



The decoupling effect between net agricultural carbon emissions and economic growth based on LCA

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Received: 11 May 2023 / Accepted: 14 November 2023
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Abstract

Measuring carbon emissions in agricultural production comprehensively and accurately are the basis for promoting low-carbon emission reduction in agriculture and a prerequisite for improving sustainable agricultural development. Existing literature has lacked analysis of the measurement of net carbon emissions from regional agricultural production and its decoupling status from economic growth. This study constructs a net carbon emissions measurement system for agricultural production by fully considering the carbon sources and sinks in the whole process of agricultural production activities from the perspective of the whole life cycle of agricultural production. In addition, it introduces the spatial Moran index, combines the analysis of time-series characteristics, constructs an evaluation method for the time-series evolution and spatial distribution characteristics of regional agricultural carbon emissions (ACE), and proposes a method to characterise the decoupling state of ACE from the perspective of net carbon emissions by time period. Finally, taking Anhui Province as an example, the feasibility of the method was verified. It was found that the ACE in Anhui Province reached a maximum of 19.35 million tonnes in 2013 during the study period, and different regions have differences in ACE. The positive spatial correlation of the carbon emissions intensity of agricultural production showed an increasingly strong trend, and the decoupling state was optimised across Anhui Province as a whole. Our findings provide theoretical support for the formation of scientific and accurate policies to reduce carbon emissions and promote sustainable development in agriculture.

Keywords Carbon sinks · Moran index · Tapio decoupling index · Low-carbon agriculture

List of symbols

AC_1	Is the agricultural energy consumption's carbon emissions, Ton
AC_2	Is the carbon emissions from crop growth, Ton
AC_3	Is the carbon emissions from straw combustion, Ton
T_k	Is the inputs of k -th carbon source in agricultural production, Ton
C_k	Is carbon emission factors for k -th carbon sources

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A	Is the area of paddy field, hm^2
δ	Is the CH_4 emission factor of paddy field, kg/hm^2
W_p	Is the crop's economic yield, Ton
S_j	Is the grass-to-grain ratio of j -th crops
x_l, x_s	Are the observations in regions l, s
\bar{x}	Is the mean of each region
w_{ls}	Is used to measure the distance between regions l and s
M	Is the coefficient of burning straw
C	Is straw carbon emission factor.
C_f	Is carbon absorption of crops, Ton
C_{jq}	Is carbon absorption by q -th crop, Ton
α_q	Is the water content of p -th crop, %
β_q	Is the carbon uptake rate of p -th crop, %
H_q	Is the economic coefficient of p -th crop, %
NAC	Is the agriculture production's net carbon emissions, Ton
AGDP	Is the gross agricultural product, million Yuan
APOP	Is the rural population, person
NACI	Is net carbon emissions intensity of agriculture
NAPC	Is carbon emissions per capita from agriculture

1 Introduction

Currently, the world is experiencing the serious threats of agricultural production and the climatic crisis (Yasmeen et al., 2022), one of the factors of environmental degradation is the intensive use of chemical substances in agriculture (Covino & Boccia, 2014), whereas one way to tackle climate change is to reduce carbon emissions (Di Vaio et al., 2023). The Chinese government has set a "double carbon" aim to reach peak carbon emissions by 2030 and carbon neutrality by 2060 in order to solve the significant issue of global carbon emissions (Chen et al., 2021). Agricultural low-carbon and green growth, which is a crucial method for achieving the decrease in carbon emissions, is currently receiving extensive attention from governments and scholars. Against the background of carbon neutrality, global rural and agricultural construction and development has entered a new stage towards the development of low carbon.

Acceleration of low-carbon development in rural agriculture is widely considered to be the way to drive high-quality rural revitalisation and is also a key means to fulfil the "double carbon" objective (Cui et al., 2021). The agriculture's sustainable development can only be achieved by reducing agricultural carbon emission (ACE) and achieving a win-win situation in terms of agricultural economic growth, while ensuring the continuous development of the agricultural economy. Therefore, finding a balance between carbon emissions and agricultural output and developing practical emission-reduction plans are crucial, while ensuring that agricultural output meets the needs of social development (Sun et al., 2022). ACE are one of the key characteristics of agroecological development (Zhou et al., 2010). According to Boccia et al. (2019), large amounts of biowastes are produced at each stage of agricultural production. Therefore, carbon emissions from agricultural production need to be considered in a whole life cycle perspective. Alternatively, the environmental, economic, and social aspects are the three pillars of the sustainability idea (Di Vaio et al.,

2022), so for sustainable agricultural development, it is critical to understand how ACE and economic growth are uncoupled.

In this context, the purpose of this study is to construct a method for measuring and evaluating the net ACE based on life cycle assessment theory. We measure the net ACE by fully considering the carbon sources and sinks during the course of agricultural production operations, introducing the spatial Moran index, and combining the temporal characteristics to analyse the temporal evolution and spatial distribution of carbon emissions from regional agriculture. We further identified the decoupling state of regional ACE. This helps to develop regional strategies for reducing emissions in agriculture and offers a practical foundation for the advancement of environmentally conscious agriculture.

The structure of the remaining is as follows: The literature is reviewed in Sect. 2, and the theoretical approach used is presented in Sect. 3. Section 4 selects Anhui Province as a case study and measures net ACE across the province over the past decade, using a decoupling effects and geographical and temporal difference analysis. In Sect. 5, management insights are covered, and Sect. 6 concludes the paper.

2 Literature review

ACE are the result of agricultural production and lifestyles that release greenhouse gases like carbon dioxide into the atmosphere. In existing studies, the calculation of ACE and regional differences (Tian et al., 2014), agricultural low-carbon emission reduction (Guo & Zhang, 2023), and decoupling analysis of carbon emissions and economic development in agriculture (Raza et al., 2023; Xu et al., 2022) have all attracted the attention of scholars.

The measurement and calculation of ACE often use the three different methods of measurement: material balance, real, and emissions coefficient (Wu et al., 2020), and some studies have applied life cycle assessment (LCA) to study ACE (Yang et al., 2022). Such as, Zhang et al. (2022) used the LCA method to estimate the carbon emissions of urban green space in China and discussed the factors affecting the carbon balance. Bamber et al. (2022) used the LCA method to assess the carbon emissions of organic field crops. The LCA-based method is being improved, but further research is needed to measure the net ACE as a source and sink (Luo, 2022).

Agroecosystems have become a common area of concern for carbon reduction, including carbon sources and sinks in their production process. Numerous academics have studied the decrease in ACE around the measurement of agricultural carbon sinks. For example, She et al. (2017) gathered information on the carbon costs of China's main crops, calculated the impact of farms as a source and sink of carbon, and found that rice is the largest carbon sink of crops. Additionally, Fan et al. (2019) quantified the changes in soil organic carbon stocks of agricultural land in Canada from 1971 to 2015 and noted that increasing agricultural production is a crucial means to achieve greenhouse gas emissions reduction. More recently, Cui et al. (2022) estimated China's ACE taking into account the carbon sink impact and utilised kernel density estimation to analyse the temporal and geographical dynamic evolutionary features and polarisation trends of China's planting carbon emission intensity and per capita carbon emissions. Further research could consider carbon sinks at the provincial level to analyse the temporal and spatial differences in ACE and to study ways to reduce ACE.

The decoupling index has steadily gained popularity as a useful tool for analysing the link between economic development and carbon emissions. It is particularly useful for

analysing the relationship between economic growth and resource use or environmental strain (Chen et al., 2020a, 2020b; Zhang et al., 2015). Scholars have also conducted pertinent research about the decoupling impact of ACE and the growth of the economy. For example, When Luo et al. (2017) examined the decoupling of China's ACE from agricultural production across several areas and years, they discovered that East China had more instances of robust decoupling between carbon emissions and agricultural output. While Jiang et al. (2021) found six decoupling states between 2008 and 2017 for China's agriculture sector in 30 provinces. Additionally, Chen et al. (2020a, 2020b) examined the decoupling of agricultural energy use and economic development in 89 countries, finding that only 18 had significant decoupling between 2000 and 2016.

Many scholars have achieved fruitful results in ACE reduction, but there is still some room for optimisation. (1) Existing research on carbon emission measurement shows that the calculation of net carbon emissions considering carbon sources and sinks still needs further research. In the meanwhile, according to the literature review, carbon emissions measurement needs to further consider the whole process of agricultural production to achieve accurate measurement results. (2) Current research focuses on the features of carbon emissions distribution at the national and interprovincial levels, with regional agriculture receiving less attention. Further research of the geographical and temporal aspects of regional ACE is required before proposing targeted optimisation methods. (3) When scholars examine the decoupling effect, they mainly analysed the ACE of production, while the trend of the economic growth decoupling on the net ACE is still unclear.

To overcome the above research gaps, in terms of the life cycle perspective, agricultural production's carbon emissions are measured and analysed in this study, and with the following innovations and contributions: (1) Considers carbon sources and sinks with the whole agricultural production life cycle, with a view to proposing a more accurate measurement and evaluation method of carbon emissions from agricultural production and further enriching the study of ACE. (2) Using time-series characteristics analysis and the Moran index, the time-series characteristics and spatial heterogeneity of regional net ACE are analysed to provide a scientific basis for sorting out the disparities in ACE among areas. (3) From the perspective of net carbon emissions from agricultural production, the decoupling of economic growth on net ACE will be studied over time to understand the decoupling status at the regional level, providing theoretical support for the formulation of scientific and accurate carbon emissions reduction policies and the promotion of sustainable agricultural development.

3 Methods

This section introduces a life cycle-based measurement and evaluation method for agriculture carbon emissions established in this paper, including an inventory analysis of carbon sinks and sources in agricultural production, the construction of an LCA-based framework for measuring net carbon emissions from agricultural production, a spatial correlation test, and a theoretical approach to decoupling models.

3.1 Method flow

This study established a life cycle-based measurement and evaluation method for ACE. According to the agricultural production life cycle perspective, this study collected data on

the consumption of various energy inputs and crop production in agricultural production, constructed a carbon sequestration and carbon emissions measuring system in agricultural production, and assessed the net carbon intensity and average carbon emissions in agricultural output. Based on the measurement results, the spatial Moran index was introduced and combined with the time-series characteristics analysis to construct a method for the time-series evolution and the features of regional ACE' distribution, and a method is proposed to characterise the situation of carbon emissions decoupling in agriculture from the perspective of net carbon emissions by period. Finally, taking Anhui Province as a case, the feasibility of the method was verified. The method supports the exploration of low-carbon development paths in agriculture and as Fig. 1 illustrated.

3.2 A framework for measuring net carbon emissions in agricultural production based on life cycle

The measurement of the net ACE was the logical starting point for this study. Accurate measurement of net carbon emissions, while accounting for carbon sinks and carbon emissions, was the core of this study. Based on life cycle assessment theory, the study focused on the entire process of agricultural producing operations, including the production preparation period, agricultural production period, and harvesting period, and comprehensively

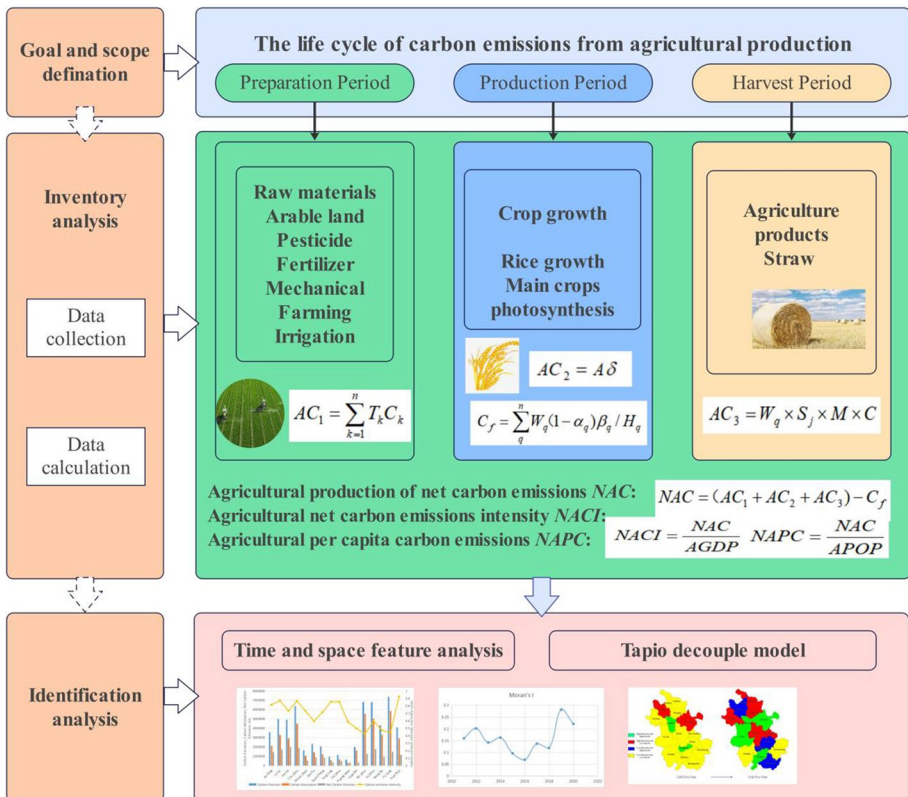


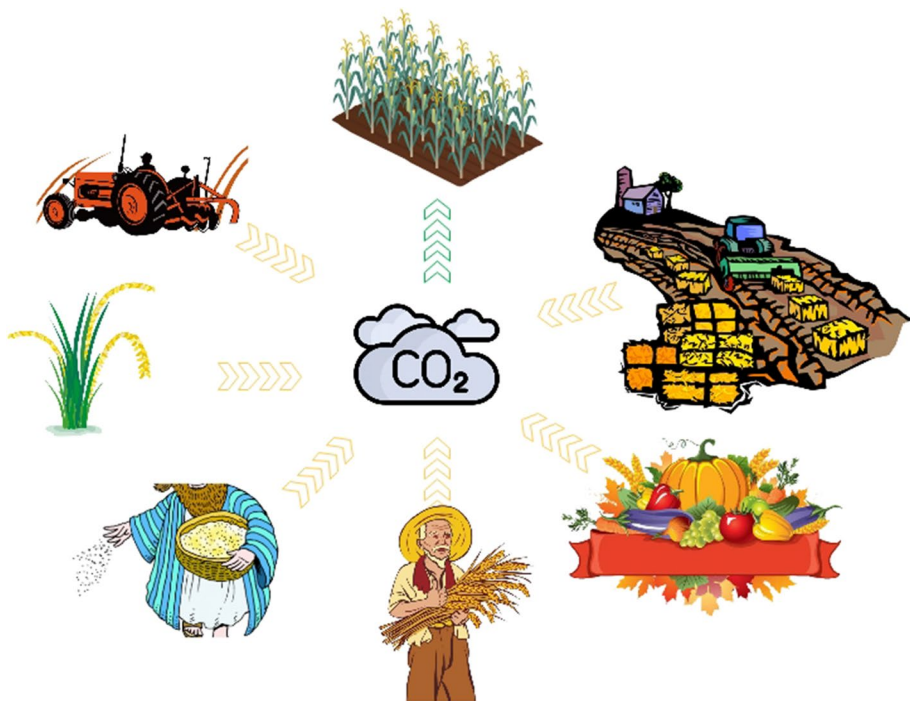
Fig. 1 Method flow

considered the material and resource inputs consumed in the process, harvesting, waste recycling, and other elements (Yang et al., 2003), as shown in Fig. 2. A framework for measuring net ACE was then constructed.

3.2.1 Carbon emission calculations

Carbon emissions and carbon sequestration occur during the agricultural production preparation, production, and harvesting phases, respectively. In terms of carbon emissions, this study considered three main aspects. First, emissions from agricultural energy consumption, that is, emissions from agricultural inputs such as fertilisers, pesticides, agricultural films, agricultural machinery, ploughing, and irrigation in the agricultural production process (Tian et al., 2013a; Tian et al., 2013b), are denoted as AC_1 . Second, carbon emissions from crop growth, which were measured based on the release of CH_4 during the growth of rice (Cui et al., 2022), are denoted as AC_2 . Third, carbon emissions from straw burning (Cui et al., 2022) are denoted as AC_3 . Appendix 1 displays the specific carbon emissions measurement index system and measurement factors. The carbon emissions factors are all carbon equivalent standards. The grass-to-grain ratio of the crops involved in the calculation of AC_3 is shown from Appendix 2.

The emissions factor approach was used to calculate the carbon emissions from agricultural production energy consumption AC_1 , where T_k denotes the input of the k -th carbon



The Life Cycle of Carbon Emissions from Agricultural Production

Fig. 2 Agricultural production processes

producer in agricultural production, and C_k denotes the carbon emissions factor for the k -th carbon producer. The calculations are as follows:

$$AC_1 = \sum_{k=1}^n T_k C_k \tag{1}$$

Carbon emissions from rice growth, calculated as the product of the rice field area and the rice field CH_4 emission factor, are calculated as follows:

$$AC_2 = A\delta \tag{2}$$

Straw burning also produces carbon emissions, and the emissions of carbon from the burning of straw for the 12 major crops listed are considered in [Appendix 3](#), using the crop's economic yield W_q , the grass-to-grain ratio S_j , the straw burning factor M , and the straw carbon emissions factor C . The calculations are as follows:

$$AC_3 = W_q \times S_j \times M \times C \tag{3}$$

With these calculations, carbon emissions are measured by taking full account of the carbon sources in agricultural production systems.

3.2.2 Calculation of carbon absorption

Aside from carbon emissions, it is worth noting that in agricultural production, a variety of crops, including wheat, rice, maize, and potatoes, exert CO_2 uptake through photosynthesis, yet most studies on ACE lack measurements of carbon sinks. In this study, existing scholars' measurements of economic coefficients, carbon uptake rates, and water content of major crops in China were reviewed (Cui et al., 2022; Tian et al., 2014), and the rate of carbon uptake by different crops across the study area, denoted as C_f , was measured. The list of measurements for Anhui Province, for example, is shown in [Appendix 3](#) and calculated as follows:

$$C_f = \sum_q C_{fq} = \sum_q W_q (1 - \alpha_q) \beta_q / H_q \tag{4}$$

where C_f reflects the carbon uptake by crops, C_{fq} is the carbon uptake by the q -th crop, and α_q , β_q , and H_q represent the water content, the rate of carbon uptake, and economic coefficient of the q -th crop, respectively.

3.2.3 Agriculture's net carbon emissions strength and per capita carbon emissions

Agriculture's net carbon emissions are the consequence of a two-way "game" between the sources and sinks of carbon. On the basis of the above estimates of the emissions and sequestrations of carbon, the net ACE in the study area devoted as NAC and can be obtained as follows:

$$NAC = (AC_1 + AC_2 + AC_3) - C_f \tag{5}$$

The agricultural sector carbon emissions may thus be evaluated more accurately by taking full account of the carbon sequestration and emissions that exist during the agricultural manufacturing process.

Carbon emissions, the strength of carbon emissions, and per capita carbon emissions are the main indicators for evaluating carbon emissions (Cui et al., 2022), and in this study, NAC divided by the gross agricultural output value (AGDP, million yuan) can be used to obtain the net carbon emissions intensity of agriculture, denoted as NACI in tonnes per million yuan, can be calculated as follows:

$$\text{NACI} = \frac{\text{NAC}}{\text{AGDP}} \quad (6)$$

Dividing the net emissions from agricultural production by the number of rural people in each locality, APOP (persons), gives the ACE per capita in each locality denoted as NAPC in tonnes per person, can be calculated as follows:

$$\text{NAPC} = \frac{\text{NAC}}{\text{APOP}} \quad (7)$$

3.3 Spatial correlation test

There are geographical variations and spatial dependencies in ACE (Yang et al., 2021). To investigate whether there is an imbalance and spatial autocorrelation among ACE from production in Anhui, and to further study the regional characteristics of the NACI in Anhui, Moran's I is used (Moran, 1950).

Moran's I, which may be split into global Moran's I (GI) and local Moran's I (LI), is a frequently used statistic to assess geographic connection. GI is used to reflect the overall correlation and degree of variation of observations of spatial or spatially proximate regional units and is calculated as follows:

$$\text{GI} = \frac{n \sum_{l=1}^n \sum_{s=1}^n w_{ls} (x_l - \bar{x})(x_s - \bar{x})}{\sum_{l=1}^n \sum_{s=1}^n w_{ls} \sum_{l=1}^n (x_l - \bar{x})^2} \quad (8)$$

When $\text{GI} > 0$, a positive spatial relationship is indicated, the greater the value, in which case the more spatial correlation is significant; when $\text{GI} < 0$, a negative spatial relationship is indicated, the less the value, in which case the more spatial difference is significant.

If the GI exhibits autocorrelation, then the LI was used as a local indicator of spatial association (LISA) to further examine the spatial clustering around a region, calculated as follows:

$$\text{LI}_l = \frac{x_l - \bar{x}}{D} \sum_s w_{ls} (x_s - \bar{x})$$

$$D = \sum_{s=1, s \neq l}^n x_s^2 / (n-1) - \bar{x}^2 \quad (9)$$

If the result of LI passes the significance test, when $\text{LI}_l > 0$, denotes that high-(low) values in region l are encircled by high-(low) values; when $\text{LI}_l < 0$, denotes that high-(low) values in region l are encircled by low-(high) values.

3.4 Model of Tapio decoupling

The decoupling theory explains the relationship between resource use and carbon emissions and economic growth. This study used the NAC and gross agricultural product to represent ACE and agricultural economic development, respectively, and the Tapio decoupling index to measure the degree of decoupling between regional net ACE and economic growth in order to better understand the relationship between regional agricultural economic growth and carbon emissions. The calculation formula is as follows:

$$T_{\text{NAC,AGDP}} = \frac{\Delta \text{NAC} / \text{NAC}}{\Delta \text{AGDP} / \text{AGDP}} = \frac{(\text{NAC}_t - \text{NAC}_{t_0}) / \text{NAC}_{t_0}}{(\text{AGDP}_t - \text{AGDP}_{t_0}) / \text{AGDP}_{t_0}} \quad (10)$$

where NAC_t , AGDP_t denote the t -period values of NAC and AGDP, respectively, and NAC_{t_0} , AGDP_{t_0} denote the base period values of NAC and AGDP, respectively. Judging from the decoupling index, the relationship that exists between economic growth and carbon emissions can be classified according to several states, as shown in Table 1. In the context of China's 5-year plan, this study uses a 5-year period for decoupling and measures the decoupling indices for the periods 2011–2015 and 2015–2020 to reflect the features of net ACE's decoupling from its economic growth throughout several 5-year plan periods.

4 Results

4.1 Selection of study area and data sources

Anhui, a representative province of China with large agricultural resources, is at a strategic point of economic growth in China. The agriculture of Anhui has grown significantly in the last several years, and its comprehensive agricultural production capacity has been greatly improved (Wu et al., 2022). Under the "double carbon" aim, Anhui Province's agricultural growth is under increased pressure to reduce carbon emissions. The examination of both the space and time characteristics of net ACE and the decoupling effect is important for agricultural emissions reduction in Anhui Province was used as a case study and is also a good reference value for related studies in various regions of China.

In order to gauge the net ACE in Anhui Province, the study determined how much fuel, film, and fertiliser were used in agriculture in each municipality between 2011 and 2020, measured in tonnes. The area under crop cultivation, irrigation, and paddy cultivation in Anhui Province was in thousands of hectares; the total machinery power was in 10,000 kilowatts; and the economic production of various crops was in tonnes. The Anhui Provincial Statistical Yearbook was the source of the data.

4.2 The measurement of carbon emissions in agricultural production of Anhui

To see the carbon emissions over the province of Anhui from 2011 to 2020 visually, a heatmap of NAC, NACI, and NAPC across Anhui Province was drawn, as shown in Fig. 3. The data were divided into 20 intervals from minimum to maximum, each with a different colour, and the data for each city corresponded to a gradual transition from green to lighter to white and from white to darker to red, depending on the interval in which it is located.

Table 1 Classification of decoupling status

Status	Relationship	Carbon emissions change (ΔNAC)	Economic change ($\Delta AGDP$)	Decoupling index
Strong decoupling	Negative carbon emissions growth, positive economic growth	-	+	$(-\infty, 0)$
Weak decoupling	$\Delta NAC < \Delta AGDP$	+	+	$(0, 0.8)$
Declining decoupling	$\Delta NAC > \Delta AGDP$	-	-	$(1.2, +\infty)$
Expanding negative decoupling	$\Delta MAC < \Delta AGDP$	+	+	$(1.2, +\infty)$
Strong negative decoupling	Positive carbon emissions growth, negative economic growth	+	-	$(-\infty, 0)$
Weak negative decoupling	$\Delta NAC > \Delta AGDP$	-	-	$(0, 0.8)$
Growth links	Same proportional, approximately linear relationship	+	+	$(0.8, 1.2)$
Recessionary link	Same proportional, approximately linear relationship	-	-	$(0.8, 1.2)$

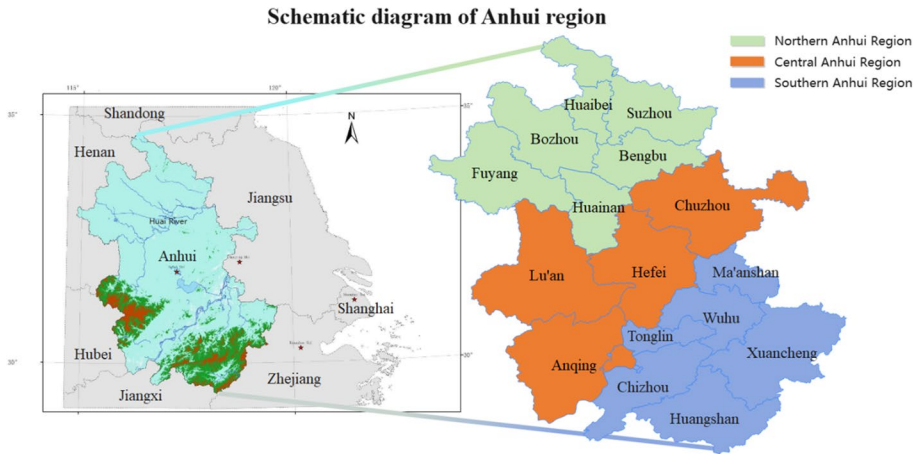


Fig. 3 Regional location map of Anhui Province

As shown in Fig. 4, the amount of carbon emitted by various locations in various years varies. Across the study area, NACI were low in Chizhou, Huangshan, Huabei, and Tongling. Fuyang had high NAC, while both NACI and NAPC were low. Tongling had low NAC, while NACI and NAPC were not on the low side. The overall trend of NACI in all regions was decreasing over time.

At some point, when doing horizontal comparisons between areas, NACI performs a better job of accurately reflecting the degree of regional ACE. Figure 5 shows that the overall NACI in Anhui Province in 2020 shows the characteristics of South Anhui > Central Anhui > North Anhui, and there are obvious differences. Among them, Huainan has the highest NACI of 0.9235 t/yuan, while Bozhou has the lowest NACI of 0.4246 t/yuan, less than one-half of Huainan.

4.3 The features of variations in carbon emissions from agricultural output in Anhui throughout time and space

Figure 6 displays the data for the years 2011–2020 after the measurements of carbon sequestration, carbon emissions, and NAC in Anhui Province. There are two sections to the research period: China's 12th Five-Year Plan, or 12th-5, runs from 2011 to 2015. China's 13th Five-Year Plan, or 13th-5, runs from 2016 to 2020.

As shown in Fig. 5, during the 12th-5, the carbon emissions from agricultural in Anhui Province increased from 59.816 million tonnes in 2011 to 62.6515 million tonnes in 2015, indicating a general higher trend; Anhui Province's carbon absorption from agricultural production experienced a trend of first falling and then rising again, while NAC rose from 16.410 million tonnes in 2011 to 19.35 million tonnes in 2011 before falling to 17.945 million tonnes in 2015. During the 13th-5, both carbon emissions and net carbon emissions showed an overall decreasing trend, which indicates that there was a noticeable decrease in emissions from agricultural in Anhui Province throughout this time. The ACE in reached a maximum of 44.707 million tonnes in 2015 for the study period, and net carbon emissions reached a maximum of 19.35 tonnes in 2013.

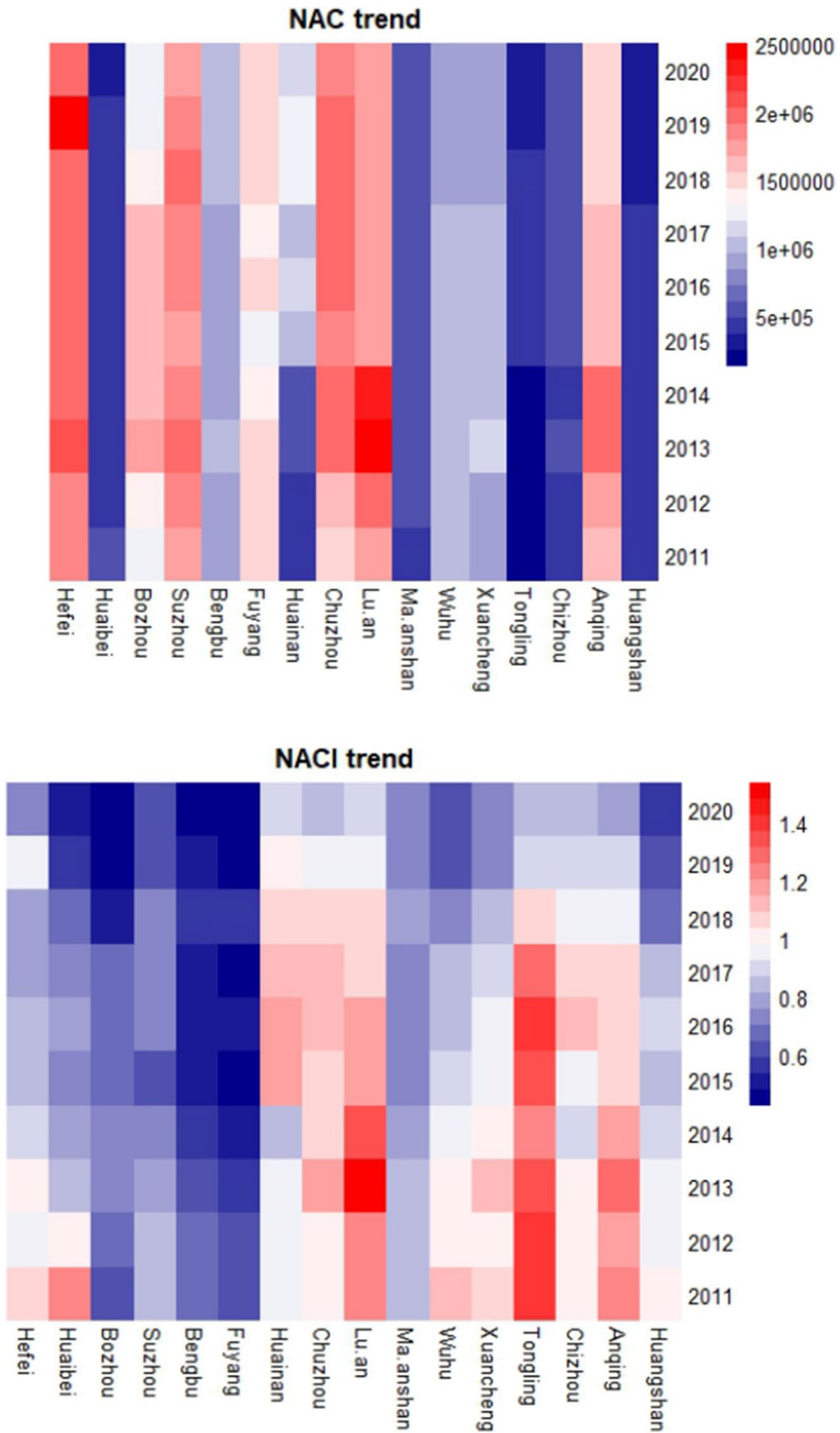


Fig. 4 Heatmap of NAC, NACI, and NAPC in Anhui, 2011–2020

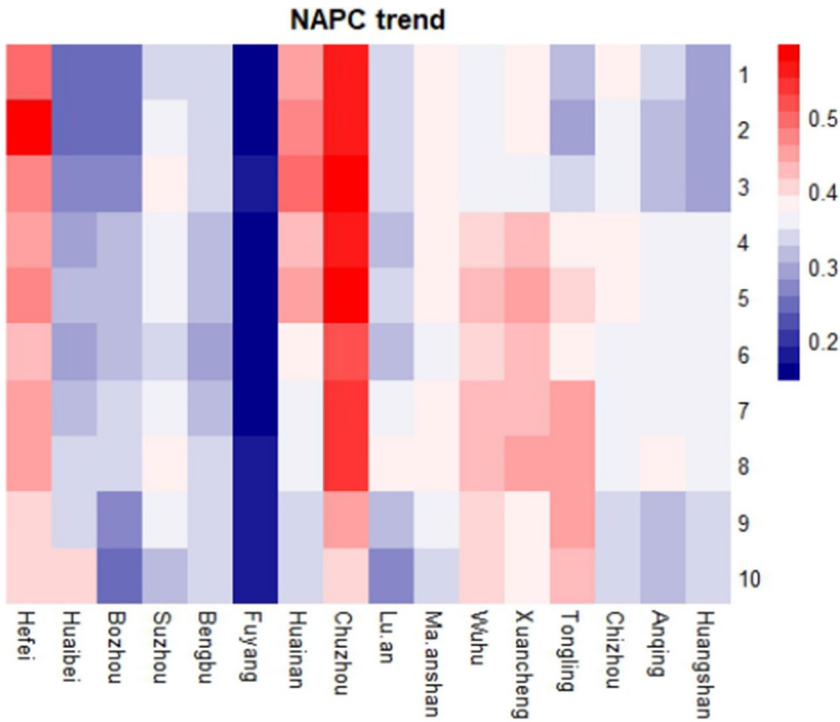


Fig. 4 (continued)

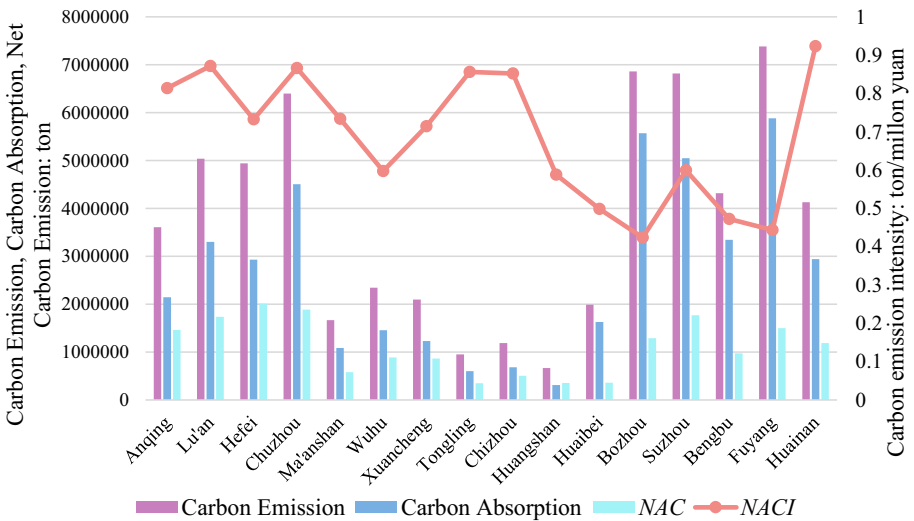


Fig. 5 Net carbon emissions and net carbon intensity of agricultural emissions across Anhui Province in 2020

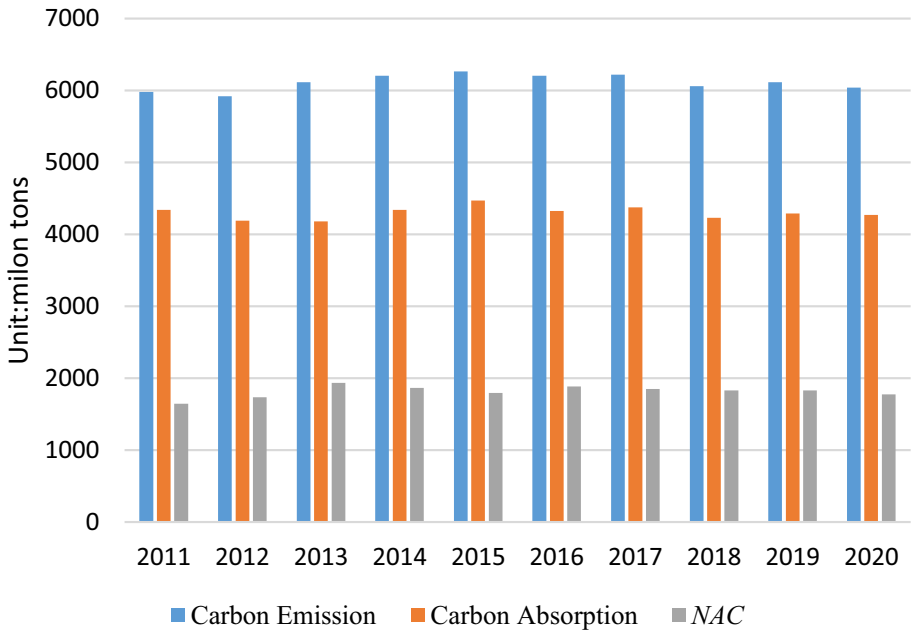


Fig. 6 Carbon emissions from agricultural production in Anhui Province, 2011–2020

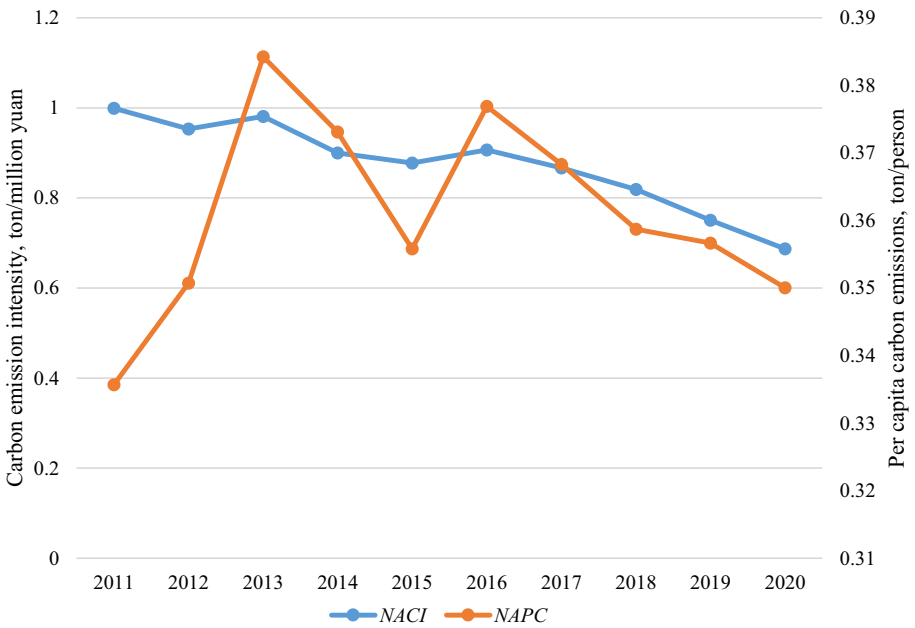


Fig. 7 Time series of agricultural carbon emissions, Anhui, 2011–2020

Figure 7 shows the NACI and NAPC in Anhui Province from 2011 to 2020. Regarding the intensity of carbon emissions, the annual average value of net carbon emission intensity in Anhui Province shows a clear downwards trend during the study period, from 0.999 *t*/yuan in 2011 to 0.687 *t*/yuan in 2020. From the perspective of net carbon emissions per capita, there was a trend of increase followed by decrease in Anhui during the 12th-5 and a decreasing trend in the 13th-5 as a whole, with net carbon emissions per capita reaching a peak in 2013.

As shown in Fig. 8, in the makeup of ACE, the main ACE were generated from agricultural production inputs. There was little fluctuation in the emissions of each type of carbon within the duration of the study. Overall, there has been a tendency for the percentage of carbon emissions from rice growth to decline, while the share of agricultural production inputs increased and then decreased from 2010 onwards. Initially, there was a tendency for the percentage of carbon emissions from burning straw to decline, reaching a minimum in 2018, and then tended to increase, reaching a maximum in 2020.

To better compare the changes in ACE in Anhui Province during the 12th-5 and 13th-5, the NACI and NAPC for each region were calculated, respectively, as shown in Fig. 9. Except for Huainan, the NACI of all regions in Anhui Province decreased significantly during the 13th-5 compared with the 12th-5, with the three cities with the largest decreases in net carbon emissions intensity being, in order, Liuan, Huabei, and Wuhu, while the net carbon emissions per capita of Hefei, Huainan, Chuzhou, Ma’anshan, and Chizhou increased during the 13th-5 compared with the 12th-5, with Huainan showing the largest increase in net carbon emissions per capita. This indicates that there is variability in the development of the ACE situation across the regions.

4.4 Analysis of agricultural carbon emission intensity spatial correlation

The global spatial autocorrelation results of the NACI in 16 cities and regions of Anhui Province between 2011 and 2020 were obtained by using GeoDa software to choose Monte Carlo simulations based on the rook first-order neighbourhood weight matrix to test Moran’s I index 999 times. Table 2 illustrates this process.

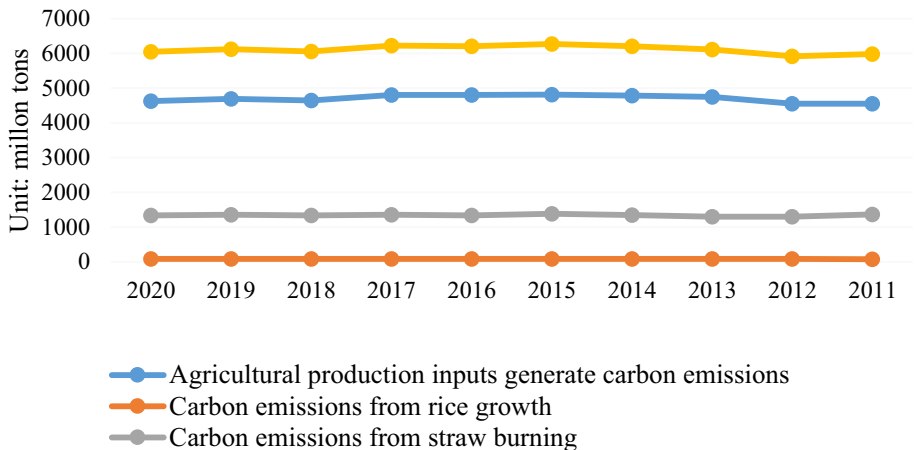


Fig. 8 The makeup of carbon emissions, Anhui, 2011–2020

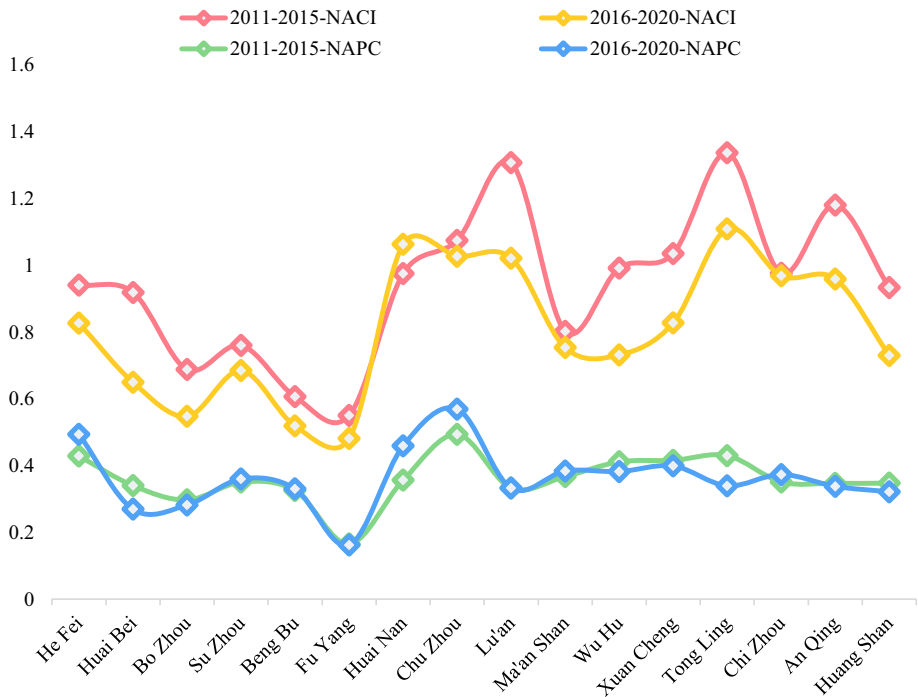


Fig. 9 The agricultural carbon emissions of different regions, 2011–2020

Table 2 Moran's I statistical values, 2011–2020

Moran's I	Z-value	P	Year
0.1596	15.092	0.078	2011
0.2019	1.7815	0.045	2012
0.1419	1.3249	0.093	2013
0.1628	1.489	0.08	2014
0.0961	1.0443	0.150	2015
0.0691	0.8543	0.197	2016
0.137	1.3101	0.100	2017
0.1188	1.1692	0.114	2018
0.2817	2.2123	0.020	2019
0.22074	1.837	0.043	2020

Through calculation, it was found that, except for the 4 years between 2015 and 2018, which failed the significance test, the rest of the years passed the 10% significance test, especially 5% in 2012, 2019, and 2020. Therefore, in 2012, 2019, and 2020, the NACI in Anhui displayed a remarkable positive global spatial autocorrelation.

As shown in Fig. 10, Moran's I index of the NACI in Anhui Province shows an overall trend of first decreasing and then increasing during 2011–2020, achieving a 0.0691 minimum value in 2016 and a maximum value of 0.2817 in 2019, reflecting that the positive spatial correlation of the NACI shows an increasingly strong trend.

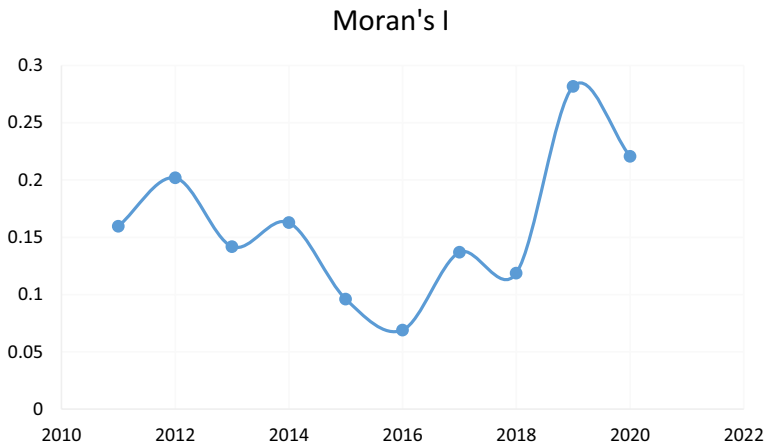


Fig. 10 Trend of Moran's I index, 2011–2020

LISA clustering and LISA significance analysis were chosen in order to further assess the geographical correlation and variations between the NACI in each municipality and the surrounding agricultural output. Table 3 displays the analysis's findings. During the period 2011–2020, Anqing, Hefei, and Huabei all passed the 5% significance test, while Anqing was always in the high–high region of agglomeration, Hefei was in the region of low–high agglomeration in 2012, 2015, 2016, 2017, and 2018, and the rest of the years were in the area of high–high agglomeration. Huabei was in the low–low region of agglomeration during 2013–2020, and the rest of the years were in the area of high–low agglomeration.

4.5 Analysis of decoupling effects

In the light of China's 5-year plan's history, this study conducts decoupling research every 5 years and calculates the decoupling index for the two periods of 2011–2015 and 2015–2020 to depict how ACE and economic growth relate to one another across various 5-year planning horizons decoupling features. This paper takes 2011 and 2016 as the base years and calculates the decoupling results during the 12th-5 (2011–2015) and the 13th-5 (2016–2020), Table 4 illustrates this.

During the 12th-5, the decoupling type of five cities in Anhui Province was strong decoupling, six regions had weak decoupling, two cities had expansion negative decoupling, and two cities had growth links. In most areas of Anhui Province, a phenomena of both strong and weak decoupling between ACE and growth in the agricultural economy were observed. With the worst decoupling status and the highest decoupling index of 21.23 at this time, Lu'an's ACE growth rate exceeded that of the agricultural economy. This indicates that the city is experiencing recessionary decoupling. With negative growth in ACE and a rapidly developing agricultural sector, Huaibei had the lowest decoupling index and the best decoupling status.

Table 3 Results of LISA significance and agglomeration distribution

Year	Significant areas	High-high	Low-high	Low-low	High-low
2011	Anqing, Hefei, Chizhou, and Huaibei	Anqing, Hefei, and Chizhou			Huaibei
2012	Anqing, Chizhou, Hefei, Bozhou, and Huaibei	Anqing and Chizhou	Hefei	Bozhou	Huaibei
2013	Anqing, Hefei, Bozhou, and Huaibei	Anqing and Hefei		Bozhou and Huaibei	
2014	Anqing, Hefei, Bozhou, and Huaibei	Anqing and Hefei		Bozhou and Huaibei	
2015	Anqing, Hefei, and Huaibei	Anqing	Hefei	Huaibei	
2016	Anqing, Hefei, and Huaibei	Anqing	Hefei	Huaibei	
2017	Anqing, Hefei, and Huaibei	Anqing	Hefei	Huaibei	
2018	Anqing, Hefei, and Huaibei	Anqing	Hefei	Huaibei	
2019	Anqing, Hefei, and Huaibei	Anqing, Hefei	Hefei	Huaibei	
2020	Anqing, Hefei, and Huaibei	Anqing, Hefei		Huaibei	

Table 4 The situation of decoupling in Anhui

City	12th-5 (2011–2015)		13th-5 (2016–2020)	
	Decoupling index	Status	Decoupling index	Status
Hefei	0.1375	W	0.086	W
Huabei	-0.9487	S	-0.6558	S
Bozhou	1.2971	E	-0.967	S
Suzhou	0.0815	W	-0.5031	S
Bengbu	-0.2878	S	0.298	W
Fuyang	-0.5068	S	0.2198	W
Huainan	1.4692	E	0.1675	W
Chuzhou	1.1699	G	-0.2836	S
Lu'an	21.2339	D	-0.0007	S
Ma'anshan	0.246	W	0.8484	G
Wuhu	-0.0558	S	-0.4129	S
Xuancheng	0.5091	W	-1.2469	S
Tongling	0.9778	G	-0.8593	S
Chizhou	0.5741	W	-0.0994	S
Anqing	-0.2248	S	-0.4033	S
Huangshan	0.1798	W	-0.7158	S

S is strong decoupling, *E* is expanding negative decoupling, *W* is weak decoupling, *G* is growth links, and *D* is declining decoupling

During the 13th-5, most areas in Anhui Province showed a relatively good decoupling state. There were 11 prefectures and cities with strong decoupling, four prefectures and cities with weak decoupling, and only Ma'anshan city with growth links. During this period, Xuancheng had the lowest decoupling index and the best decoupling status. From the 12th-5 to 13th-5, Anhui Province had a rise in the number of prefectures and cities with significant decoupling, and the global situation of decoupling has been optimised. This also shows that the sustainable and green development of agriculture in Anhui Province has achieved good results.

5 Discussion

5.1 Comparing related literature

Throughout the previous literature, scholars specialised on the calculation of ACE in the study of ACE reduction. Compared to Jiang et al. (2021) and Liu et al. (2022), this study measures the ACE more accurately, considers carbon sources and sinks from the perspective of the whole life cycle, and measures the ACE in Anhui Province. The major sources of ACE in Anhui Province and the trends in the share of each source have been analysed. Second, while examining the features of ACE's temporal and geographical dispersion, different from Zhang and Li (2022) and Cui et al. (2022), the Moran index was used to

analyse the ACE across Anhui Province in this study. After evaluating the worldwide spatial autocorrelation of agricultural carbon emission intensity across the research period, it was determined that, from 2011 to 2020, there was a rising tendency in the positive spatial correlation of agricultural production's carbon emission intensity; the local autocorrelation of different years in different parts of Anhui Province during 2011–2020 was analysed. Furthermore, the Tapio decoupling index utilised in the decoupling impact investigation by Jiang et al. (2021) and Wang et al. (2017) has been incorporated into this work. In the light of China's 5-year plans, the decoupling impact between ACE and agricultural economic growth was examined for both the 12th and 13th Five-Year Plan periods. The definition and comparative analysis of each region's decoupling status by period better investigates the state of sustainable agricultural development and development trends across Anhui Province.

5.2 Theory implications

Firstly, the goal of this research is to provide a life cycle assessment theory-based method for calculating net ACE that account for carbon sources, sinks, and the entire agricultural production process. This enables the ACE to be mapped more accurately and enhances the conceptual basis of research on ACE. Secondly, in the process of evaluating regional net ACE status, the spatial correlation analysis method is incorporated, which could more intuitively present the dynamical trend of evolution and configuration characteristics of ACE. When compared to earlier research, a more accurate and comprehensive evaluation of ACE has been achieved, laying the foundation for proposing targeted agricultural carbon emission reduction optimisation measures. Finally, in the framework of China's 5-year plan, a decoupling impact analysis was carried out to examine the link between net ACE and economic development in various 5-year planning periods. Based on the examination of regional agricultural decoupling states, it offers a more accurate and scientific theoretical foundation for advancing sustainable agricultural growth.

5.3 Managerial implications

A theoretical foundation for standardising the measurement of carbon emissions from agricultural output may be established by looking at net ACE from the standpoint of carbon sources and sinks. The analysis of the dynamic evolution trend and distribution characteristics of ACE provides advice and suggestions for the formulation of targeted emission reduction measures and superior advancement in agricultural production. Moreover, this study analysed the decoupling characteristics of ACE and economic growth in different 5-year planning periods in the context of China's 5-year planning and, based on the analysis results, provided decision support for the government and agricultural researchers to address low-carbon and sustainable development in agriculture.

5.4 Policy recommendations

In the light of the data analysis's findings and conclusions, the following suggestions are offered to further encourage low-carbon growth in agriculture: (1) Considering the complexity and differences between regions, differentiated farming practices that reduce carbon emissions ought to be developed according to local conditions. Regarding areas with low per capita and carbon emissions intensity, industrial and structural changes should be mainly encouraged to guide agricultural production in the direction of modernisation and development. (2) Scientific and technological innovation and promotion, especially in the area of total mechanical power, should be strengthened, and research efforts to raise the capacity for agricultural output to lower emissions should be enhanced. (3) Finally, the regions can actively introduce the resource allocation role of the carbon market and play the government's primary role in planning, market regulation, and operation to create a favourable environment for agricultural development.

6 Conclusions

It is important to accurately measure the ACE and to reasonably evaluate the state of ACE and economic growth to promote global sustainable development. This study constructed a method to measure net carbon emissions from agricultural production based on the LCA perspective and to analyse the decoupling state between net carbon emissions from agricultural production and economic growth at different time periods. The feasibility of the method was verified using Anhui Province as an example. There were regional variations in ACE, and the positive spatial correlation of the intensity of carbon emissions from agricultural production indicated a strong trend. It was discovered that the net carbon emissions from agricultural production in Anhui Province peaked in 2013 at 19.35 million tonnes, as did the per capita carbon emissions. In Anhui Province, the number of municipalities with strong decoupling grew during the 13th Five-Year Plan period compared to the 12th Five-Year Plan period, and the decoupling status was optimised overall. The defining of Anhui's decoupling status and the examination of the calculation of net carbon emissions from agricultural output have both aided in the successful promotion of sustainable regional agricultural growth.

However, some limitations exist in this study. Firstly, carbon emissions from all agricultural activities, such as manure management, were not considered when measuring carbon emissions from agricultural production, while carbon sinks were only considered for rice cultivation. Secondly, only ACE were analysed in terms of both spatial and time features, without further analysis of the drivers. In further research, the accuracy of the net carbon emissions assessment will be increased by sorting the carbon emission components more thoroughly and taking into account the carbon sinks of different crops according to the region's true relevance. Moreover, future study on ACE can also improve the findings by building appropriate regression models to measure the elements that influence ACE.

Appendix 1

See Table 5.

Table 5 Inventory of measured carbon emissions, agricultural production, Anhui

Indicators	Elements	Forms	Carbon emission factor	References	
Carbon emissions	Fertilisers	Nitrogen fertiliser	3.392 kg (C)/kg	Cui et al. (2022)	
		Phosphate fertiliser	0.636 kg (C)/kg	Cui et al. (2022)	
		Potash	0.180 kg (C)/kg	Cui et al. (2022)	
		Compound fertilisers	0.38097 kg (C)/kg	Cui et al. (2022)	
	Pesticides		4.9341 kg (C)/kg	Cui et al. (2022)	
	Agricultural film		5.18 kg (C)/kg	IREEA	
	Diesel		0.5927 kg (C)·kg ⁻¹	IPCC (2006)	
	Irrigation		266.48 kg (C)/hm ²	Tian et al. (2014)	
	Tilling		312.6 kg (C)/km ²	College of Biotechnology, China Agricultural University	
	Machinery	Crop area		16.47 kg (C)/hm ²	Cui et al. (2022)
		Total machinery power		0.18 kg (C)/kW	Cui et al. (2022)
	Rice production	Area of paddy fields		31.90 g (C)/m ²	He et al. (2022)
Straw burning	Straw yield		1.515 kg (C)/kg	Streets et al. (2003)	

Appendix 2

See Table 6.

Table 6 Grass-to-grain ratio for various crops

Name	Grass valley ratio	Name	Grass valley ratio
Rice straw	0.9	Oilseed rape	1.5
Wheat straw	1.1	Peanut	0.8
Maize	1.2	Sugarcane	0.06
Beans	1.6	Sugar beet	0.1
Potato	0.5	Tobacco	1.6
Cotton straw	3.4	Sesame	2.2

Appendix 3

See Table 7.

Table 7 Inventory of carbon sequestration measurements for agricultural production in Anhui Province

Varieties	Economy factor	Water content (%)	Carbon absorption rate
Rice	0.45	12	0.414
Potato	0.7	70	0.423
Wheat	0.4	12	0.485
Sugarcane	0.5	50	0.45
Maize	0.4	13	0.471
Sugar beet	0.7	75	0.407
Beans	0.34	13	0.45
Vegetables	0.6	90	0.45
Rapeseed	0.25	10	0.45
Melons	0.7	90	0.45
Peanuts	0.43	10	0.45
Tobacco	0.55	85	0.45
Sunflower	0.3	10	0.45
Cotton	0.1	8	0.45
Other crops	0.4	12	0.45

Author contributions YMW helped in conceptualisation; FWG and MCL helped in methodology; YMW and DC worked in data curation; YMW and MCL contributed to writing—original draft preparation; and YMW and ZZL contributed to writing—review and editing. All authors read and approved the final manuscript.

Funding This work was supported by the general project of Anhui Provincial Philosophy and Social Science Planning Project (Grant number [AHSKY2022D082]).

Data availability The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval Not applicable.

Consent to participate Not applicable.

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