increase in the input of fertilizers, pesticides, and other materials. As a result, the problem of agricultural environmental pollution is becoming increasingly prominent, leading to a large amount of greenhouse gas emissions and seriously hindering the achievement of carbon peak goals. Reasonably and accurately estimating the agricultural carbon emissions in Anhui province is of great significance for formulating effective emission reduction measures, as well as providing a basis for evaluating the effectiveness of these measures and achieving the peak of agricultural carbon reduction. However, there are few reports on measuring and studying the influencing factors agricultural carbon emissions in Anhui province and studying the agricultural carbon emissions in Anhui Province. We aim to quantify carbon emissions generated by most agricultural production activities in Anhui province from 2000 to 2022, as well as the spatiotemporal characteristics of these emissions and their influencing factors. This analysis intends to establish a theoretical foundation for agricultural carbon reduction strategies and achieving carbon peaking targets.

Materials and methods

Measurement of agricultural carbon emission and emission intensity

The measurement of agricultural carbon emissions mainly relies on the carbon emission coefficient method provided by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations to assess regional agricultural carbon emissions (Huang et al., 2022). The primary sources of agricultural carbon emissions in Anhui province are from planting and animal husbandry activities.

Carbon emission of planting industry

The carbon emissions of plantation industry mainly come from agricultural land and methane (CH_4) production during rice cultivation. Specifically, carbon emissions from agricultural land stem come from the consumption of chemical fertilizers, pesticides, agricultural film, diesel oil, agricultural irrigation, and ploughing activities. Meanwhile, the emission of methane from paddy fields accounts for the carbon emissions in rice cultivation. The calculation formula is as follows (Chang et al., 2023):

$$E_{\mathrm{u}} = \sum U_i \times \delta_i \tag{Eq.1}$$

$$E_r = S_r \times \alpha \tag{Eq.2}$$

$$E_c = E_u + E_r \tag{Eq.3}$$

where *Ec* is the planting carbon emission; E_u represents the carbon emission of agricultural land (10^4 t); U_i and δ represent the actual consumption (10^4 t) and carbon emission coefficient of i carbon sources, respectively (*Table 1*). E_r is the carbon emission of rice planting (10^4 t). S_r is the rice planting area (10^3 hm^2); α is the carbon emission factor of rice planting (g/m^2, calculated as C), and $\alpha = 31.91$ (He et al., 2018).

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***Table 1.** Main carbon sources and carbon emission coefficients of planting industry (Chang et al., 2023)*

Carbon source	Emission coefficient (calculated in C)	Data source
Fertilizer	0.89 kg/kg	Oak Ridge National Laboratory, USA
Agricultural film	5.18 kg/kg	Institute of Agricultural Resources and Ecological Environment, Nanjing Agricultural University
Pesticide	4.93 kg/kg	Oak Ridge National Laboratory, USA
Agricultural diesel	0.59 kg/kg	Intergovernmental Panel on Climate Change (IPCC) (Yang et al., 2022)
Plowing	312.60 kg/hm^2	Yang et al. (2022)
Irrigate	266.48 kg/hm^2	Yang et al. (2022)

Carbon emissions of animal husbandry

The animal husbandry mainly focuses on the greenhouse gases produced by enteric fermentation and Fecal management of animals. This study mainly considers the carbon emissions of pigs, cattle, sheep and poultry, and the specific calculation formula is as follows (Chang et al., 2023):

$$E_a = k_{CH_4} \times \sum f_i \times m_i + k_{N_2O} \times \sum f_i \times n_i \quad \text{(Eq.4)}$$

where E_a is the carbon emission from livestock (10^4 t); k is the global warming potential, $k_{CH4} = 21$, and $k_{N2O} = 310$ f_i represents the average annual number of livestock and poultry (10^4 head); m_i and n_i refer to CH_4 and N_2O emission coefficients of livestock and poultry, respectively, as shown in *Table 2*.

***Table 2.** CH_4 and N_2O emission coefficient for livestock and poultry breeding industry*

Carbon source	Intestinal fermentation	Fecal management	
	(kg·head^{-1} ·a^{-1}, calculated in CH_4)	(kg·head^{-1} ·a^{-1}, calculated in CH_4)	(kg·head^{-1} ·a^{-1}, calculated in N_2O)
Pig	1	4	0.53
Cattle	47	1	1.39
Sheep	5	0.16	0.86
Poultry	--	0.02	0.02

Agricultural carbon emission intensity

Agricultural carbon emission intensity refers to the amount of carbon consumed per unit of agricultural economic output (Wang et al., 2023). Agricultural carbon emission intensity can be expressed as follows:

$$H = \frac{E}{G} \quad \text{(Eq.5)}$$

where H is the agricultural carbon emission intensity (t per ten thousand yuan); E is the total agricultural carbon emission (t), and G is the total agricultural output value (ten thousand yuan).

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Measurement of ecological pressure of agricultural carbon emission

The ecological carrying coefficient of agricultural carbon emission is an index reflecting the regional agricultural carbon sink capacity. The calculation formula is as follows (Chang et al., 2023):

$$P = \frac{T_i/T}{Q_i / Q} \qquad \text{(Eq.6)}$$

$$Q = \sum A_i \times Y_i \times (1 - W_i) / C_i \qquad \text{(Eq.7)}$$

where P is the ecological carrying coefficient of agricultural carbon emission; T_i and Q_i refer to the agricultural carbon uptake (10^4 t) and carbon emissions (10^4 t) in each city, respectively; T and Q refer to the agricultural carbon uptake (10^4 t) and carbon emissions (10^4 t) in the whole province respectively; A_i and Y_i are the carbon absorption rate (%) and grain yield (10^4 t) of various crops, respectively; W_i and C_i represent the moisture content (%) and economic coefficient of various crops, respectively. The key parameters of agricultural carbon sink are calculated as shown in *Table 3*. If P is greater than 1, it indicates that the contribution rate of carbon absorption of this region is higher than the carbon emission, indicating that the region has strong carbon sink capacity and significant positive externalities. On the contrary, it implies a low agricultural carbon ecological capacity in the region, which has a negative impact on the surrounding ecological environment.

Table 3. *Key parameters of agricultural carbon sink calculation (Li et al., 2023a)*

Crop	Carbon absorption rate	Water content	Economic coefficient
Rice	0.41	0.12	0.45
Wheat	0.49	0.12	0.4
Corn	0.47	0.13	0.4
Soya bean	0.45	0.13	0.35
Cotton	0.45	0.08	0.1
Peanut	0.45	0.10	0.43

Modeling mechanism of carbon emission driving factors

Driver index selection

The factors that affect agricultural carbon emissions are mainly population, economy, technology, and scale. In this study, the grey correlation method is used to investigate the correlation between agricultural carbon emissions and rural economic development level, agricultural modernization level, non-urbanization rate, industrial structure, and agricultural production scale (Xia et al., 2020; Li et al., 2023b). The corresponding correlation of different time series for the same research object are analyzed to identify the driving factors of agricultural carbon emissions (*Table 4*).

Rural economic development level: Rural economic development level is positively correlated with agricultural investment and the subsequent increase in agricultural carbon emissions. The per capita disposable income of rural residents serves as an indicator reflecting the level of rural economic development.

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Agricultural modernization level: The level of agricultural modernization requires the establishment of agriculture based on contemporary scientific principles, equipped with advanced science and technology as well as modern industrial practices, and the cultivation of high-yield and efficient agricultural ecosystem. This study quantifies agricultural modernization by evaluating the intensity of fertilizer use, mechanization levels, and rural electricity consumption.

People employed in agricultural: People employed in agriculture includes the non-urbanization rate and the proportion of agricultural employees in the total workforce. The non-urbanization rate refers to the percentage of individuals involved in agricultural activities in a specific region. A higher non-urbanization rate indicates a higher proportion of the population engaged in agricultural production in the region. Generally, regions with high non-urbanization rates tend to show higher levels of agricultural carbon emissions.

Industrial structure: The industrial structure reflects the optimization level of the internal agricultural system, and the dominant industry in the agricultural structure have a more significant impact on agriculture carbon emissions. This study quantifies the regional industrial structure by calculating the ratio of total agricultural production to the combined output of agriculture, forestry, fishery, and animal husbandry. The total agricultural production value is determined by summing the crop cultivation and animal husbandry.

Agricultural production scale: The agricultural production scale reflects the level of agglomeration development in regional agriculture. Usually, the larger the scale of agriculture, the higher the absolute carbon emissions. However, expanding agricultural operations also helps to adopt advanced management technologies, optimize resource utilization, reduce carbon emissions, and improve overall emission efficiency.

Table 4. *Index system of influencing factors of agricultural carbon emissions*

Indexes	**Measurement**	**Unit**
Rural economic development level	Per capita disposable income of rural residents	10 000 yuan
Fertilizer use strength	Amount of agricultural fertilizer/crop sown area	$t \cdot hm^{-2}$
Mechanization level	Total power of machinery/crop sown area	$kw \cdot hm^{-2}$
Rural electricity consumption level	Rural electricity consumption/crop sown area	$kwh \cdot hm^{-2}$
Agricultural production scale	Crop sown area	hm^2
Industrial structure	Gross agricultural product/Gross production value of agriculture, forestry, fisheries and animal husbandry	%
Non-urbanization rate	Rural population/total regional population	%
Proportion of people employed in agriculture	Agricultural practitioners/entire workforce	%

Grey correlation model

The mainstream model for evaluating the factors affecting carbon emissions is the Kaya model (Ang, 2005). This model establishes a connection between economic development, population dynamics, policy measures, and other relevant factors related to carbon emissions generated by human activities. In addition, it also examines the complex relationship between regional carbon emissions and human activities within specific region. The non-stationarity of certain macro variables may hinder the resolution of

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variable interactions and their underlying mechanisms. The agricultural production system is a complex entity that includes multiple factors, including known information about finite timeframes and various restrictions on changes in agricultural carbon emissions, as well as unknown information in the future years. The documented historical records of policies, technological advancements, alterations in agricultural inputs that affect crop structure and socio-economic factors are often incomplete and not fully comprehended. The “grey system theory” provides a unique set of modeling methods for simulating “grey systems” with incomplete information, utilizing its “grey” to enhance the similarity between the objective system and the model’s representation of reality.

To comprehensively analyze the factors influencing agricultural carbon emissions in Anhui province, it is recommended to establish a grey correlation analysis model to examine the total carbon emissions and their influencing factors. This approach will help identify the main factors driving carbon emissions and provide a scientific basis for this issue. The main steps of grey correlation analysis include data transformation, calculation of correlation coefficients, determination of correlation degrees, and ranking correlation degree of influential factors. Through evaluating the grey correlation degree between the total agricultural carbon emissions and fluctuations in various production factors, we can effectively determine the relative importance of each influencing factor.

(1) Build original series of the model

Reference series:

$$x_0(k) = \{x_0(1), x_0(2), \cdots, x_0(n)\} \quad \text{(Eq.8)}$$

Comparative series:

$$x_i(k) = \{x_i(1), x_i(2), \cdots, x_i(n)\} \;\; (i = 1, 2, \cdots m) \quad \text{(Eq.9)}$$

(2) Process original data without dimensions

The original data has different dimensions and quantities, making it difficult to obtain accurate results through comparison. To ensure the consistency of the original data, it is necessary to transform and normalize the data. The initial value method is used here for data processing.

(3) Calculation of different sequence

$$\Delta x_{0i}(k) = | x_0(k) - x_i(k) | \;\; (i = 1, 2, \cdots m; k = 1, 2, \cdots n) \quad \text{(Eq.10)}$$

(4) Calculate Z_{max} and Z_{min} of the reference and comparison sequences

$$Z_{\max} = \max_i \max_k \Delta x_{0i}(k), \;\; Z_{\min} = \min_i \min_k \Delta x_{0i}(k) \quad \text{(Eq.11)}$$

(5) Calculation of correlation coefficient:

$$\mu_{0i}(k) = \frac{Z_{\min} + \delta Z_{\max}}{\Delta x_{0i}(k) + \delta Z_{\max}} \quad \text{(Eq.12)}$$

where δ is the resolution coefficient, $\delta \in (0,1)$, and here δ = 0.5.

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(6) Calculation of correlation degree:

$$r_{0i} = \frac{1}{n}\sum_{i=1}^{n}\mu_{0i}(k) \qquad \text{(Eq.13)}$$

(7) Correlation of degree ranking.

Data source

The main data, especially the quantities of fertilizer, pesticide, agricultural film, and agricultural diesel in Anhui province from 2001 to 2022; crop sown areas and irrigated area; crop yields; livestock stocks of pigs, cattle, sheep, and poultry at year-end; total agricultural output value; proportion of agricultural employees; agricultural industrial structure; per capita disposable income of rural residents; total power of agricultural machinery, and rural electricity consumption, are all sourced from the Yearbook (2002-2023) published by the Anhui Provincial Statistics Bureau (http://tjj.ah.gov.cn/). Data analysis and visualization are processed using Excel and Arcg is 10.2 software.

Results and analysis

Temporal characteristics of agricultural carbon emission and carbon emission intensity

The results of agricultural carbon emissions in Anhui province are shown in *Figure 1* and *Table 5*. It can be seen that agricultural carbon emissions in Anhui province show a fluctuating pattern in the study period, characterized by a decline, followed by an increase, then a further decline, and finally an increase again. It is worth noting that the emission rate is more pronounced from 2001 to 2007, with emissions decreasing from 2 339.074 × 10^4 t in 2001 to 1 588.081 × 10^4 t in 2007, equivalent to a reduction of about 750.993 × 10^4 t, with an average annual reduction rate of about 4.58%. Afterwards, agricultural carbon emissions fluctuated slightly, s increasing to 1 906.099 × 10^4 t in 2015. Overall, the net carbon emissions from agriculture in Anhui province have been continuously decreasing year by year, with a slight rebound observed after 2020, indicating the effectiveness of current agricultural emission reduction is uneven. The data in *Table 5* and *Figure 2* indicate that the agricultural carbon absorption in Anhui Province continues to increase annually, indicating a steady growth in grain production and a notable enhancement of the province's carbon sequestration capacity. Among different crop types, grain crops (wheat, rice, and corn) contributions significantly to the overall carbon uptake in Anhui province, with their respective uptakes showing fluctuating patterns. Anhui province is an important grain production base in China, with a total grain output of 4 100.100 × 10^4 tons in 2022, ranking the fourth position nationwide and accounting for 5.97% of the country's overall grain output. It is worth noting that wheat is the main contributor to carbon absorption, with a surge from 172.914 × 10^4 t in 2001 to 383.597 × 10^4 t in 2022, marking an increase of 210.682 × 10^4 t.

Carbon emission intensity refers to the amount of carbon consumed per unit of agricultural output value, and is an indicator for evaluating the relationship between regional economy and carbon emissions. The lower the value of carbon emission

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intensity, the better the energy-saving and emission reduction effect in the process of economic development. With the transformation and optimization of the agricultural industry in Anhui province, the carbon emission intensity of agriculture has continued to decline year-on-year (*Fig. 1*). The peak occurred in 2002 at 2.268 t/10 000 yuan, decreasing from 2.208 t/10 000 yuan in 2001 to over 0.401 t/10 000 yuan in 2022, a decrease of over 80%, with an average annual decline rate of 3.72%. This indicates that continuous adjustment and optimization of the agricultural industrial structure in Anhui province have gradually improved agricultural production efficiency and achieved significant energy saving and emission reduction.

Table 5. *Agricultural carbon emissions and structure in Anhui province from 2001 to 2022*

	Carbon emissions of planting industry (10^4 t)	**Percentage**	**Carbon emissions of animal husbandry (10^4 t)**	**Percentage**	**Total agricultural carbon emissions (10^4 t)**	**Agricultural carbon uptake (10^4 t)**	**Net carbon emissions (10^4 t)**
2001	596.877	25.52%	1 742.197	74.48%	2 339.074	508.838	1 830.236
2002	606.410	25.57%	1 764.810	74.43%	2 371.220	548.626	1 822.594
2003	617.215	26.20%	1 738.985	73.80%	2 356.200	441.136	1 915.064
2004	641.072	28.19%	1 633.364	71.81%	2 274.436	560.543	1 713.893
2005	662.809	30.65%	1 499.590	69.35%	2 162.399	535.963	1 626.436
2006	677.244	34.98%	1 258.855	65.02%	1 936.098	596.419	1 339.679
2007	690.954	43.51%	897.127	56.49%	1 588.081	618.977	969.104
2008	699.045	42.49%	946.046	57.51%	1 645.091	648.205	996.886
2009	708.914	41.93%	981.648	58.07%	1 690.562	656.866	1 033.696
2010	728.159	42.59%	981.452	57.41%	1 709.611	659.480	1 050.131
2011	740.739	42.87%	987.080	57.13%	1 727.818	673.005	1 054.813
2012	750.464	41.52%	1 056.845	58.48%	1 807.309	705.133	1 102.176
2013	781.049	41.85%	1 085.071	58.15%	1 866.121	704.720	1 161.401
2014	782.719	41.77%	1 090.965	58.23%	1 873.684	735.742	1 137.942
2015	791.232	41.51%	1 114.867	58.49%	1 906.099	761.381	1 144.718
2016	774.934	41.90%	1 074.383	58.10%	1 849.317	735.381	1 113.936
2017	878.284	51.13%	839.391	48.87%	1 717.675	866.430	851.245
2018	865.022	51.24%	823.242	48.76%	1 688.264	863.233	825.031
2019	854.830	51.43%	807.345	48.57%	1 662.175	872.583	789.592
2020	849.185	47.25%	948.190	52.75%	1 797.376	865.022	932.354
2021	847.368	45.88%	999.409	54.12%	1 846.777	879.914	966.863
2022	854.952	44.85%	1 051.477	55.15%	1 906.429	881.105	1 025.324

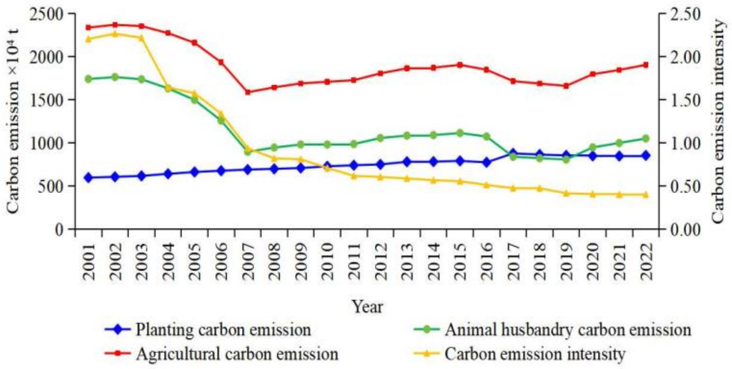

Figure 1. *Changes of agricultural carbon emissions in Anhui province during 2001-2022*

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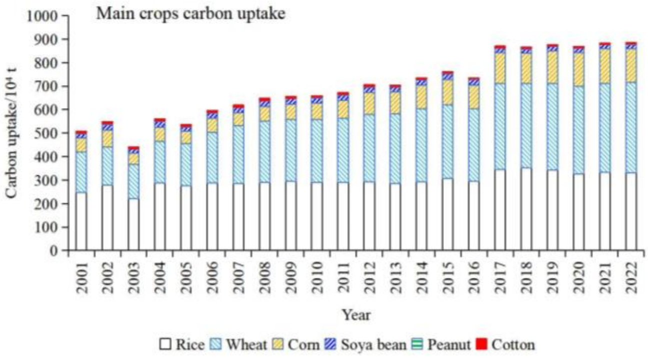

***Figure 2.** Agricultural carbon uptake structure in Anhui province during 2001-2022*

Analysis of temporal characteristics of agricultural carbon emission structure

From 2001 to 2022, the average annual carbon emissions of planting industry in Anhui province accounted for 39.31% of the total agricultural carbon emissions, and that off animal husbandry accounted for 60.69%. It can be seen from *Figures 3* and *4* that agricultural land is the main source of carbon emissions in the planting industry, and rice cultivation contributed insignificantly to such emissions. In agricultural land, chemical fertilizer, mechanical tillage, and agricultural irrigation made the largest contributions to carbon emissions, accounting for 36.33%, 20.87%, and 13.88% respectively. On the contrary, the impacts of agricultural film, pesticides, and diesel oil on carbon emission were relatively small, at 6.51%, 6.03%, and 5.26% respectively. *Figure 5* shows that the average annual carbon emissions of pigs, cattle, sheep and poultry were 36.33%, 26.25%, 22.38% and 15.04%, respectively. *Figure 1* and *Table 4* show that the interannual variation of carbon emissions in the planting industry is continuously increasing. This trend reached its peak of 878.284×10^4 t in 2017 with a contribution rate of 51.13%. The main driving force behind this increase can be attributed to the progressive annual growth in agricultural science and technology investments aimed at ensuring optimal harvest yields. However, starting from 2018, there has been a slight decline in planting-related carbon emissions. The trend of carbon emissions in animal husbandry is similar to the trend of the total agricultural carbon emissions, which underwent significant changes between 2001 and 2007 and gradually increased until reaching its peak in 2017. This can be attributed to the country's commitment to addressing the pollution caused by rural farming at its source. Since the implementation of the "ban policy" in 2017, the number of villagers engaged in animal husbandry has significantly decreased.

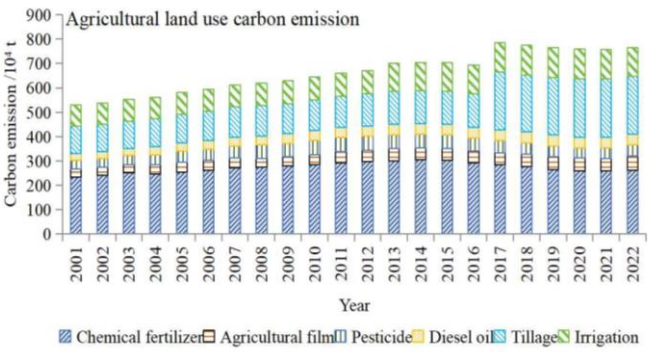

***Figure 3.** Carbon emission structure of agricultural land in Anhui province from 2001 to 2022*

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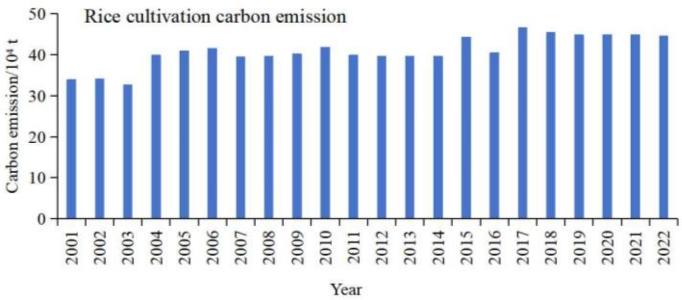

Figure 4. *Carbon emissions from rice cultivation in Anhui province from 2001 to 2022*

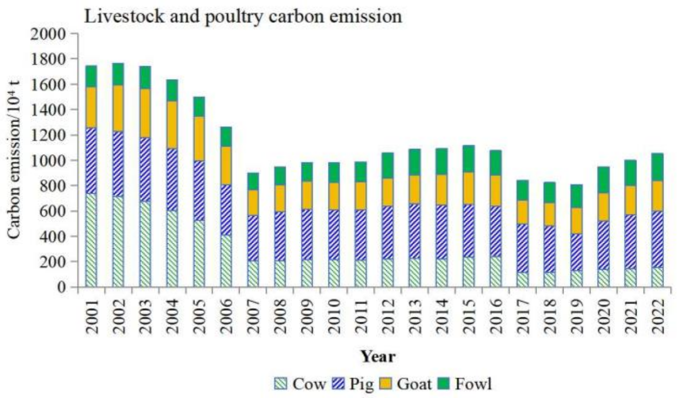

Figure 5. *Carbon emission structure of animal husbandry in Anhui province from 2001 to 2022*

Spatial difference of agricultural carbon emissions in Anhui province

The characteristics of agricultural carbon emissions in Anhui province are visualized using the natural discontinuous method in graded color, utilizing ArcGIS 10.2. Due to the administrative division adjustments in 2011 aimed at ensuring data comparability, 2011 and 2020 are selected to analyze the spatial characteristics of the total agricultural carbon emissions, carbon emission intensity, and ecological pressure resulting from agricultural carbon emissions in Anhui province (*Figs. 6–8*).

As shown in *Figure 6*, the total agricultural carbon emissions decreased gradually from the northern to southern of Anhui province. Since the main features of northern Anhui province are flat terrain, expansive plains, and fertile soil, this contributes to the relatively advanced agricultural development in this region. Due to the large agricultural planting area, it is an important grain production base in Anhui Province. In addition, to ensure the sustained increase of grain production, the agricultural production process has strong input capacity of production factors, a high level of agricultural mechanization, and well-developed farmland irrigation facilities, which is conducive to the increase of agricultural production and income, but also leads to high agricultural carbon emissions. In 2011, the total agricultural carbon emissions in Suzhou, Fuyang, Bozhou, Lu’an, Chuzhou and Hefei exceeded 1.8 million tons. The total agricultural carbon emissions of Bengbu and Anqing were more than 1.6 million tons, that of Wuhu and Xuancheng were 700 000 – 800 000 tons, and that of Huaibei, Huainan, Maanshan, Tongling, Chizhou and Huangshan were less than 600 000 tons. The administrative areas of Huaibei, Huainan, and Tongling have limited spatial coverage and insufficient

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capacity, resulting in relatively low total carbon emissions; Wuhu and Maanshan have strong industrial foundation and prosperous economies. However, farmers have little enthusiasm for farming. In addition, the challenging terrain of Chizhou and Huangshan, as well as other mountainous regions in southern Anhui province, has hindered the utilization of agricultural machinery and adoption of advanced management, leading to a reduction in carbon emission intensity. From 2011 to 2020, the spatial distribution of agricultural carbon emissions in Anhui province showed a decrease in most regions. However, Huainan and Tongling have slightly increased, while Fuyang, Xuancheng, and Chizhou have maintained relatively stable levels.

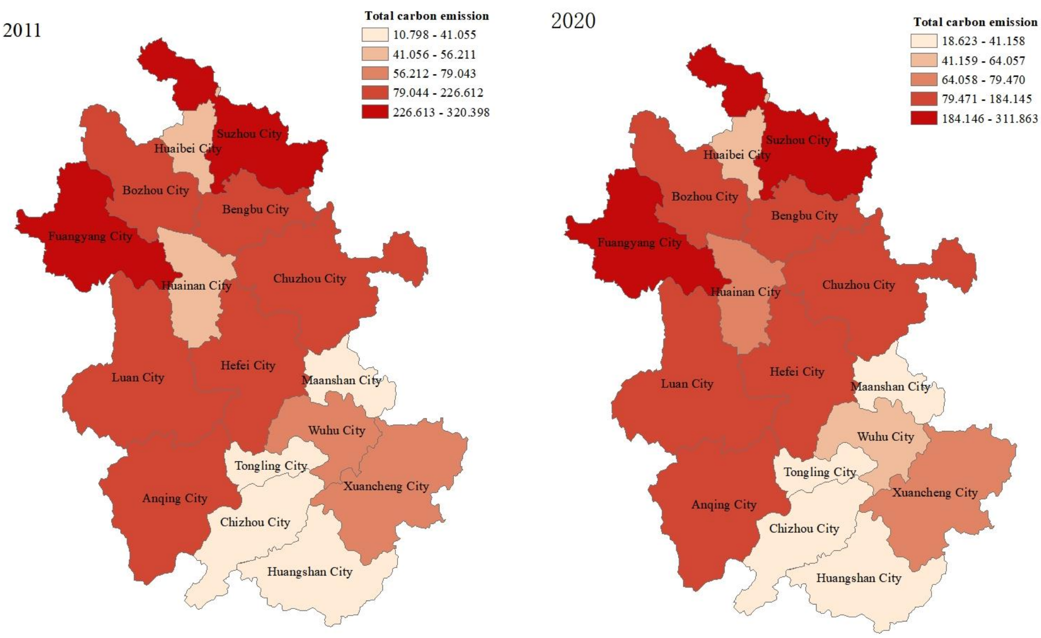

Figure 6. *Spatial distribution of total agricultural carbon emissions in Anhui province in 2011 and 2020*

From the perspective of agricultural carbon emission intensity (*Fig. 7*), carbon emission intensity more accurately reflects the degree of emissions compared to carbon emissions. In 2011, Suzhou, Lu’an, Tongling, and Bengbu were classified as the first echelon in terms of carbon emission intensity, with a range of 0.81.0 t/10 000 yuan. Subsequently, Huaibei, Huainan, Chuzhou, Bozhou and Anqing had a carbon emission intensity ranging from 0.7 to 0.8 t/10 000 yuan; Huangshan, Chizhou and Hefei had a carbon emission intensity of 0.62 to 0.66 t/10 000 yuan. Finally, Wuhu and Maanshan showed a lower carbon emission intensity in the range of 0.5 - 0.8 t/10, 000 yuan. The agricultural carbon emission intensity of various cities in Anhui province was generally lower in 2020 compared to 2011, ranging from 0.32 to 0.64 t/10 000 yuan. Among them, Suzhou had the highest emission intensity of 0.639 t /10 000 yuan, Lu’an, Chuzhou, Anqing and Fuyang followed closely with the emission intensities of 0.519, 0.489, 0.478 and 0.468 t/10 000 yuan, respectively. On the other hand, Maanshan, Tongling and Wuhu had the lowest emission intensities of 0.356, 0.324 and 0.321 t/10 000 yuan respectively. The emission intensities of remaining cities ranged from 0.38 to 0.45t/ 10 000 yuan. Compared to 2011, the carbon emission intensity of all cities

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in 2020 decreased. Tongling had the most significant decrease of 61.91%, followed by Huaibei, Huainan, Bengbu, and Bozhou, each with a decline of over 45%. These results demonstrated the remarkable achievements of Anhui province in the adjustment and optimization of agricultural structure.

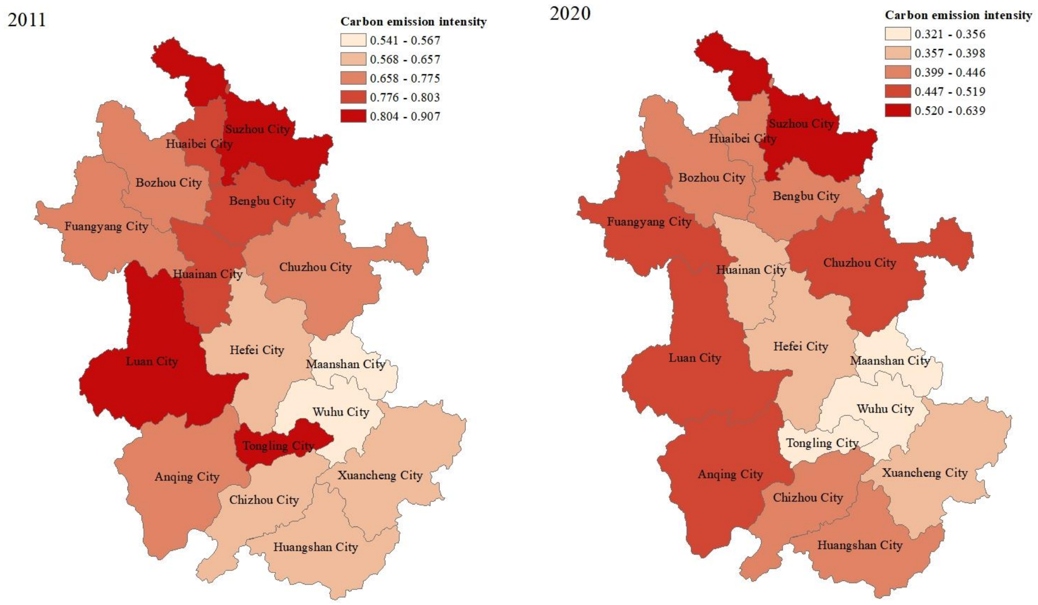

Figure 7. *Spatial distribution of agricultural carbon emission intensity in Anhui Province in 2011 and 2020*

The ecological pressure coefficients of agricultural carbon emissions in Anhui province were calculated using formulas (6) and (7), and the spatial distribution disparity is shown in *Figure 8*. The ecological pressure coefficients of carbon emissions decreased from north to south, which is essentially consistent with the distribution pattern of total carbon emissions. Moreover, the pressure coefficients of most cities were between 0.7 and 1.8. In 2011 and 2020, there were six cities with ecological pressure coefficients greater than 1, i.e. Huaibei, Bozhou, Bengbu, Huainan, Chuzhou, and Maanshan. In addition, Fuyang reached a coefficient of 0.998. The agricultural carbon emissions in these regions accounted for 46.47% of the total emissions in the province, while carbon absorption accounted for 60.13% of the total absorption capacity in the province. The findings indicated that these regions have significant ecological capacity due to the strong carbon sequestration of agriculture, effectively alleviating carbon emission pressures in other areas. The ecological pressure coefficients of carbon emissions in mountainous area of southern Anhui are lower than 0.8, especially in Huangshan where the coefficient is lower than 0.4. This can be attributed to the mountainous terrain, inadequate agricultural infrastructure, and low level of intensification in this region, which collectively hinders the expansion of local ecological capacity and resulted in limited carbon absorption capacity. Compared to 2011, the pressure coefficients of Tongling, Huainan, Bozhou, and Wuhu increased at different levels. This indicates that the ecological capacity of these regions is gradually expanding and their carbon sequestration capacity is increasing. The growth of Tongling and Huainan is particularly significant, reaching 87.50% and 48.45%, respectively.

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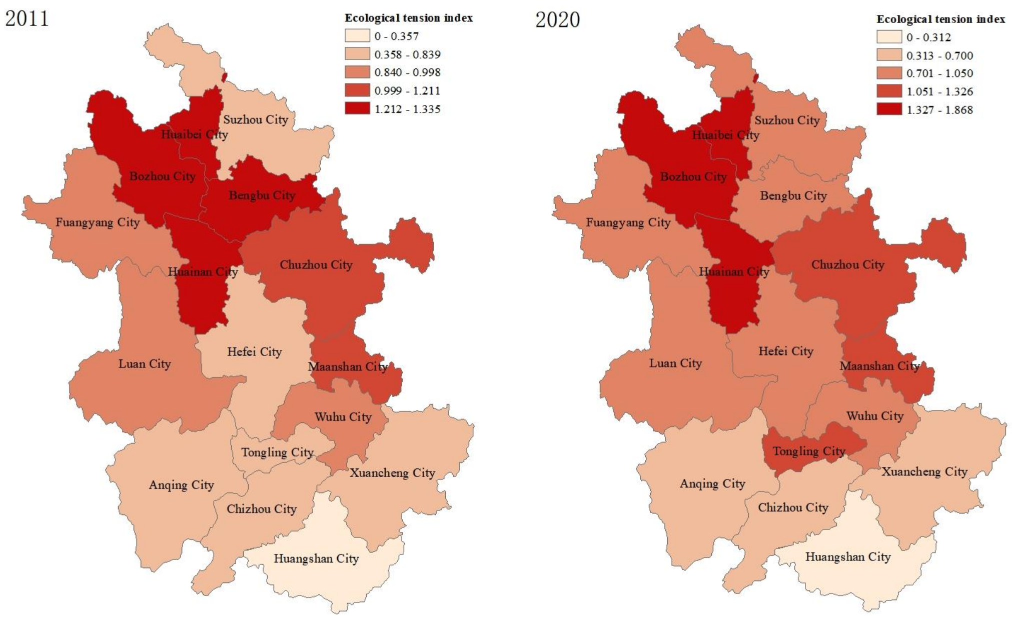

Figure 8. *Spatial distribution of ecological pressure of agricultural carbon emissions in Anhui province in 2011 and 2020*

Analysis of driving factors of agricultural carbon emissions

The correlation between total agricultural carbon emissions and influencing factors in Anhui province were calculated based on the mechanism and formula of the grey correlation model, as shown in *Table 6*.

Table 6. *Grey correlation between agricultural carbon emission and influencing factors*

Level of rural economic development	Fertilizer intensity	Mechanization level	Rural electricity consumption level	Per capita planted area	Non-urbanization rate	Agricultural industrial structure	Proportion of agricultural employees
0.642	0.739	0.824	0.810	0.861	0.830	0.913	0.711

Agricultural industrial structure and agricultural production scale

Agriculture is the backbone of agroforestry, animal husbandry, and fisheries. The level of agricultural output value will directly impact farmers' willingness to engage in agricultural production and has a certain impact on carbon emissions. The correlation between agricultural industrial structure and per capita sowing area were 0.913 and 0.861 respectively, ranking the first and second among all influencing factors. Since 2004, the state and local government have strengthened their support for agriculture, rural areas, and farmers, greatly increasing their enthusiasm for engaging in agricultural production. The total agriculture output value has significantly increased from 105.954 million yuan in 2001 to 474.956 million yuan in 2022, with a growth of 3.5 times or an average annual growth rate of 15.83%. This increase in production motivation among farmers had led to a continuous expansion of agricultural sowing area and input levels. During this period, the agricultural sowing area significantly increased by 341.69×10^3 hm^2. In addition, the proportion of agricultural workers has decreased by nearly 1.4 times from 64.95% in 2001 to 27.14% in 2022. The number of agricultural

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employees has decreased, and the agricultural sowing area continued to expand. At the same time, the per capita sowing area continues to increase, and the scale of agricultural production continues to expand. The growth of agricultural cultivation has led to an increase in the use of machinery, fertilizers, and pesticides, resulting in higher levels of agricultural carbon emissions.

Scientific and technological factors

Agricultural modernization is reflected in the progress of agricultural science and technology. The key indicators include the total power of agricultural machinery, rural electricity consumption, and fertilizer usage intensity, with correlation coefficients of 0.824, 0.810 and 0.739, respectively. With the rapid development of economy, farmers' disposable income has been greatly improved, leading to an annual increase in agricultural inputs year by year such as fertilizers, pesticides, machine tillage. Compared with 2001, the total power of machinery and rural electricity consumption in 2022 increased by $3\ 905.126 \times 10^3$ kW and 156.840×10^8 KWh, and the total mechanical power and rural electricity consumption per hectare increased by 2.19 times and 4.16 times, respectively. In 2014, the No. 1 Central document proposed the "Developing Eco-friendly Agriculture", and in 2015, the "zero-growth action of fertilizer and pesticide use by 2020" began to be implemented, leading to a gradual decline of pesticide and fertilizer use in Anhui province since 2017. The process of urbanization will lead to a decrease in the proportion of agricultural workers, requiring greater reliance on science and technology to improve agricultural productivity. Therefore, scientific and technological progress will continue to play an important role in stabilizing and maintaining agricultural output value in the future, which is a significant factor affecting agricultural carbon emissions.

Economic development and agricultural employees

The correlation coefficients between rural economic development and the proportion of agricultural employees are merely 0.642 and 0.711, respectively, ranking the behind. Economic development and urbanization will affect the production and lifestyle of the population. During the study period, the non-urbanization rate of Anhui province continued to decline, while the urbanization rate relatively increased, rising from 29.30% in 2001 to 60.15% in 2022, indicating a significant growth of 30.85%. Rapid urbanization has led to a large influx of original rural residents into cities, resulting in a large loss of rural agricultural population and a decrease in agricultural employment rate. This causes extensive agricultural production growth that exceeds the inhibition effect of large-scale agricultural production on carbon emissions, and a continuous rise in carbon emissions. In addition, economic development fosters an increase of farmers' disposable income, thereby driving the level of agricultural mechanization and intensifying the utilization of fertilizers, agricultural film, and agricultural diesel, leading to a sharp increase in agricultural carbon emissions.

Conclusion

Based on the agricultural statistical data of Anhui province from 2001 to 2022, the carbon emissions and carbon absorption caused by the three types of "carbon sources": agricultural land cultivation, rice cultivation and livestock breeding, are

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calculated. Their spatio-temporal characteristics were analyzed to clarify the change rules of carbon emissions in Anhui province in different years. At the same time, the influence of factors such as rural economic development, agricultural modernization, the structure of agricultural industry, the scale of agricultural production and the proportion of agricultural employees on agricultural carbon emissions in Anhui province were analyzed by using grey correlation method. The following conclusions were drawn:

(1) From 2001 to 2022, agricultural carbon emissions in Anhui province showed a trend of decreasing-increasing-declining-increasing, and the intensity of agricultural carbon emissions showed an overall trend of fluctuating and decreasing. The minimum value observed in 2007 was 1 588.081 × 10^4 t, with a significant annual reduction rate of 4.58% from 2001 to 2007. Subsequently, agricultural carbon emissions experienced slightly recovered and fluctuated slightly. At the same time, the annual increase in agricultural carbon absorption in Anhui province signified a steady growth in grain production and a significant enhancement in carbon sequestration capacity.

(2) From 2001 to 2022, the average annual proportion of carbon emissions from the planting industry in Anhui Province accounted for 39.31% of total agricultural carbon emissions, while animal husbandry contributed to an average annual proportion of 60.69%. Agricultural land was the main source of carbon emissions in crop production, with rice cultivation contributing minimally to such emissions. In agricultural land use practices, chemical fertilizer application, mechanical tillage and irrigation were significantly 36.33%, 20.87%, and 13.88%, respectively. In terms of animal husbandry, the annual carbon emission rate of pigs accounted for 36.33%, followed by cattle (26.25%), sheep (22.38%) and poultry (15.04%).

(3) The differences in agricultural resources and industrial structure in different regions of Anhui province led to significant differences in agricultural carbon emissions and emission intensity. The total agricultural carbon emissions in Anhui province generally decreased from north to south, with the carbon emission intensity closely linked to economic development and agricultural industrial structure. Especially, Suzhou, Fuyang, Lu’an, Bozhou from most agricultural cities showed higher carbon emission intensity, while Wuhu, Maanshan, Tonglin, and other regions with a strong industrial base demonstrated lower carbon emission intensity. The spatial distribution difference of ecological pressure coefficients of farmland carbon emissions in Anhui province also decreased from north to south, which is basically consistent with the trend of total carbon emissions. The pressure coefficients of most cities were between 0.7 and 1.8.

(4) The grey correlation analysis revealed that the agricultural industrial structure and the scale of agricultural production were the main determinants influencing agricultural carbon emissions, while scientific and technological factors were the main drivers affecting such emissions. In addition, economic development and the number of agricultural employees played a crucial role in shaping agricultural carbon emissions.

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