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Article

Spatiotemporal analysis of greenhouse gas emissions from agriculture: case study in Shandong Province, China

Fang Yin[1,2], Shijuan Guo[1,2], Linchen Liu[1,2], Shouhan Li[1,2], Xiaoyan Zhang[1,2], Chaobin Zhang[1,2], Liping Yang[1,2,*], Zhaohua Wang[1,2,*]

[1] Institute of Agricultural Information and Economics, Shandong Academy of Agricultural Sciences, Jinan 250100, China
[2] Rural Revitalization Research Institute, Shandong Academy of Agricultural Sciences, Jinan 250100, China
*** Corresponding authors:** Liping Yang, yangping96@163.com; Zhaohua Wang, wangzhaohua1971@163.com

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Abstract: The role of agriculture in greenhouse gas emissions and carbon neutrality is a complex and important area of study. It involves both carbon sequestration, like photosynthesis, and carbon emission, such as land cultivation and livestock breeding. In Shandong Province, a major agricultural region in China, understanding these dynamics is not only crucial for local and national carbon neutrality goals, but also for global efforts. In this study, we utilized panel data spanning over two decades from 2000 to 2022 and closely examined agricultural carbon dynamics in 16 cities of the Shandong Province. The method from the Intergovernmental Panel on Climate Change (IPCC) was used for calculating agricultural carbon sinks, carbon emissions, and carbon surplus. The results showed that (1) carbon sink from crops in the Shandong Province experienced growth during the study period, closely associated with the rise in crop yields; (2) a significant portion of agricultural carbon emissions was attributable to gastrointestinal fermentation in cattle, and a reduction in the number of stocked cattle led to a fall in overall carbon emissions; (3) carbon surplus underwent a significant transition in 2008, turning from negative to positive, and the lowest value of carbon surplus was noticed in 2003, with agriculture sector reaching the carbon peak; (4) the spatial pattern of carbon surplus intensity distinctly changed before and after 2005, and from 2000 to 2005, demonstrating spatial aggregation. This research elucidates that agriculture in Shandong Province achieved carbon neutrality as early as 2008. This is a pivotal progression, as it indicates a balance between carbon emissions and absorption, highlighting the sector's ability in maintaining a healthy carbon equilibrium.

Keywords: agricultural carbon sink; carbon surplus; spatial heterogeneity; carbon peak; carbon neutrality

1. Introduction

Global climate change is a monumental issue that affects us all in different ways. Carbon neutrality is about balancing the scale between emitting carbon and absorbing carbon, leading to no net increase in CO_2 levels in the atmosphere. Rogelj et al.'s definition puts it well—it's about CO_2 emissions from all sources caused by human actions being effectively zero. To achieve this, the CO_2 we produce needs to be either captured and stored, or absorbed by processes such as reforestation or through carbon capture technologies (Fankhauser et al., 2022; Rogelj et al., 2015; Van Soest et al., 2021). Indeed, global greenhouse gas (GHG) emissions have been on an upward trend due to a variety of factors, such as unsustainable energy use, land use and land-use change, consumption and production patterns, and inequality among regions and histories (Calvin et al., 2023). In 2019, there was 59.1 billion tons of CO_2—equivalent globally, reaching the highest GHGs emissions in human history. The world is on track for more than 3 °C of warming by the end of the century (Holden et al., 2018; Sha et al., 2022). Consequently, recognizing and addressing these challenges is crucial in the fight against climate change. The increase in GHGs emissions highlights the urgency for more aggressive and efficient mitigation strategies. These include transitioning to renewable energy, upgrading infrastructure for energy efficiency, adopting sustainable agriculture practices, and investing in green technologies.

Agriculture operates on both sides of the carbon equation. It's a significant source of emissions, while also having great potential for carbon sequestration. First, the conversion of forests and grasslands to farmland leads to large upfront emissions due to the loss of carbon stored in vegetation and soils. Then, ongoing emissions come from agricultural practices such as rice production and the raising of livestock, especially ruminant animals like cows that produce methane. The use of synthetic fertilizers also leads to significant nitrous oxide emissions. Finally, energy use in the agriculture sector, from machinery to transport, contributes to its overall emissions (She et al., 2017). Agricultural activities are responsible for the potential greenhouse effect, CO_2 has the greatest climate forcing potential (57%), while CH_4 and N_2O account for 27% and 16%, respectively (Johnson et al., 2007; Zhong et al., 2017). Conversely, agriculture can play a significant role in carbon sequestration, which is the process of capturing and storing atmospheric carbon dioxide through photosynthesis. In this paper, we focus on the carbon sink from crops planting, and the carbon emissions from inputs and livestock breeding during producing processing. By concentrating on the production process, we aim to shed light on the environmental implications of different aspects of the agrarian system and propose actionable steps for creating more sustainable, less carbon-intensive farming practices in the future.

China is a large agricultural producer as well as a developing country and is highly dependent on agriculture, the emission from agriculture accounting for 16–17% of the total emissions (Liu and Yang, 2021), higher than the global average proportion 11.5% (Cui et al., 2022; Liu et al., 2020). The Chinese government's pledge to peak its CO_2 emissions before 2030 and achieve carbon neutrality by 2060 at the 75th UN General Assembly in 2020 demonstrates its determination to tackle climate change and contribute to global emission reduction efforts (Hou, 2023). To realize this goal, various sectors in China including energy, manufacturing and agriculture will have to undergo significant transformations. For the agricultural sector, this includes adopting practices that enhance carbon sinks in crop production and minimize carbon emissions associated with inputs and livestock breeding. Over the last few decades, China's crop production has been developed under intensive agriculture with high inputs of fertilizers and pesticides but limited use of conservation tillage (Gong, 2020). However, low carbon approaches have been recently encouraged by the national climate change policy of China (She et al., 2017; Zeng et al., 2022). In this paper, the carbon sink from crops planting and carbon emission from inputs of agricultural materials and livestock breeding were both estimated to figure out whether agriculture could be carbon surplus and contribute to the total carbon neutrality.

Shandong Province have had the highest agricultural total output value (ATOV) in China since 1990, and it has 6% cropland and 1% water resource to produce 8% crops, 11% fruit and 12% vegetable, which indeed makes it an interesting and representative case study for agricultural practices. The ecological protection and high-quality development strategy in the Yellow River basin since 2012, especially in an agriculturally significant region such as Shandong, makes it an excellent choice as a study area. Given its agricultural prominence and location along the Yellow River basin, changes implemented in Shandong Province could have significant implications for China's efforts to reach its CO_2 emissions goals (Wang et al., 2023). Studying agricultural structure and practices, carbon sinks and carbon emissions in Shandong can provide useful insights that could potentially be applied more widely across China and even other countries with similar contexts. Moreover, these findings could guide local and national policy development and implementation toward more sustainable agriculture (Deng and Gibson 2019). The outcomes and improvements seen in Shandong Province could hence serve as a model for other regions in China and globally, providing practical steps for other regions to follow in achieving net-zero CO_2 emissions. It also serves as a reminder of the intricate links between local agricultural policies and practices and global environmental goals.

At present, the research on agricultural carbon emission is relatively abundant and extensive at various scales—global, national and regional (Chen et al., 2020; Frank et al., 2019; Liu and Yang 2021; Xiong et al., 2016; Zhang et al., 2010) on the whole agricultural cycle (Cui et al., 2022) and specifical steps (Finger et al., 2023; Liu et al., 2015). Some studies on the sequestering C in agricultural soil (Jian et al., 2020; Jiang et al., 2014; Sun et al., 2020; Vendig et al., 2023), and as a carbon sink, crop production was also analyzed deeply (Kenne and Kloot 2019; She et al., 2017). Furthermore, differ from industry, agriculture has the dual characteristics of carbon emission and carbon sink, carbon emission has negative externalities, while carbon sink has positive externalities (reduction effect), but most measurements of agricultural emissions have been partial and fail to provide a comprehensive view, accounting for both these aspects. This makes it challenging to formulate effective and differentiated reduction policies that optimally balance these dual characteristics. Performing a scientific and accurate assessment of these net carbon emissions—considering both the emissions and absorption by agricultural activities—is truly an essential step. By understanding the spatiotemporal evolution of these emissions, one can identify key trends and hotspots, to develop tailored strategies for specific regions. Additionally, it can shed light on the influence of various farming practices on the overall carbon balance, further guiding mitigation actions.

The methods on carbon emissions estimation mainly include: atmospheric models, mostly predicting global and regional emissions (García et al., 2020; Hulley et al., 2016; Zeng et al., 2022) process models, simulating biological and physical processes that directly affect carbon stocks and GHG emission (Zheng et al., 2020); emission inventories, summarizing the enumerated emission factors with emission coefficients (Akbar et al., 2021; Chen et al., 2021; Liang et al., 2021) empirical models, based on observational data and statistical methods and integrated assessment models, incorporating the interaction of physical, chemical, and biological processes within the Earth system (Calvin et al. 2023). Each method has its distinct advantages and shortcomings, which need to be considered carefully in deciding which one to use for specific applications or analyses. Using a combination of robust and complementary methodologies could also help to ensure a more comprehensive and reliable assessment of carbon emissions (Chen et al., 2020; Huang et al., 2019). This paper would present a comprehensive analysis of carbon sinks and emissions specifically from the agricultural sector in Shandong Province. The central aim is to elucidate the role this key sector plays in enabling the province to reach its national carbon-neutral ambitions. The remaining sections of this paper are organized as follows. Section 2 describes the detailed information of Shandong Province, the sources of study materials and methods. Section 3 illustrates the results to capture the findings from the analysis of carbon sinks and emissions from the agricultural sector in Shandong Province. Discussion, and conclusions are provided in Sections 4 and 5, respectively.

2. Materials and methods

2.1. Study area

Shandong Province holds a significant role in China being one of the country's breadbaskets. This strategic location has achieved a milestone of reaching an agricultural output of a thousand billion yuan, demonstrating its critical contribution to China's agroeconomics. Geographically, Shandong Province is nestled in the eastern coastal region of China, spanning longitudes 114°47.5′ E to 122°42.3′ E, and latitudes 34°22.9′ N to 38°24.0′ N. The area covers a substantial total landmass of 15.8 million hectares, nearly half (48.2%) of which is composed of cropland, equating to about 7.6 million hectares. The region is characterized by its high-quality soil, a fundamental aspect for abundant agricultural productivity. The hydrographic system of Shandong Province displays a radial pattern due to higher elevations at the center, with lower surrounding areas, creating a unique topographic setting for water distribution. Climate-wise, Shandong Province falls under a warm temperate monsoon category. It enjoys four distinct seasons with a favorable combination of hot temperatures coinciding with the rainy period, creating a conducive environment for a variety of agricultural activities. The annual average temperature fluctuates between 11 °C and 14 °C, while the precipitation levels range from 550 mm to 950 mm. This climatic scenario aids in maintaining soil fertility and crop health, essential factors for agriculture-based provinces like Shandong.

2.2. Data

The research deployed for the study primarily draws upon data extracted from two substantive sources: the Shandong Statistical Yearbook and the China Rural Statistical Yearbook, covering a substantial period from 2000 to 2022. The study incorporated a comprehensive approach by creating a vast and diverse panel dataset at the provincial and prefectural levels. Querying the databases yielded abundant data that not only included crop-specific statistics such as harvested area, production, and yield for a wide variety of crops like rice, corn, wheat, sorghum, millet, beans, tuber crops, cotton, vegetables and so on, but also encompassed relevant livestock data. The latter considered the count of several livestock types, including cattle, pigs, sheep, goats, poultry, and hare at the end of each year, along with the number of livestock slaughtered annually. This information helps to understand the contributions of different animal farming sectors to the overall agricultural landscape. To make the research even more comprehensive, agricultural inputs were included in the panel data. These inputs switch focus to areas such as usage of fertilizers, pesticides, and plastic film; total power of agricultural machines; diesel used, and the total irrigated area. Total agricultural output added value in this dataset was converted into current monetary value by using the production price index. This conversion accounts for inflation and other economic changes over time, thereby providing a clearer understanding of the agricultural sector's economic value in today's terms. Overall, this panel dataset forms a crucial part of the study, offering a robust basis for assessing Shandong's agricultural practices, output, and their implications for carbon sequestration and emissions.

2.3. Carbon sink from agriculture

In the context of agriculture, a carbon sink refers to the process by which plants absorb carbon dioxide from the atmosphere during photosynthesis, store it in their tissues, and then release oxygen back into the environment. In this study, key elements such as the structure of planting and data availability were considered, and fourteen crops were selected for scrutiny based on these criteria. According to crops' production, moisture content, carbon absorption rate and economic coefficient, carbon sink can be calculated, and the formula shown as follows:

$$C_s = \sum_{i=1}^{14} C_{fi} \cdot P_i \cdot (1 - w_i)/H_i \tag{1}$$

In Equation (1), C_s stands for the carbon absorption of crops (Ton), namely carbon sink; C_{fi} means carbon absorption rate; P_i refers to production of crop (Ton); w_i indicates moisture content rate; and H_i presents economic coefficient of crops. For each crop, the carbon absorption rate, moisture content rate and economic coefficient were shown in **Table 1**.

Table 1. Economic coefficient, moisture content and carbon absorption rate of main crops in China*.

Crops	Carbon absorption rate (C_{fi})	Moisture content (w_i)	Economic coefficient (H_i)
Wheat	0.485	0.12	0.4
Rice	0.414	0.12	0.45
Corn	0.471	0.13	0.4
Millet	0.45	0.12	0.42
Sorghum	0.45	0.12	0.35
Other cereal	0.45	0.12	0.4
Bean	0.45	0.13	0.34
Tuber	0.4226	0.7	0.65
Cotton	0.45	0.08	0.1
Peanut	0.45	0.1	0.43
Rapeseed	0.45	0.1	0.25
Tobacco	0.45	0.85	0.55
Vegetable	0.45	0.9	0.6
Melon	0.45	0.9	0.7

* From IPCC and Tian (2013).

2.4. Carbon emission estimation from agriculture

The greenhouse gases with the largest contribution to rising temperature are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The converting coefficients of C, N_2O and CH_4 to CO_2 are 44/12, 28 and 265, respectively. To sum up total emissions, we calculated carbon equivalents (C_{eq}) for methane and nitrous oxide from all sources.

In this study, the calculation of agricultural carbon emissions was done using emission inventories. The analysis considered various aspects related to agriculture and their correlation to carbon emissions, including agricultural material inputs, land use and livestock farming. By taking all these aspects into consideration with their respective emission coefficients, a comprehensive estimation of agricultural carbon emissions was attained. The study referred to the research findings of the Intergovernmental Panel on Climate Change (IPCC) and the agricultural carbon emissions model was established in Equation (2).

$$C_e = \sum E_i = \sum (T_i \times \delta_i) \tag{2}$$

where, C_e refers to the total carbon emission from agriculture, E_i presents carbon emission from i carbon sources, T_i stands for the activity level of i carbon sources, i.e., the amount of a production factor put into use or livestock production; and δ_i is the corresponding carbon emission coefficient (**Table 2**).

Table 2. Carbon emission sources, coefficient for plantation industry*.

Carbon sources: agriculrual material input	Carbon emission coefficients	Carbon sources: land utilizaiton	Carbon emission coefficients
Fertilizer	0.8956 kg (C)/kg	Rice	210 kg (CH_4)/hm^2 4.59 kg (N_2O)/hm^2
Pesticides	4.9341 kg (C)/kg	Wheat	1.75 kg (N_2O)/hm^2
Plastic film	5.18 kg (C)/kg	Soybean	2.29 kg (N_2O)/hm^2
Power of agricultural machine	0.18 kg (C)/kw	Corn	2.532 kg (N_2O)/hm^2
Land tilling	3.126 kg (C)/hm^2	Vegetables	4.944 kg (N_2O)/hm^2
Irrigation	20.476 kg (C)/hm^2	Cotton	0.95 kg (N_2O)/hm^2
Diesel	0.5927 kg (C)/kg	Other crops	0.95 kg (N_2O)/hm^2

* The reference sources include Oak Ridge Nation Laboratory, USA (ORNL)and Institute of Resource, Ecosystem and Environment of Agriculture, Nanjing Agricultural University (IREEA), and College of Agronomy and Biotechnology, China Agricultural University (CAB).

For livestock, T_i would be the average breeding amount, and since the breeding cycles are different for different livestock type, the amount needed to adjust following Equation (3).

$$APP = \begin{cases} Herds_{end}\ Days < 365 \\ Days \times \left(\frac{N}{365}\right), Days < 365 \end{cases} \tag{3}$$

where, APP is the breeding amount for a year, $Herds_{end}$ is the stocked amount at the end of the year, $Days$ is the breeding days for livestock, and N is the slaughtered amount for livestock in the year. Pig, hare, and poultry would be adjusted with the breeding-cycle days: 200, 105 and 55, respectively. The carbon emission coefficient of livestock was shown in **Table 3**.

Table 3. Carbon emission coefficient for livestock*.

Carbon source	Gastrointestinal fermentation	Manure management	
	kg (CH_4)/(head•a)	kg (CH_4)/(head•a)	kg (N_2O)/(head•a)
Cattle	63.7	4.25	1.118
Sheep	8.6	0.16	0.093
Pig	1.0	3.12	0.227
Poultry	–	0.01	0.007
Hare	0.254	0.08	0.02

* Reference source is IPCC (2006).

Carbon emission coefficient of cattle is the average of emission coefficients of cows and cattle with the ratio of cow and cattle in Shandong Province in 2021, i.e., cow:cattle = 86.1:279.76; that of sheep is the average of goats and sheep, since the amount of them are almost equal; that of poultry is the average of chickens, geese, ducks, and turkey.

The carbon net contribution to carbon neutrality from agriculture was defined as carbon sink subtracting carbon emission, i.e., net carbon, as following Equation (4):

$$C_n = C_s - C_e \tag{4}$$

where, C_n is net carbon absorbed by agriculture, C_s and C_e are the estimation results of agricultural carbon sink and carbon emission from Equations (1) and (2).

2.5. Intensity of carbon surplus

The intensity of net carbon (INC) is the indicator for level of agricultural development, and the INC could be established as carbon surplus divided by GDP of primary industry. The estimation formula of INC can be expressed as follows:

$$INC = C_n / PriGDP \tag{5}$$

where INC indicates intensity of carbon surplus from agriculture, C_n has the same meaning as Equation (4), $PriGDP$ is the GDP of primary industry, also called agricultural added value.

2.6. Spatial exploratory analysis

Moran's I reflects the spatial aggregation or diffusion characteristics. To test whether INC of a certain city is related to or convergent with its neighboring cities, we calculated the global Moran's I as followed Equation (6):

$$MI = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} \omega_{ij} \left(INC_i - \overline{INC}\right)\left(INC_j - \overline{INC}\right)}{\sigma^2 \sum_{i=1}^{n} \sum_{j=1}^{n} \omega_{ij}} \tag{6}$$

where ω_{ij} is an element of the spatial weight matrix, and in this study we use contiguity principle to generate the spatial matrix (Zhou and Lin, 2008). INC is the result from Equation (5), $\overline{INC}$ is the average INC of each city in Shandong Province. MI means Moran's I value in [−1, 1]. A value exceeding 0 indicates a positive spatial correlation, and on the contrary, a value less than 0 indicates a negative spatial correlation. When MI closer to 0, the more random spatial distribution of INC.

3. Results

3.1. Temporal characteristics of carbon sink and carbon surplus

3.1.1. Carbon sink from planting industry

The total carbon sink of the planting industry, which measures the amount of carbon dioxide absorbed from the atmosphere by plants, has shown a growth trend. The study found that the total carbon sink increased from 5.02×10^7 tons to 6.76×10^7 tons, indicating a substantial enhancement in the carbon capture capacity of the industry (**Figure 1**). This increase corresponds to an annual growth rate of 1.58%, suggesting a consistent and significant improvement year-over-year. But from 2000 to 2002, there was a slight decline in the total carbon sink of the planting industry. This decrease is attributed to the decline in the yield of wheat and corn during this period. Since wheat and corn are the primary crops in Shandong Province from the production and yield, carbon sink from them accounted for the most part of total amount, increasing from 3.48×10^7 tons to 5.46×10^7 tons, and the proportion increased from 69% to 82%. Vegetables took the third place for the total carbon sink at average about 10%, but at decreasing trend. The follows ranking for the proportion are peanut and cotton, and that of peanut fluctuant declined from 7% in 2000 to 4% in 2022, while that of cotton increased from 5% in 2000 to 9% 2004 but dropped to 1% in 2022. We also calculated the carbon sink from each crop per hectare (Appendixes **Table A1**). All types of crops increased in the carbon sink per hectare since the yield of each crop increased during the study period. Carbon sink per hectare from wheat, rice and corn were much higher than that from other crops, with 5.01, 5.08 and 5.75 tons/ha in 2000 and 7.04, 6.89 and 6.94 tons/ha in 2022, respectively.

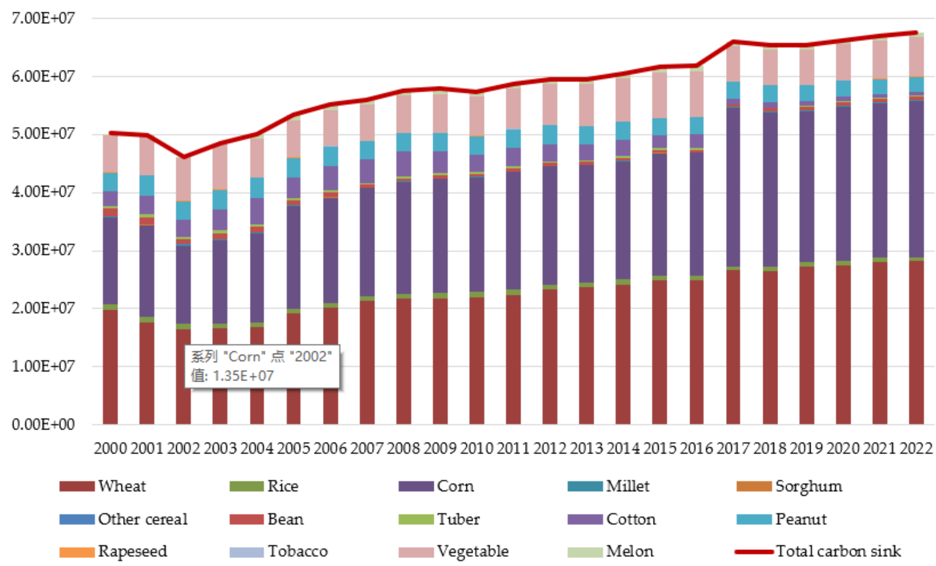

Figure 1. Total and structure of carbon sink in Shandong Province, 2000–2022.

3.1.2. Carbon emission from agricultural material inputs, land utilization and livestock breeding

- Carbon emission from agricultural material inputs

Figure 2 presented indicate a two-stage trend in the total carbon emissions caused by material inputs in agriculture. Before 2007, there was an observed increase in carbon emissions. It increased by 25% from 6.70 × 10^6 tons in 2000 to 8.35 × 10^6 tons in 2007, but after 2007, the trend reversed and there was a subsequent decline by 27% to 6.07 × 10^6 in 2022. Among all the agricultural material inputs, fertilizer use is the predominant contributor to carbon emissions, accounting for an average of 54% of the total emissions. The temporal characteristics of carbon emissions produced by fertilizer use follow a similar trend to the total carbon emissions from all agricultural inputs. The use of plastic films, diesel, and pesticides were also major contributors to carbon emissions in agricultural practices. The proportion of plastic film increased gradually from 17% to 22% during 2000 to 2022, while that of diesel and pesticides decreased with fluctuation. The Supplementary **Table A2** in the paper provides a more comprehensive breakdown of the proportion of carbon emissions originating from all types of inputs used in agricultural practices. This includes not only fertilizers, plastic films, diesel, and pesticides but also other factors that were not explicitly mentioned, such as land tilling, machinery, and irrigation.

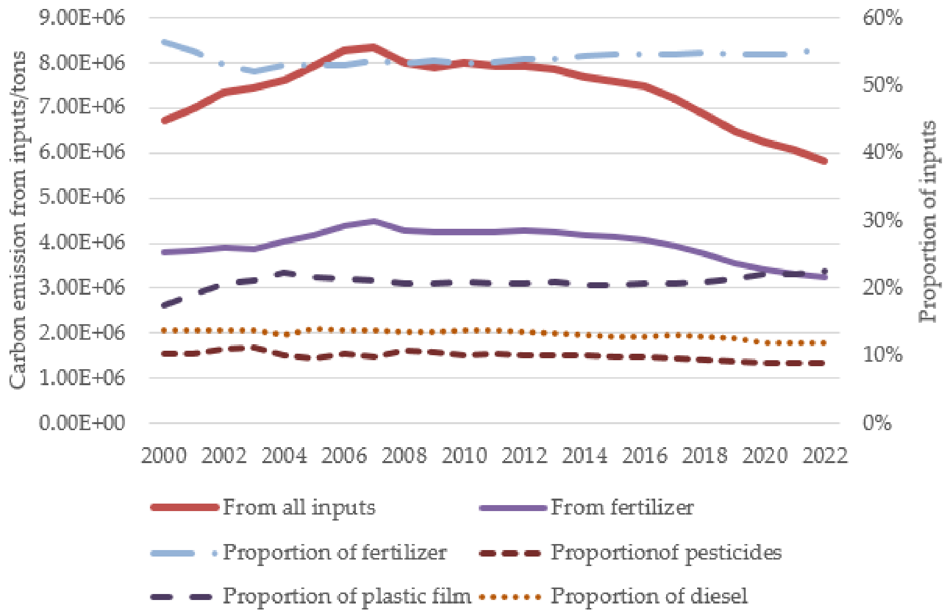

Figure 2. Carbon emission from material inputs and fertilizer, and proportion of main inputs in Shandong Province, 2000–2022.

- Carbon emission from land utilization

The carbon emissions resulting from land use in agriculture are largely dependent on the structure of crops, meaning the types and proportions of different crops grown in a specific area. In this context, the carbon emissions associated with rice cultivation emerge as a dominant factor. Rice paddies are known to emit significant amounts of methane, a potent greenhouse gas, due to the anaerobic decomposition of organic matter in flooded fields. In 2022, we found that rice cultivation accounted for a substantial 90% of carbon emissions related to land use (**Figure 3**). The data shows a marked reduction in carbon emissions associated with rice cultivation in Shandong Province from 2000 to 2022 due to a decrease in the area used for rice plantations.

There was a substantive 37% decrease in this category of emissions over the period, going from 2.89 million tons in 2000 down to 1.82 million tons in 2022. What stands out is that the largest drop in carbon emissions from rice cultivation happened in just three years, from 2000 to 2003, where they slumped by 36%. Interestingly, this reduction was identical to the overall decrease in carbon emissions from total land use in that same period.

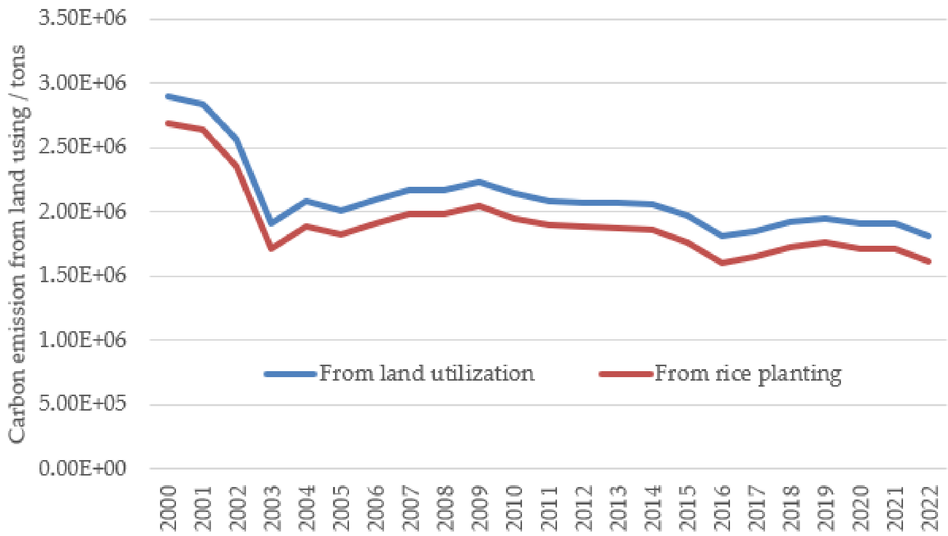

Figure 3. Carbon emission from land using in Shandong Province, 2000–2022.

- Carbon emission from livestock breeding

As per **Figure 4**, it's observed that carbon emissions from livestock in Shandong Province have been showing a noticeable decline from the year 2000 through to 2022. The results suggest some fluctuation in emissions from 2000 to 2020, but with a general downward trend. Initially, carbon emissions increased slightly from 73.5 million tons in 2000 to 78.3 million tons in 2003. However, a significant drop was noted over the next six years, with emissions falling to 44.7 million tons in 2009. Following this, there was a brief period of increasing emissions, rising by 6% from 44.7 million tons in 2009 to 47.5 million tons in 2015. Nevertheless, this upward trend did not last, with emissions subsequently plummeting to 29.2 million tons in 2020, the lowest recorded value in the given study period.

Breaking down the data by livestock type provides further insights into emission sources. It's found that in Shandong Province, cattle and sheep contributed significantly to the total emissions from livestock, making up to 91% of total emissions at the beginning of the study period. Interestingly, the carbon emissions from cattle followed a similar pattern to the overall trend, potentially showing fluctuations but generally decreasing over the period. This suggests that the strategies or factors influencing the overall decrease in livestock emissions are likely closely aligned with those specific to cattle rearing. On the other hand, the contribution of sheep emissions to the total displayed an opposing trend. Instead of a decrease, the percentage rose from 24% to 30% over the study period. In addition to cattle and sheep, another significant source of carbon emissions from livestock in Shandong Province is pig farming. The proportion of carbon emissions linked to pig farming expanded from a relatively small 8% at the beginning of the period to a significant 24% by the end. Looking at the carbon emissions from different stages of the breeding cycle, it turns out that gastrointestinal fermentation is a critical element, registering the highest contribution. However, with a decrease in cattle breeding activities over the study period, emissions from this source have notable declined from 6.54 × 10^7 tons to 2.41 × 10^7 tons. Not only did the absolute emissions from gastrointestinal fermentation decrease, but its relative contribution to total emissions also saw a drop. The proportion fell from 89% in 2000 to 77% in 2022.

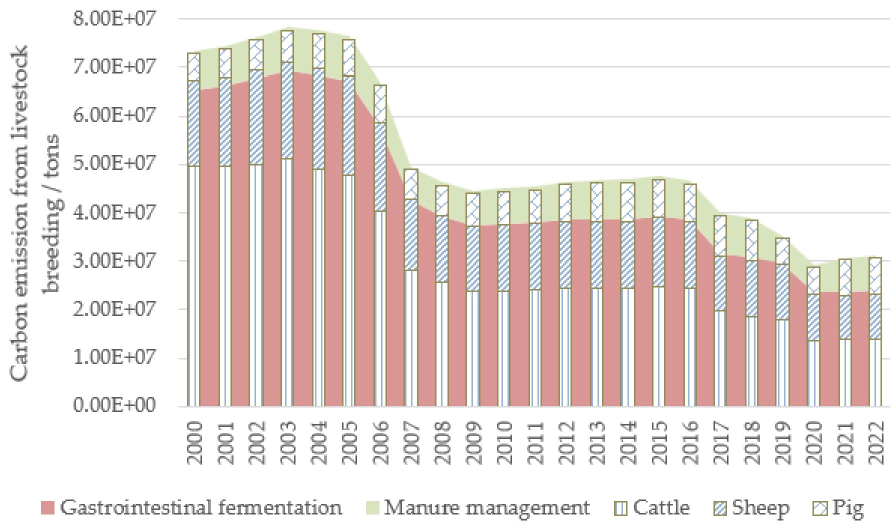

Figure 4. Carbon emission from livestock breeding in Shandong Province, 2000–2022.

- Total carbon emission from agriculture

As is calculated before, carbon sources in agricultural sector includes land utilization (crops planting), livestock breeding and material inputs. The overall pattern of total carbon emissions in Shandong Province closely mirrored the trend seen in emissions from livestock breeding. Total carbon emission in the region decreased from 8.31 × 10^7 tons to 3.88 × 10^7 tons over the observed period (**Table 4**). As stated, livestock breeding was responsible for a large portion of the province's carbon emissions, ranging from 78% to 89%. Although livestock breeding accounted for a major portion of carbon emissions in the province, there was a shift observed from 2000 to 2022. Over this period, the percentage of carbon emissions resulting from livestock breeding saw a decrease, dropping from 88% to 80%. The contribution of crop planting and the use of inputs to total carbon emissions increased. For crop planting, its contribution rose from 3% to 5%. Similarly, the proportion accounted for by inputs also saw an increase, going up from 8% to 15%.

Table 4. Total carbon emission from agriculture and the proportion of each source.

Year	Total carbon emission/ ×10^7 tons	Land utilization	Livestock	Inputs
2000	8.31	3%	88%	8%
2001	8.43	3%	88%	8%

Table 4. (*Continued*).

Year	Total carbon emission/ $\times 10^7$ tons	Land utilization	Livestock	Inputs
2002	8.62	3%	89%	9%
2003	8.77	2%	89%	9%
2004	8.73	2%	89%	9%
2005	8.65	2%	89%	9%
2006	7.75	3%	87%	11%
2007	6.02	4%	83%	14%
2008	5.67	4%	82%	14%
2009	5.48	4%	82%	14%
2010	5.52	4%	82%	14%
2011	5.54	4%	82%	14%
2012	5.65	4%	82%	14%
2013	5.67	4%	83%	14%
2014	5.67	4%	83%	14%
2015	5.71	3%	83%	13%
2016	5.60	3%	83%	13%
2017	4.90	4%	81%	15%
2018	4.78	4%	82%	14%
2019	4.37	4%	81%	15%
2020	3.74	5%	78%	17%
2021	3.87	5%	79%	16%
2022	3.88	5%	80%	15%

3.1.3. Net carbon from agriculture

Since 2008, agricultural practices underwent a fundamental shift and transformed into a carbon-sink sector (**Figure 5**). The net carbon changed from negative to positive, which means after 2008, agricultural sector had a caron deficit, contributing positively to carbon neutrality. In 2002, agriculture in Shandong Province reached its peak in carbon emissions, where the agricultural activities produced the highest amount of greenhouse gases. By 2008, the sector achieved carbon neutrality. Following 2008, the sector not only maintained this balance but even contributed to overall carbon neutrality. Net carbon increased from -4.00×10^7 tons in 2002 to 2.90×10^7 tons in 2020. The slight decrease in net carbon from 2000 to 2002 was due to decreasing carbon sequestration from crops. Another decrease was noticed from 2020 to 2022, attributable to increased emissions from livestock.

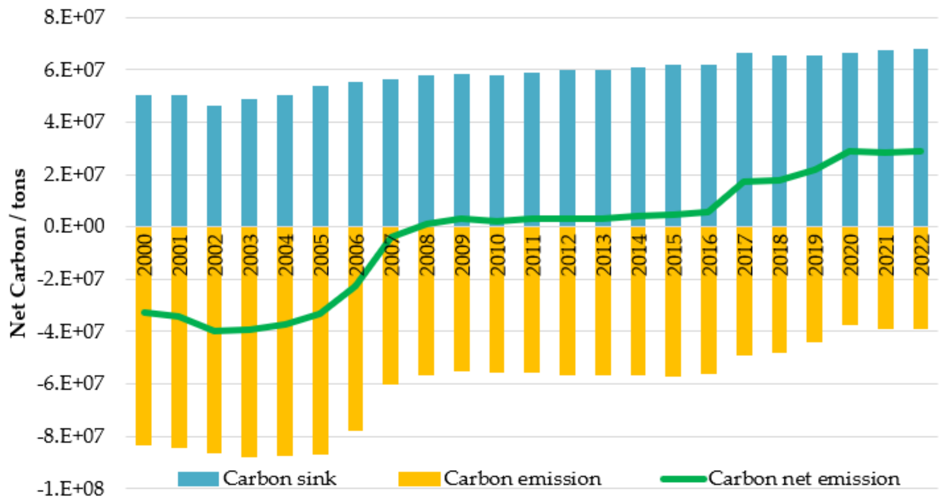

Figure 5. Net carbon absorbed from agriculture in Shandong Province, 2000–2022.

3.2. Spatial–temporal characteristics of net carbon

The concept of spatial heterogeneity in relation to net carbon refers to the uneven distribution and varying intensity of carbon emissions due to differences in the agricultural structures across distinct regions. the variability in net carbon at the city level illustrates just how diverse the influences can be on a region's carbon footprint. The shift from a negative to a positive net carbon in many regions over different years suggests a transition from these areas being carbon sources (emitting more carbon than they absorb) to becoming carbon sinks (absorbing more carbon than they emit). The peak of carbon emission occurred at different times for each of these cities. As in **Figure 6**, between 2000 and 2005, all cities, except Dongying, reached their own peak of carbon emission: Binzhou in 2002, Dezhou in 2004, Heze in 2003, Jinan in 2004, Jining in 2005, Liaocheng in 2003, Linyi in 2002, Qingdao in 2004, Rizhao in 2003, Tai'an in 2003, Weifang in 2002, Yantai in 2004 and Zibo in 2003. Dongying, on the other hand, had its peak carbon emission much later, in 2013. The peak carbon emissions exceeding 5 million tons in Dezhou, Heze, Jinan, and Liaocheng. Since 2006, Liaocheng has led this initiative, and Heze has followed suit since 2020.

The diverse experiences of Weihai, Zaozhuang, and Dongying highlights the complexity of carbon dynamics and the many factors at play. Weihai's ability to maintain a consistent carbon sink throughout the study period is commendable. On the other hand, Zaozhuang faced a severe challenge in 2003, when a significant decrease in corn production led to an increase in carbon emissions to 57,135 tons. Meanwhile, Dongying's persistent state of carbon emission. The cumulative net carbon emissions data from 2000 to 2022 showcases the varying environmental impacts across different cities. Jinan stands out as the most significant carbon emitter during this period, followed closely by Dezhou, indicating the urgency for these cities to address their carbon footprints. Liaocheng, on the other hand, showed a significant carbon deficit, which suggests it's absorbing more carbon than it's emitting. This can be attributed to effective carbon sequestration efforts, robust green space management, or sustainable practices in industry and agriculture.

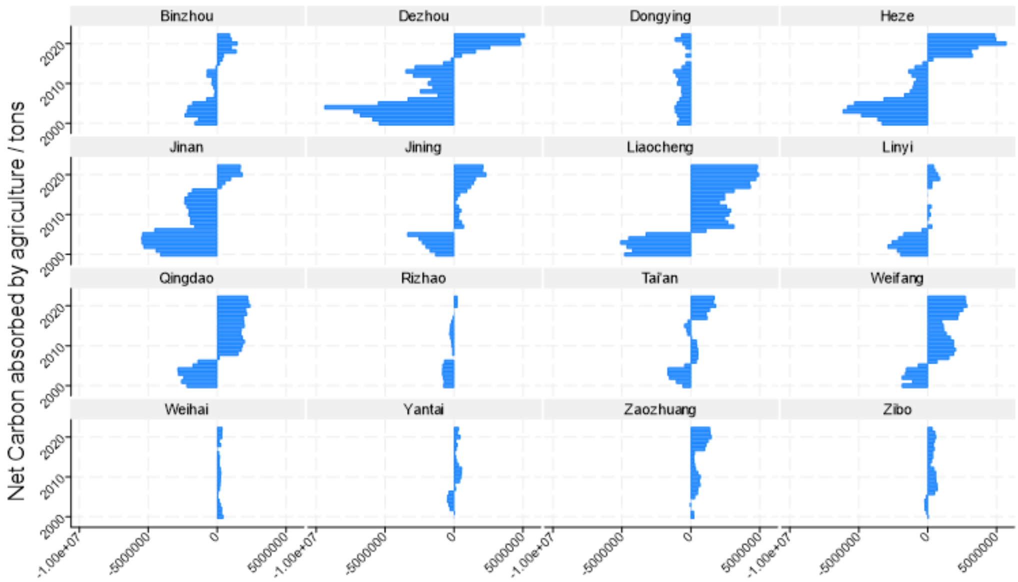

Figure 6. Net Carbon absorbed by agriculture of cities in Shandong Province, 2000–2022.

3.3. Intensity of Net Carbon surplus (INC) from agriculture

Looking at the overall trend, the correlation between intensity and net carbon, which generally transitioned from negative to positive, points to some interesting insights. The distribution maps in **Figure 7** could provide a visual representation of these trends across various cities. Liaoning and Dezhou had the highest INC in 2000, larger than 500 tons per million yuan. Meanwhile, the agriculture in Weihai, Zaozhuang and Zibo had positive intensity of net carbon, and the INC in Weihai and Zaozhuang were larger than 50 tons per million yuan. In 2005, a total of 14 cities were identified as having agricultural carbon emissions. This means these cities were net producers of carbon dioxide attributed to their agricultural practices. From 2005 to 2010, 8 of these cities successfully transitioned their agricultural sectors from carbon emission to carbon deficit. By 2010, only 6 of the original 14 cities had agriculture that continued to emit carbon. During 2010 to 2015, only Binzhou shifted from a carbon-emitting city to experiencing a carbon deficit. In the next five-year period, from 2015 to 2020, agriculture became a carbon surplus sector in five additional cities. In 2020, Heze stood out with the highest Intensity of Net Carbon (INC), exceeding 150 tons per billion-yuan **Figure 7e**. This implies that Heze's economic gain of every billion yuan was accompanied by a net carbon surplus of over 150 tons. Finally, by 2022, out of all these cities only Dongying's agriculture continued to be a source of carbon emissions. This implies that all other cities mentioned in the context had successfully transitioned to carbon-neutral or carbon-positive agricultural sectors. In 2000 and 2005, the Moran's I coefficients were 0.397 and 0.353, respectively. These positive values indicate that there was indeed spatial clustering in those years, with cities having similar carbon factors located relatively close to each other. These findings are statistically significant, as indicated by a p-value less than 0.05 (under 5%) (**Table A3**).

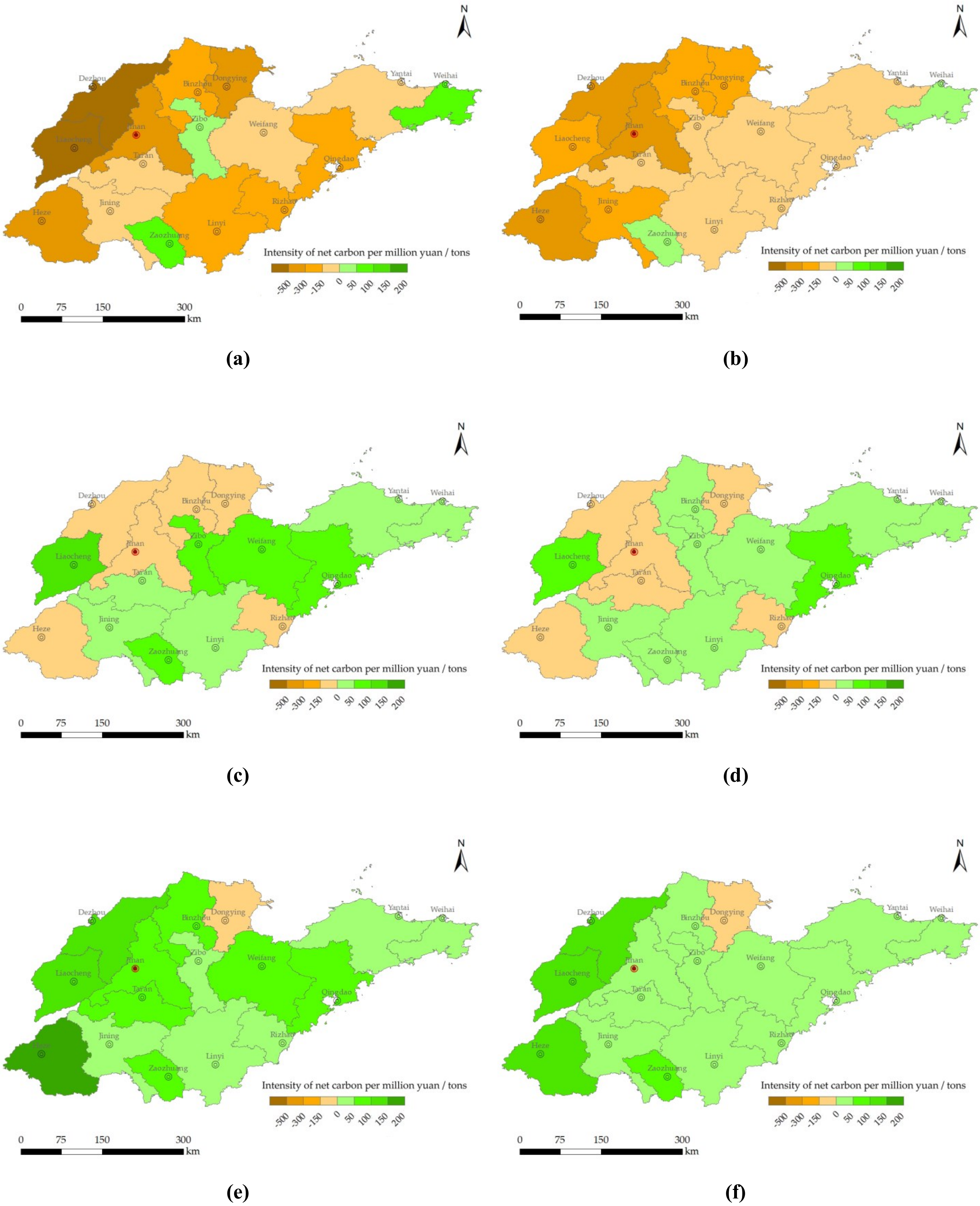

Figure 7. Spatial distribution of intensity of carbon surplus from agriculture in Shandong Province at 5-year interval. **(a)** 2000; **(b)** 2005; **(c)** 2010; **(d)** 2015; **(e)** 2020; **(f)** 2022.

Cultivated land forms the major land use type within the Shandong Province, covering more than 60% of the total land area. This large expanse dedicated to cultivation is an important factor in the carbon dynamics of the region. In 2020, Shandong Province had an Intensity of Net Carbon (INC) of 540.27 tons per million yuan. This substantial INC suggests that, per million yuan of economic output, the province absorbs over 540 tons of carbon. **Figure 8** suggests a strong correlation between the proportion of cultivated land in each city within the province and its intensity of net carbon, as indicated by an R-squared value of 0.83 (**Figure 8**). An R-squared value of 0.83 indicates that 83% of the variation in the INC can be explained by the proportion of cultivated land. The high degree of correlation underscores the importance of cultivated lands in helping to sequester carbon and contribute towards a net carbon surplus. Therefore, cultivation and farm management practices play a crucial role in controlling carbon emissions and maximizing the potential of cultivated land to act as carbon sinks in Shandong Province.

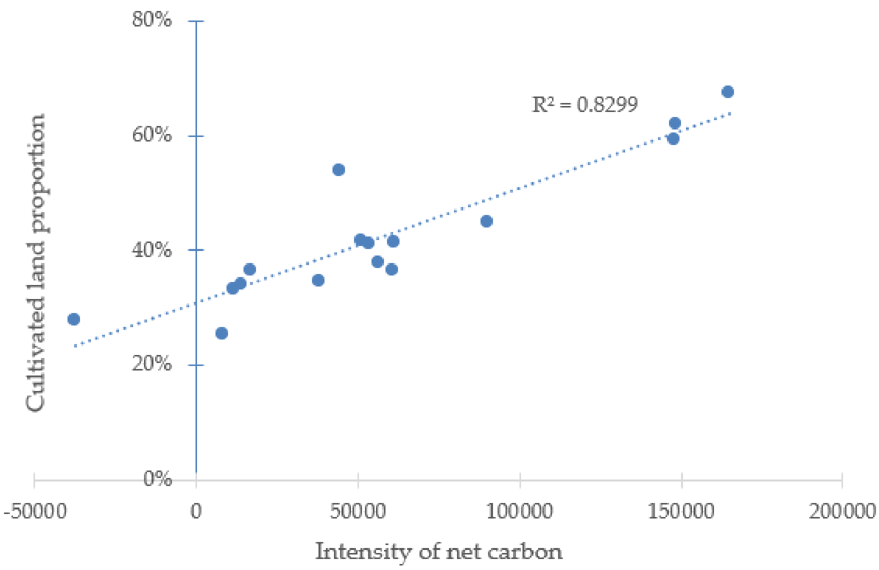

Figure 8. Correlation of cultivated land and intensity of net carbon in 2020.

4. Discussions

Agricultural carbon emissions are a key measure of the ecological impact of farming activities. Agricultural practices can both emit and absorb carbon, impacting the global carbon balance. Thus, understanding and controlling these emissions is critical for ecological balance, climate change mitigation, and sustainability. To improve this aspect, the main strategy is to enhance the carbon emission intensity, which can also be interpreted as improving the efficiency with which agriculture uses carbon. The goal is to generate more output (grow more crops, yield larger harvests) while emitting less carbon. The study results show that livestock farming contributes the most significant portion of agricultural carbon emissions. In particular, the entire livestock production chain is responsible for about 15% of global anthropogenic greenhouse gas emissions. These emissions originate from various sources such as enteric fermentation from ruminants, manure decomposition, and the production of livestock feeds (Gerber, 2013). Addressing this prominent source of emissions requires a multifaceted approach. Improving livestock breeding technologies can help reduce the number of animals needed to produce the same amount of meat, milk, or eggs. Ruminants have lower feed use efficiency than monogastric livestock, and produce higher reactive nitrogen and methane emissions, but can utilize human-inedible biomass through foraging and straw feedstock (Uwizeye et al., 2020). Cheng et al. (2022) found switching 12% of global livestock production from monogastric to ruminant livestock could reduce nitrogen emissions by 2% and greenhouse gas emissions by 5% due to land use change and lower demand for cropland areas for ruminant feed. As a result, carbon reduction could be realized directly from cutting down the production, but its corresponding effects need to be considered for sustainable human welfare and global climate neutrality.

To increase the carbon sink, since cultivated land was limited, crop yield and its productivity are the breakthrough, but in microeconomic analysis of agricultural development, if farmers are rational maximizers, a profit or utility maximization model can be applied to the analysis of farmers' behaviors in developing countries (Otsuka and Fan, 2020). Environmental-friendly technologies and materials were developed (Yang, Lin, et al. 2024; Yang, Liu, et al. 2024). The adoption of green technologies is quite low that restricted by topography, while the chemical products are heavily applied to increase output. Known as China's granary, the develop pace in Shandong gradually lag other regions both economically and technically with the deepen of the reform and opening-up, low green technology adoption and high chemical use causes high agricultural carbon emission (Shen et al., 2020). Technological and institutional changes are induced through responses of actors to changing resource endowments, for example, optimized fertigation to maintain high yield (Nayak et al., 2015; Zhang et al., 2019).

The diversity in agricultural practices, technology implementation, and resource distribution across Shandong leads to spatiotemporal variation in agricultural carbon emissions. To mitigate these emissions and move towards carbon neutrality, it's essential to apply tailored strategies that consider the unique conditions and resources of each specific region. In regions of Shandong with an abundance of high-quality cultivated land, a combination of management practices and the cultivation of improved crop varieties can help reduce carbon emissions. Improved crop varieties may have higher yield potential or better resistance to diseases and pests, which in turn may lead to an increased carbon absorption. Enhanced management practices can also contribute to carbon reduction in such regions. For instance, crop rotation, cover cropping, or optimized use of fertilizers can improve soil health and carbon sequestration capability. In addition, these practices can reduce the need for added synthetic fertilizers, which contribute to GHG emissions. In areas where livestock farming is dominant, employing precision feeding technology can play a significant role in achieving carbon neutrality. Precision feeding involves providing livestock with nutritionally balanced diets that meet their exact needs, minimizing waste. This optimizes animal growth and health, decreasing per-animal GHG emissions because less animal feed is required for the same amount of produced meat, milk, or eggs. In addition, optimized feeding strategies can reduce methane emissions associated with digestion in ruminants.

5. Conclusions

This paper employs emission factors for each carbon source to calculate agriculture's carbon sink and emissions from the years 2000 to 2022. Through this analytical approach, significant findings were unveiled regarding agricultural carbon emissions, signifying important implications for Shandong province and its journey towards carbon neutrality. The agricultural carbon emissions in Shandong province peaked in 2003. However, improvement in management and technology allowed agricultural practices in the province to start contributing to carbon neutrality from 2007 onwards. One key contributor to the agricultural carbon emissions was found to be livestock farming, particularly cattle breeding. This is largely due to the gastrointestinal fermentation process common in ruminants. Carbon emissions from agricultural material inputs also contributed significantly, reaching its peak in 2007 but have been on a declining trend thereafter. From a land utilization perspective, no significant changes were anticipated due to the grain production policy implemented in Shandong. However, that doesn't mean efforts do not continue to optimize land use for better carbon outcomes. Bar Dongying, all cities in the province had hit carbon neutrality in their agricultural sectors by 2020, indicative of solid progress made towards sustainable practices. In 2022, Liaocheng was found to have the largest carbon surplus. Western Shandong, consisting of Dezhou, Heze, and Liaocheng, had larger intensities of carbon surplus due to their higher crop production yield. Such achievements were possible due to low-till or no-till farming, improved livestock management, and better manure management. When it comes to mitigating GHG emissions, the agricultural sector has demonstrated its potential and impact. By optimizing sustainable practices, the sector could fortify its role in mitigating climate change and pave the way for the establishment of a more efficient and sustainable agricultural system, ultimately helping achieve carbon neutrality—a goal that beholds significant merit for both regional and global environments.

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Appendixes

Table A1. Carbon sink per hectare from each crop (Unit: tons).

Year	Wheat	Rice	Corn	Millet	Sorghum	Other cereal	Bean	Tuber	Cotton	Peanut	Rapeseed	Tobacco	Vegetable	Melon
2000	5.01	5.08	5.75	2.86	3.15	3.05	2.59	1.16	4.49	3.57	3.18	0.23	3.05	2.12
2001	4.98	5.13	6.27	3.04	3.30	2.76	2.62	1.37	4.40	3.58	3.42	0.22	3.07	1.92
2002	4.86	5.70	5.33	2.80	3.54	2.83	2.56	1.05	4.50	3.30	3.61	0.26	3.18	2.04
2003	5.38	5.60	6.01	3.09	3.46	2.68	2.93	1.36	4.12	3.39	3.73	0.27	3.24	2.04
2004	5.44	5.89	6.26	3.61	4.26	4.07	3.41	1.50	4.29	3.72	3.78	0.24	3.38	2.84
2005	5.86	6.47	6.51	3.51	4.00	4.90	3.12	1.38	4.14	3.83	3.89	0.27	3.49	2.96
2006	6.01	6.87	6.55	3.43	3.99	3.57	3.20	1.45	4.56	3.90	4.03	0.32	3.59	3.01
2007	6.05	6.83	6.52	2.90	3.70	2.40	2.77	1.49	4.60	3.88	4.62	0.31	3.67	2.98
2008	6.16	6.84	6.73	2.81	3.80	2.80	2.75	1.55	4.85	3.97	4.57	0.30	3.75	3.03
2009	6.16	6.74	6.75	2.84	3.61	2.90	2.82	1.52	4.76	4.02	4.59	0.31	3.82	3.06
2010	6.17	6.72	6.70	2.88	3.47	2.84	2.83	1.49	3.91	3.97	4.52	0.34	3.82	3.10
2011	6.25	6.76	6.77	3.08	3.82	3.45	2.99	1.52	4.32	4.00	4.09	0.32	3.84	3.20
2012	6.41	6.76	6.77	2.96	3.72	3.52	2.80	1.48	4.19	4.17	4.23	0.32	3.90	3.25
2013	6.45	6.81	6.58	2.85	3.61	2.64	2.82	1.50	3.82	4.17	4.12	0.33	3.95	3.29
2014	6.46	6.68	6.52	2.99	3.75	3.41	2.84	1.47	4.64	4.13	4.12	0.31	4.02	3.35
2015	6.59	6.62	6.62	2.98	3.92	3.38	2.92	1.49	4.31	4.06	4.20	0.32	4.08	3.40
2016	6.53	6.74	6.60	3.00	3.55	3.45	3.06	1.52	4.88	4.09	4.17	0.33	4.14	3.42
2017	6.52	6.70	6.82	3.13	3.70	3.65	3.09	1.55	4.91	4.16	4.27	0.33	4.17	3.46
2018	6.50	7.01	6.79	3.52	3.66	3.60	3.24	1.58	4.90	4.15	4.10	0.32	4.15	3.34
2019	6.81	7.05	6.76	3.38	3.42	3.23	3.28	1.58	4.79	4.02	4.12	0.30	4.19	3.34
2020	6.97	7.11	6.87	3.40	3.43	3.24	3.38	1.66	5.30	4.15	4.16	0.32	4.25	3.37
2021	7.04	6.98	6.81	3.48	3.50	3.27	3.37	1.67	5.27	4.20	4.19	0.32	4.33	3.45
2022	7.04	6.89	6.94	3.38	3.44	3.15	3.11	1.67	5.29	4.17	4.15	0.32	4.38	3.49

Table A2. Proportion of each type for total carbon emission of inputs.

Year	Fertilizer	Pesticides	Plastic film	Machinery	Land tilling	Irrigation	Diesel
2000	56.54%	10.33%	17.40%	0.01%	0.54%	1.29%	13.89%
2001	54.98%	10.25%	19.12%	0.20%	0.50%	1.25%	13.71%
2002	52.91%	11.00%	20.61%	0.20%	0.47%	1.16%	13.65%
2003	52.00%	11.31%	21.25%	0.20%	0.46%	1.09%	13.70%
2004	53.02%	9.97%	22.25%	0.21%	0.44%	1.07%	13.04%
2005	52.90%	9.70%	21.70%	0.21%	0.42%	1.04%	14.03%
2006	52.93%	10.20%	21.47%	0.21%	0.40%	1.02%	13.76%
2007	53.66%	9.79%	21.16%	0.21%	0.40%	1.02%	13.75%
2008	53.28%	10.69%	20.78%	0.23%	0.42%	1.07%	13.52%
2009	53.63%	10.56%	20.59%	0.25%	0.43%	1.10%	13.45%

Table A2. (*Continued*).

Year	Fertilizer	Pesticides	Plastic film	Machinery	Land tilling	Irrigation	Diesel
2010	53.26%	10.18%	20.93%	0.26%	0.42%	1.10%	13.84%
2011	53.38%	10.23%	20.75%	0.27%	0.43%	1.12%	13.82%
2012	53.85%	10.09%	20.80%	0.28%	0.43%	1.12%	13.44%
2013	53.92%	9.95%	21.03%	0.29%	0.44%	1.18%	13.19%
2014	54.49%	10.03%	20.55%	0.31%	0.45%	1.21%	12.96%
2015	54.66%	9.81%	20.57%	0.32%	0.45%	1.25%	12.94%
2016	54.68%	9.81%	20.64%	0.24%	0.46%	1.29%	12.88%
2017	54.67%	9.63%	20.63%	0.25%	0.48%	1.36%	12.97%
2018	54.83%	9.33%	20.89%	0.27%	0.50%	1.43%	12.73%
2019	54.61%	9.16%	21.34%	0.30%	0.53%	1.49%	12.57%
2020	54.58%	9.02%	22.02%	0.32%	0.54%	1.54%	11.99%
2021	54.70%	8.79%	22.14%	0.33%	0.56%	1.54%	11.93%
2022	55.66%	8.89%	22.57%	0.36%	0.59%	1.61%	11.93%

Table A3. Moran's I of intensity of net carbon absorbed by agriculture (INC) from 2000 to 2022.

Year	Moran's I	Standard error	*p*.value
2000	0.397	0.1776	0.0090
2001	0.408	0.1733	0.0061
2002	0.458	0.1757	0.0028
2003	0.410	0.1777	0.0073
2004	0.377	0.1619	0.0061
2005	0.353	0.1802	0.0200
2006	−0.080	0.1801	0.9427
2007	−0.230	0.1713	0.3396
2008	−0.203	0.1782	0.4433
2009	−0.169	0.1808	0.5719
2010	−0.149	0.1785	0.6461
2011	−0.174	0.1775	0.5449
2012	−0.092	0.1773	0.8854
2013	−0.069	0.1755	0.9885
2014	−0.218	0.1734	0.3831
2015	−0.332	0.1727	0.1250
2016	−0.348	0.1597	0.0787
2017	−0.089	0.1676	0.8952
2018	−0.069	0.1699	0.9901
2019	0.073	0.1726	0.4175
2020	0.169	0.1769	0.1823
2021	0.162	0.1740	0.1888
2022	0.205	0.1751	0.0740