

Research on Agricultural Carbon Emissions and Regional Carbon Emissions Reduction Strategies in China

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Abstract: Carbon emissions and strategies for reducing them have become hot topics in recent years. This study firstly measured the total amount and the intensity of agricultural carbon emissions (i.e., agricultural carbon emission per capital) in China. The results show that China's total carbon emission in 2016 was 272.022 million tons, which is 26.67% more than that in 2000, with an average annual increase of 1.67%. It then compared the regional differences of agricultural carbon emissions in China using the method of coefficient of variation and the Theil index. Following this, this paper finally provides scientific and technological support for the reduction of agricultural carbon emissions in China based on a matrix of carbon emission reduction strategies.

Keywords: agricultural carbon emissions; intensity of carbon emissions; analysis of regional differences; strategy for carbon emission reduction

1. Introduction

Carbon emission has become a key cause of climate change [1]. According to the Special Report on Global Warming of 1.5°C (SR15) released by the Intergovernmental Panel on Climate Change (IPCC), strict carbon emission control and emission reduction actions should be taken to keep the warming within 1.5°C [2,3]. The 2019 Climate Change Conference (COP25) put forward that the world must set its goal to limit warming to 2.0°C [4]. According to the report of the IPCC on land use, carbon emissions caused by land use accounted for about 23% of total carbon emissions [5], of which the change of agricultural land use has been an important part [6]. From 2000–2016, agricultural arable land in China increased by 5.2% [7]. The role of land as a carbon sink has been greatly affected by deforestation and agricultural land use [8], as farming is eroding soil at a rate between 10 times and more than 100 times faster than new soil forms [9]. Moreover, climate change has also increased the risks of extreme high temperatures and a shortage of rainfall [10].

Agricultural carbon emissions refer to the direct or indirect greenhouse gas emissions caused by the use of fertilizers, pesticides, and fossil fuels as well as waste treatment in agricultural production [11]. With the development of modern agriculture, the use of chemical fertilizers, pesticides, and especially agricultural machinery has led to an increase in agricultural carbon emissions [12]. The diversity and complexity of agricultural production has led to the diversity of agricultural carbon emission sources [13]. On one hand, carbon emissions can be caused by the use of pesticides,

fertilizers, and energy as well as waste treatment [14]. On the other hand, rice cultivation and livestock breeding can also increase carbon emissions [15]. A large amount of CH_4 , N_2O , and CO_2 can be released during agricultural production. It has been estimated that 60%–80% of N_2O emissions are directly and indirectly caused by farmland (indirect emissions refer to the production and transportation of fertilizers), field incineration, grazing, and animal manure [16]; 50%–70% of CH_4 emissions are caused by the intestinal fermentation of livestock, rice cultivation, and animal manure; and 1% of CO_2 emissions are caused by the production and use of agricultural machinery, fertilizers, and other chemical input [17]. According to the Food and Agriculture Organization (FAO), the five major agricultural carbon emission sources are soil (38%, $\text{CH}_4+\text{N}_2\text{O}$), the intestinal fermentation of ruminant animals (32%, CH_4), biomass fuel burning (12%, $\text{CH}_4+\text{N}_2\text{O}$), rice cultivation (11%, CH_4), and animal manure (7%, $\text{CH}_4+\text{N}_2\text{O}$) [18]. The main reasons for the increase of agricultural carbon emissions include the increase of population, changes in dietary structure (increasing consumption of animal by-products) [19], and technological progress (increasing fertilizer input, promotion of irrigation, and intensive agriculture). Reasons for the reduction of agricultural carbon emissions include the improvement of land productivity, the use of conservation tillage, and the implementation of environmental and non-environmental policies [20]. The amount of CH_4 emissions caused by the intestinal fermentation of ruminant animals are related to the characteristics of the animals and the quality of fodder [19]. The amount of CH_4 emissions caused by rice cultivation can be calculated by subtracting the amount of oxidation of CH_4 by the CH_4 -oxidizing bacteria at the root of rice from the amount of CH_4 formed by methanogens in rice fields in the anaerobic environment through the conversion of organic matter in the rhizosphere of field plants. The methane emissions of rice cultivation are mainly affected by soil properties, irrigation and water conditions, use of fertilizers, rice growth, and climate conditions. The storage and treatment of livestock manure can also lead to CH_4 emissions [21]. The amount of CH_4 emissions caused by livestock manure are related to the methods of manure treatment and climate conditions. The N_2O emissions from soil are driven by the mechanism of nitrification and denitrification with the participation of soil microorganisms. It is generally believed that the mechanism of denitrification makes greater contributions to N_2O emissions than that of nitrification [22]. N_2O emissions can be affected by many factors, such as the type of crops, the quality of soil, fertilizers, irrigation technologies, and climate conditions [23].

Agricultural greenhouse gas emissions are generally estimated according to Volume 4 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [24]. Considering that greenhouse gas emissions can be affected by many factors, some experts in ecology and agronomy have adjusted the related parameters, formulas, and influencing factors based on long-term field experiments and monitoring. For example, the Rodale Institute, led by David Pimental, a well-known professor of ecology at Cornell University, conducted the Farming System Trial on three plots—a traditional intensive agriculture (fertilizers) plot, an organic agriculture (manure) plot, and a legume rotation organic agriculture (plant nitrogen fixation) plot—to analyze the differences in energy input, soil organic matter, water quality, biological resources, production level, and labor input from 1981 to 2002. This experiment provided important data for estimating the potential of agricultural carbon emission reduction and analyzing the cost of emission reduction from an economic perspective [25].

Agricultural carbon emissions can be measured in many different ways. In 2002, scholars proposed measuring the agricultural carbon emissions from crop farming through the energy consumed by fertilizers, pesticides, irrigation, and seed cultivation [21]. Later, scholars began to measure the agricultural carbon emissions from the random discharge and storage of agricultural waste, livestock and poultry intestines, agricultural production processes, rice cultivation, and straw burning [16,18,20,23]. It has been estimated that the total agricultural carbon emissions in 2008 were about 427.5 tons, and within this the use of agricultural land as the main cause accounted for about 50% of the carbon emissions [14]. Moreover, carbon emissions from the intestinal fermentation of livestock and poultry accounted for about a third of the total emissions [20]. The soil carbon emissions model, which takes the climate conditions and the quality of soil into consideration, has been widely applied in the field of natural sciences. The transformation of agricultural land use can also lead to great agricultural carbon emissions. Besides, through the comparison of experiences in the USA,

Canada, and New Zealand it has been found that differences in the agricultural carbon emissions of countries could be explained by agricultural production methods [14,17].

The estimation of agricultural carbon emissions in China has been focused on carbon emission sources. For example, some scholars have estimated the agricultural carbon emissions based on the measurement of conversion factors of coal, oil, natural gas, and other resources used in agricultural production [20–23]. Some others have measured the carbon emissions caused by changes in the agricultural land use in some ethnic regions in China through the measurement of carbon emissions from fertilizers, pesticides, agricultural plastic films, diesel fuels, conservation tillage, and irrigation technology [10,12,14,15]. Besides, the perspective of input–output, which takes electricity consumption into consideration, has been used by some scholars to measure the agricultural carbon emissions in Chongqing [23]. Recently, further research has been undertaken on the carbon emissions of livestock and poultry, including cows, sheep, goats, pigs, chickens, and ducks [24,25].

In general, the measurement of agricultural carbon emissions has been modified a lot since it was proposed. A general research framework with differences in the selection of secondary indicators has been developed to make estimations of the carbon emissions caused by agricultural land use (or material input in agriculture) and livestock and poultry farming [18,20,22]. However, the estimation of carbon emissions from rice cultivation and soil has not been standardized [23]. Carbon emissions from rice cultivation are usually estimated by multiplying the area of rice cultivation by a given coefficient, which varies between institutions. Some institutions use coefficients with regional differences while others use the same coefficient for the whole country [21]. As for the carbon emissions from soil, they are usually estimated based on the relevant experimental data from a certain area rather than data collected nationwide. However, carbon emissions from soil can be affected greatly by cultivation methods. Therefore, the agricultural carbon emissions in this paper have been estimated without considering the carbon emissions from soil. Rice cultivation has been estimated with a coefficient that reflects both regional differences and differences in species.

Based on an input–output table, some economists have estimated the carbon emissions from direct and indirect energy consumption at each upstream production stage of agricultural inputs with the method of environmental input–output (EIO) and the method of the life cycle of agricultural production (LCA) [26]. Furthermore, scholars and institutions, such as the World Resources Institute, the World Business Council for Sustainable Development, Matthews, and II. S., have proposed the Tiered Input–Output Life Cycle Assessment (TIO-LCA) [27] to prioritize agricultural emission reduction actions. It should be noted that the existing studies on the estimation of agricultural carbon emissions were mainly conducted by comparing traditional intensive agriculture and organic agriculture. Some foreign scholars have conducted a comparative study on the environmental impact of traditional intensive agriculture and organic agriculture in Australia with the hybrid input–output life cycle method. Samples selected in the research covered different regions, species of crops, scales, and methods of cultivation as well as different growing seasons [16]. In terms of the research method, the direct carbon emissions from on-farm production activities and other environmental impacts were estimated with the method of the life cycle, indirect carbon emissions from off-farm production activities was estimated with the method of input–output, and the agricultural emission reduction actions were prioritized through analysis of the structural path [16]. This research provided a comprehensive estimation of carbon emissions throughout the agricultural production process, measured the energy consumption (including the consumption of electricity, fertilizers, pesticides, seeds, and fodder) of fruits, vegetables, and livestock products and compared the energy consumption structure of agricultural production in different regions of Australia. The results show that, although the amount of water utilization and labor input in organic agriculture is higher than that in traditional intensive agriculture, the indirect contributions of other aspects (such as energy utilization and greenhouse gas emissions) in organic agriculture are much better than those in traditional intensive agriculture. Therefore, the indirect impacts (especially in off-farm production activities) have to be taken into consideration when estimating the environmental sustainability of different farming methods.

According to the estimation of agricultural carbon emissions in the United States, about half of the carbon emissions caused by agricultural production come from the use of agricultural land, while about a third come from the intestinal fermentation of livestock. The proportion of agricultural carbon emissions in total carbon emissions is highly related to the agricultural practices of different countries [28]. According to the estimation of carbon emissions from different emission sources (fertilizers, energy consumption, and crop cultivation) conducted by scholars in China [29], carbon emissions from fertilizers accounted for the largest proportion of carbon emissions [30]. Carbon emissions in China have been increasing since 1995 [31], but the growth rate has declined in recent years [32]. It has been found that all the carbon emissions from farmland, carbon sequestration, and the carbon footprint in 31 provinces in China have increased. Besides, according to research conducted in Heilongjiang, the field ecosystem is the main source of carbon emissions. The research also showed a positive correlation between agricultural carbon emissions and the input of agricultural chemicals, energy consumption, and farming forms [33]. Traditional cultivation ways cause a large amount of carbon emissions. Agricultural carbon emissions can be affected by the method of land use. It has been proven that agricultural carbon emissions can be effectively reduced by afforestation and the Grain for Green Program [34]. Carbon emissions from construction land are the highest, compared with those from urban land, rural residential land, land for transportation, and agricultural land [35].

It can be seen that further research is needed into regional agricultural carbon emissions. Therefore, using the coefficient of variation and the Theil index, this paper analyzes the spatial and temporal heterogeneity of agricultural carbon emissions in different regions of China and makes policy recommendations to support the reduction of agricultural carbon emissions. The second part is method and data, the third part is the regional differences of agricultural carbon emissions, the forth part is agricultural carbon emissions per capita and intensity, the fifth part is policy recommendations for the reduction of regional agricultural carbon emissions, and the last part is conclusions and discussion.

2. Method and data

2.1. Measure of Agricultural Carbon Emissions by Province

The data in this paper were collected from the China Rural Statistical Yearbook, the China Statistical Yearbook, and the Economy Prediction System (EPS) Database (Beijing fuqua information technology co. LTD: Beijing, China). The prices used in this paper were converted according to the price in 2000.

2.1.1. Carbon Emissions from Agricultural Land Use

This paper mainly estimated the agricultural carbon emissions from fertilizers, pesticides, agricultural plastic films, diesel fuel consumption, crop sowing, and irrigation. The emission factors are shown in Table 1.

Table 1. Emission factors of different carbon emission sources in land use.

Sources	Emission Factors	References
Fertilizer	0.8956kg(C)/kg	[36–38]
Pesticide	4.9341kg(C)/kg	[36] [39,40]
Agricultural plastic films	5.18kg(C)/kg	[41–44]
Diesel fuel	0.5927kg(C)/kg	[5]
Sowing		
Irrigation	266.48kg(C)/hm ²	[45–48]

Based on these factors, the carbon emission was estimated as follows:

$$E = E_{fe} + E_{pe} + E_{pl} + E_{ga} + E_{so} + E_{ir} \quad (1)$$

where E is the total carbon emission caused by agricultural land use and E_{fe} , E_{pe} , E_{pl} , E_{ga} , E_{so} , and E_{ir} are estimated on the basis of the parameters of fertilizers, pesticides, agricultural plastic films, diesel fuel consumption, the sowing area, and the effective irrigation area.

2.1.2. Carbon Emissions from Rice Cultivation

The carbon emission of rice cultivation in this paper was estimated according to the standard of the FAO. Rice cultivation can be greatly affected by climate conditions [25]. Rice is one of the most important emission sources of CH₄. Additionally, the CH₄ emission of rice in different growth cycles can be affected by climate and hydrothermal conditions. Therefore, based on the existing calculation model of carbon emission coefficient [39], the CH₄ emission factors of rice in this paper was estimated according to the data on climate, soil, and hydrology in different provinces (see Table 2).

Table 2. Carbon emission factors of rice cultivation in different provinces.

Province	Emission Factors (g/m ²)	Province	Emission Factors (g/m ²)	Province	Emission Factors (g/m ²)
Beijing	13.23	Anhui	31.91	Sichuan	16.91
Tianjin	11.34	Fujian	34.62	Guizhou	16.12
Hebei	15.33	Jiangxi	42.2	Yunnan	5.73
Shanxi	6.62	Shandong	21.02	Tibet	6.83
Inner Mongolia	8.93	Henan	17.85	Shanxi	12.51
Liaoning	9.24	Hubei	38.23	Gansu	6.83
Jilin	5.57	Hunan	35.01	Qinghai	0
Heilongjiang	8.31	Guangdong	41.22	Ningxia	7.35
Shanghai	31.26	Guangxi	36.44	Xinjiang	10.52
Jiangsu	32.4	Hainan	38.43		
Zhejiang	35.6	Chongqing	16.91		

2.1.3. Carbon Emission from Ruminant Animals

Carbon emissions from livestock and poultry farming (especially ruminant farming) are another important source of agricultural carbon emissions. The emissions include CH₄ emissions caused by the intestinal fermentation of livestock and poultry, and the CH₄ and N₂O emissions (according to the United Nations Intergovernmental Panel on Climate Change (IPCC) and the greenhouse gas accounting method in China's "Guidelines for the Preparation of Provincial Greenhouse Gas

Inventories (Trial)", the N₂O in the atmosphere mainly comes from agricultural land, animal manure management, and the wastewater treatment processes of the waste treatment sector, among which more than 70% of the nitrogen emissions come from agricultural production. As this paper is about agricultural carbon emissions, N₂O emissions have not been measured and only the CH₄ emissions have been taken into consideration) that occur during manure treatment. In this paper, we only measured the carbon emission factors of cattle, horses, donkeys, mules, pigs, goats, sheep, and poultry [32] (see Table 3).

Table 3. Carbon emission factors of different animals.

Ruminant animal	Emission Factors of Intestinal Fermentation (kg(C)/unit/year)	Emission Factors of Manure Treatment (kg(C)/unit/year)	Ruminant animal	Emission Factors of Intestinal Fermentation (kg(C)/unit/yea)	Emission Factors of Manure Treatment (kg(C)/unit/year)
Cattle	395.56	24.55	Pig	6.82	27.28
Horses	122.76	11.18	Goat	34.11	1.16
Donkeys	68.21	6.14	Sheep	32.11	1.02
Mules	68.21	6.14	Poultry	0	0.02

Carbon emissions from livestock and poultry in each province were estimated with the number of poultry produced in each province by the end of the year and the number of other animals kept in each province by the end of the year. Based on the methods proposed in current research [27], the number of poultry used in this paper was modified as follows:

$$N = Days_alive * \frac{M}{365} \quad (2)$$

where N is the modified number of poultry, *Days _ alive* is the growth cycle of poultry (here this equals 55), and M is the number of poultry produced in each province by the end of the year.

In order to simplify the estimation, the emission of CH₄ in this paper was converted to that of standard C. According to the report issued by the IPCC, the greenhouse effect caused by 1 ton of CH₄ is equivalent to that caused by 6.82 tons of C (25 tons of CO₂).

2.2. Coefficient of Variation

In this paper, the changes in agricultural carbon emission per capita were reflected by the coefficient of variations.

$$CV = \frac{1}{\bar{X}} \left[\frac{1}{n} \sum_{i=1}^n (X_i - \bar{X})^2 \right]^{\frac{1}{2}} \quad (3)$$

where, $\bar{X}$ is the agricultural carbon emission per capita at the national level, X_i is the agricultural carbon emission per capita of the eight economic zones, and n is the number of regions in the economic zone. The larger the value of CV is, the greater the difference among regional agricultural carbon emissions per capita is.

2.3. Theil Index

The Theil index has been widely used in the measurement of income inequality since it was proposed. With the Theil index, the overall difference can be divided into two parts. One is brought about by regional differences, and the other is brought about by intra-regional differences. The Theil index was adopted here to explain the overall difference of agricultural carbon emissions in eight economic zones [49]. In this case, the contribution rates of regional differences and intra-regional differences to the overall agricultural carbon emissions were measured with the Theil index.

$$T_i = \sum_{j=1}^n \frac{GDP_j}{GDP_i} \cdot \ln \left(\frac{GDP_j}{GDP_i} \cdot \frac{ACE_i}{ACE_j} \right) \quad (4)$$

$$T_{wr} = \sum_{i=1}^n ACE_i \cdot \left(\sum_{j=1}^m ACE_{ij} \cdot \ln \frac{ACE_{ij}}{GDP_{ij}} \right) \quad (5)$$

$$T_{br} = \sum_{i=1}^n ACE_i \cdot \ln \frac{ACE_i}{GDP_i} \quad (6)$$

$$T = T_{wr} + T_{br} \quad (7)$$

$$T_{wr} \% = \frac{T_{wr}}{T} \% \quad (8)$$

$$T_{br} \% = \frac{T_{br}}{T} \% \quad (9)$$

where ACE represents the total agricultural carbon emission, GDP is the total output of the agricultural and forestry economy, GDP_j is the proportion of the j -th province's GDP within the national GDP , and GDP_i is the proportion of the i -th economic zone's GDP within the national GDP . ACE_j is the proportion of the j -th province's agricultural carbon emissions within the national agricultural carbon emissions and ACE_i is the proportion of the i -th economic zone's agricultural carbon emissions in the national agricultural carbon emissions. T is the overall difference in agricultural carbon emissions, T_{wr} is the regional difference in agricultural carbon emissions, T_{br} is the difference in agricultural carbon emissions within the regions, $T_{wr} \%$ is the contribution rate of regional differences to the overall difference, and $T_{br} \%$ is the contribution rate of differences within regions to the overall difference.

2.4. Research Area Division

Agricultural carbon emissions are different in different regions. Based on existing research [46], the research areas were divided into four parts (the eastern region, central region, western region, and northeast region) and eight economic zones (the northern coast, eastern coast, southern coast, the middle reaches of the Yangtze River, the middle reaches of the Yellow River, the northwest region, the southwest region, and the northeast region), respectively (see Figure 1), according to similarities in agricultural production activities and the possibility of regional cooperation to reduce emissions.

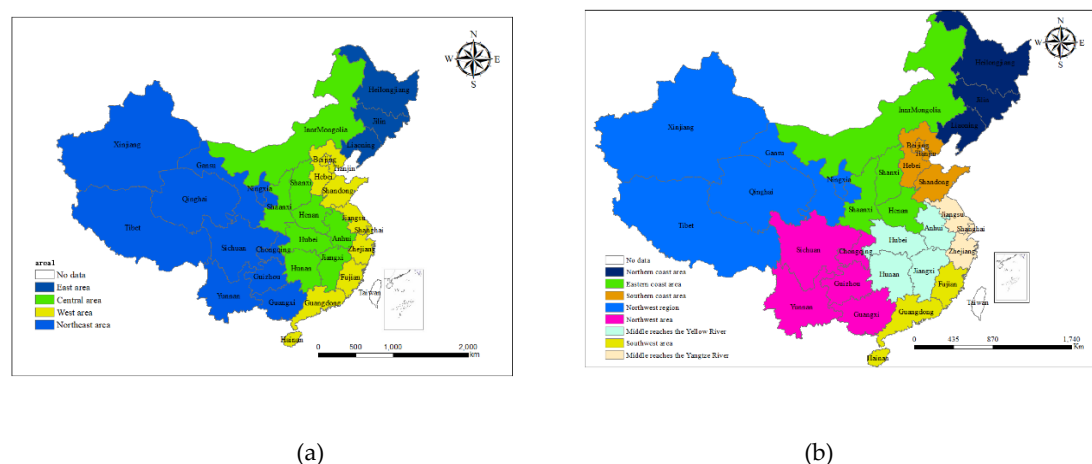


Figure 1. Division of agricultural carbon emission regions in China. (a: four parts; b: eight economic zones).

3. Regional Differences of Agricultural Carbon Emissions

3.1. Overall Analysis of Agricultural Carbon Emissions

The outcomes of the measurements of agricultural carbon emissions from 2000 to 2016 are shown in Table 4.

Table 4. Amount and composition of agricultural carbon emissions from 2000 to 2016 (10,000 tons, %).

Year	Livestock and poultry	Proportion	Rice planting	Proportion	Land use	Proportion	Total carbon emission
2000	7110.37	33.11%	6970.28	32.46%	7394.73	34.43%	21475.39
2001	7388.96	34.08%	6702.59	30.91%	7591.67	35.01%	21683.21
2002	7840.99	35.42%	6561.16	29.64%	7737.22	34.95%	22139.37
2003	8246.21	36.97%	6161.2	27.62%	7898.37	35.41%	22305.77
2004	8743.59	36.94%	6599.31	27.88%	8327.02	35.18%	23669.93
2005	9668.35	38.74%	6709.68	26.88%	8579.98	34.38%	24958.01
2006	9655.05	38.27%	6734.6	26.70%	8835.89	35.03%	25225.53
2007	7786.83	32.90%	6727.58	28.43%	9152.28	38.67%	23666.68
2008	9770.14	37.80%	6803.02	26.32%	9271.86	35.87%	25845.02
2009	8376.28	33.75%	6892.05	27.77%	9550.08	38.48%	24818.4
2010	8624.36	33.93%	6950.42	27.34%	9844.54	38.73%	25419.31
2011	8567.85	33.40%	6993.17	27.26%	10087.97	39.33%	25649
2012	8872.77	33.85%	7011.92	26.75%	10326.52	39.40%	26211.2
2013	9067.12	34.08%	7051.94	26.50%	10488.77	39.42%	26607.84
2014	9317.74	34.52%	7050.57	26.12%	10620.52	39.35%	26988.84
2015	9251.71	34.32%	7027.79	26.07%	10679.59	39.61%	26959.09
2016	9126.42	33.55%	7019.3	25.80%	11056.49	40.65%	27202.2

Data Source: calculated by the authors.

In 2016, China's total carbon emissions were 272.022 million tons, which is 26.67% more than that in 2000, with an average annual increase of 1.67%. The carbon emissions caused by land use, rice planting, and livestock and poultry were 110.5649, 70.193, and 91.2642 million tons, respectively, accounting for 40.64%, 25.8%, and 33.55% of the agricultural carbon emissions, respectively.

Agricultural carbon emissions increased greatly from 2000 to 2016 in total. However, there were several fluctuations. To be specific, agricultural carbon emissions increased slowly from 2000–2003 while they increased rapidly from 2004–2006. Later, between 2006 and 2008, agricultural carbon emissions declined slightly and then increased. Since then, agricultural carbon emissions have remained stable. This can be explained by the fluctuation of the rice cultivation acreage. Based on this, it was estimated that agricultural carbon emissions will continue to increase in the next few years.

As agricultural carbon emissions are susceptible to the total amount of resources in each province, the agricultural carbon emissions of 31 provinces in this paper were evaluated by the intensity of carbon emissions (ton/10,000 yuan), which refers to the agricultural carbon emissions caused by the gross agricultural output value per 10,000 yuan. It can be seen from Figure 2 that the intensity of carbon emissions declined from 0.86 ton/10,000 yuan in 2000 to 0.24 ton/10,000 yuan in 2016. Additionally, the largest decline appeared in 2003–2004, which was brought about by the issue of the No.1 central document with an aim to increase the income of farmers. Compared with the agricultural output value of 2003, that of 2004 was doubled and the intensity of carbon emissions has declined steadily since 2004. It can be predicted that the intensity of agricultural carbon emissions in China will continue to decline in the next few years.

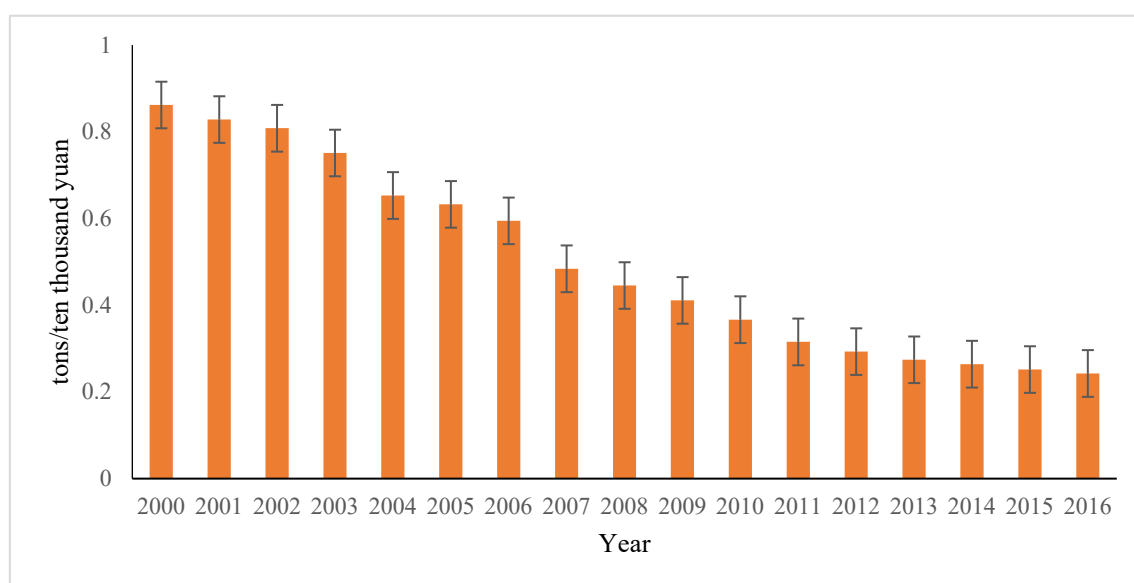


Figure 2. Intensity of agricultural carbon emissions from 2000–2016.

Agricultural carbon emissions can be divided into three categories: carbon emissions from agricultural land use, carbon emissions from rice cultivation, and carbon emissions from livestock and poultry farming. The total agricultural carbon emissions increased from 2000–2016. To be specific, carbon emissions from agricultural land use increased the fastest, from 73.9473 to 110.5649 million tons, with an average annual increase of 3.09%. This means the increase of agricultural output in China depended greatly on the increase of agricultural material input. There were great fluctuations in the carbon emissions from rice cultivation, which increased slightly from 69.7028 million tons in 2000 to 70.193 million tons in 2016 with an average annual increase of 0.04%. The carbon emissions from rice cultivation were mainly affected by the scale and structure of rice cultivation. Carbon emissions from livestock and poultry farming increased from 71.1037 million tons in 2000 to 91.2642 million tons in 2016 with an average annual increase of 1.77%. Affected by the scale and structure of

livestock and poultry farming, the change of carbon emissions from livestock and poultry farming can be divided into five periods: a period of continuous rising (2000–2005), a period of rapid declining (2006–2007), a period of rapid rising (2007–2008), a period of declining (2008–2009), and a period of steady growth (2009–2016).

3.2. Regional Variation of Agricultural Carbon Emissions

In terms of total agricultural carbon emissions, the central region has always ranked first, while the eastern region ranked second until 2013 when it was surpassed by the western region. Agricultural carbon emissions in the central region, western region, and the northeast region increased slowly from 2000 to 2016, while agricultural carbon emissions in the eastern region were stable from 2000–2006 and declined from 2010–2015. This was positively related to the technological and green transformation during this period.

The eight economic zones in China were roughly divided into four groups according to their agricultural carbon emissions from 2000 to 2016. The first group included the middle reaches of the Yangtze River and the southwest region. The second group was the middle reaches of the Yellow River. The third group included the northern coast and the northeast region. The fourth group included the eastern coastal economic zone, the southern coastal economic zone, and the northwest economic zone. To be specific, the middle reaches of the Yangtze River were the highest. The agricultural carbon emissions in the middle reaches of the Yangtze River and the Yellow River increased significantly, while those in the eastern coastal economic zone and the southern coastal economic zone remained stable.

4. Agricultural Carbon Emissions Per Capita and Intensity

4.1. Analysis of Carbon Emission Per Capita

From 2000 to 2016, the agricultural carbon emissions in four regions increased with significant differences in their trends. To be specific, carbon emissions per capita in the northeast region rose rapidly, which could be explained by the large-scale cultivation of corn. In the eastern, central, and western regions, carbon emissions per capita were highest in 2006 and then increased slowly.

From 2000 to 2016, there were great differences among agricultural carbon emissions per capita in different regions. Specifically, in 2016, agricultural carbon emissions per capita in the northeast region were 0.9986 tons, which is the highest, followed by those in the northwest region, the middle reaches of the Yangtze River, the southwest region, the northern coast, the eastern coast, and the southern coast. Emissions per capita had a positive relation with the level of economic development.

From 2000 to 2016 (see Figure 3), the intensity of agricultural carbon emissions in the four regions showed a downward trend. Moreover, agricultural carbon emissions declined rapidly from 2007–2012 and then showed a slowing rate of decline from 2013. The agricultural carbon emissions intensity in the eastern region were the lowest over the years, indicating that the carbon emissions from agricultural production in the eastern region were the lowest.

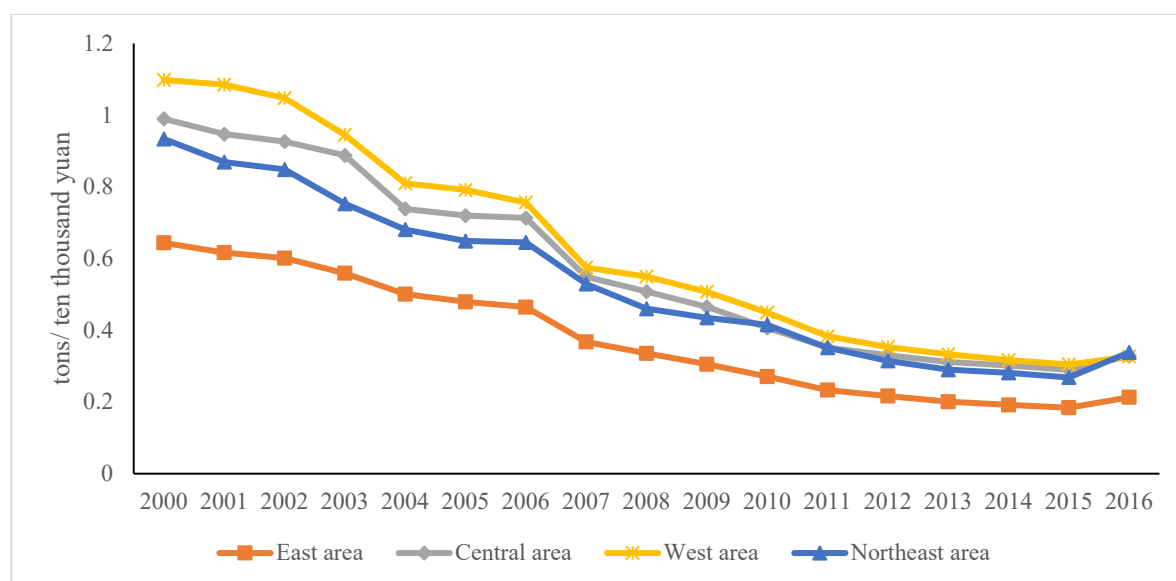


Figure 3. Intensity of agricultural carbon emissions in four regions.

4.2. Analysis of Carbon Emission Intensity

From 2000 to 2016, the carbon emission intensity in the northwest was relatively high (Figure 4), especially in 2000. However, the intensities of all economic zones dropped significantly by the year 2016, when the intensity of carbon emissions in the northwest was the highest, followed by the middle reaches of the Yangtze River, the northeast region, the middle reaches of the Yellow River, the southwest region, the northern coast, the eastern coast, and the southern coast, indicating that the intensity of carbon emissions in Guangzhou and other regions was the lowest.

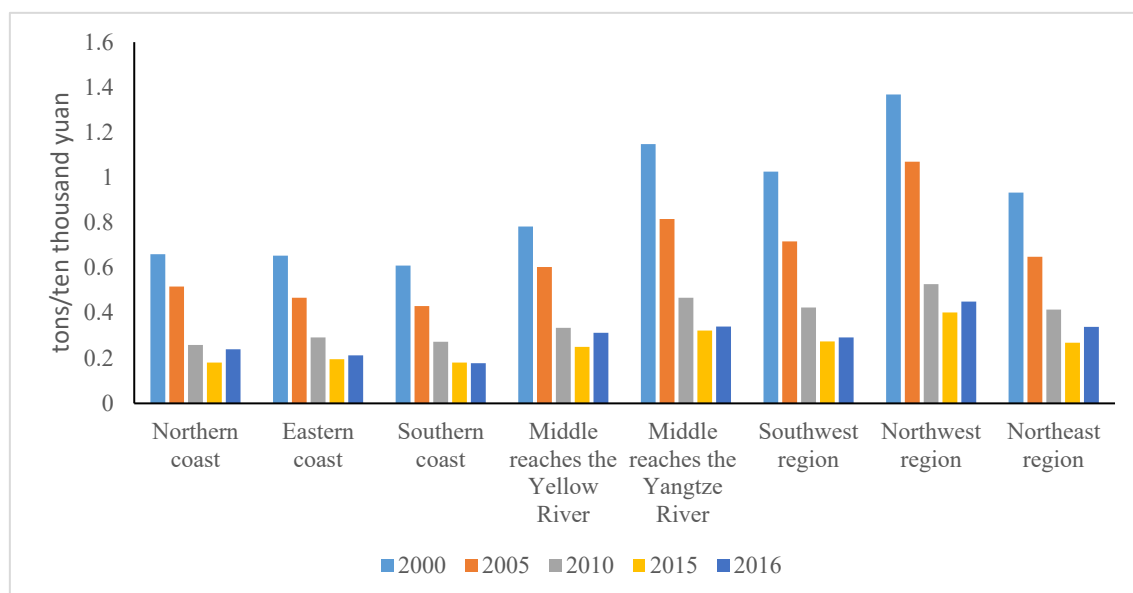


Figure 4. Intensities of agricultural carbon emissions in eight economic zones.

There were great fluctuations in the intensity of agricultural carbon emissions from 2000 to 2016. However, the intensity of agricultural carbon emissions in all province declined from 2000 to 2016. In 2016, the intensity of carbon emissions in Tibet ranked first, which was 3.93 tons/10,000 yuan, while the intensity of carbon emissions in Fujian was only 0.63 tons/10,000 yuan which was the lowest.

Except for Tibet, Qinghai, and Xinjiang, the agricultural carbon emissions in other provinces caused by agricultural land use all increased. According to the main source of the carbon emissions,

these provinces can be divided into five groups: land-use-dominated regions (the agricultural carbon emissions were mainly caused by agricultural activities), rice-cultivation-dominated regions (the agricultural carbon emissions were mainly caused by rice cultivation), livestock-and-poultry-farming-dominated regions (the agricultural carbon emissions were mainly caused by livestock and poultry farming), compound-factor-dominated regions (the agricultural carbon emissions were mainly caused by agricultural land use and rice cultivation, rice cultivation and livestock and poultry farming, agricultural land use and livestock and poultry farming, and the carbon emissions from other factors only accounted for a small proportion, usually below 20%), and balanced regions.

From 2000 to 2016, carbon emissions caused by the use of agricultural land increased year by year. Crop planting was the main agricultural activity in these regions, while livestock and poultry farming and rice cultivation only accounted for a tiny percentage of their agricultural activities. With the implementation of China's rural revitalization strategy, especially the development of green agriculture and forestry industry, agricultural carbon emissions will gradually decline.

4.3. Variation of Regional Agricultural Carbon Emissions

T represents the overall differences in carbon emissions, T_{br} represents the intra-regional differences in carbon emissions, and T_{wr} represents the regional differences in carbon emissions.

Table 5. The Theil index of overall differences in carbon emissions for eight economic zones from 2000 to 2016.

Year	T	T_{wr}	T_{br}
2000	0.183697	0.032687	0.15101
2001	0.17023	0.033136	0.137094
2002	0.165671	0.03375	0.131921
2003	0.142536	0.030557	0.11198
2004	0.162128	0.026844	0.135284
2005	0.13773	0.029721	0.108009
2006	0.150411	0.030044	0.120367
2007	0.166107	0.028339	0.137768
2008	0.166595	0.030405	0.13619
2009	0.157415	0.029726	0.127689
2010	0.180821	0.027688	0.153133
2011	0.169907	0.027065	0.142842
2012	0.152046	0.026737	0.125308
2013	0.143051	0.028387	0.114664
2014	0.148396	0.028925	0.11947
2015	0.158239	0.028747	0.129491
2016	0.131406	0.026426	0.10498

Data Source: calculated by the authors.

The three indices changed to some extent during the observation period (Table 5). Hence, the fluctuation of regional differences was relatively smooth. The changes of the Theil index were caused by intra-regional differences, which were greater than regional differences. It was found that there were some rules for the increases in regional differences of agricultural carbon emissions in the eight economic zones, which can be explained by the intra-regional differences.

4.4. The Theil Index in Eight Economic Zones

Figure 5 shows the Theil index of overall differences of agricultural carbon emissions in eight economic zones from 2000 to 2016. It can be seen that the Theil index in the middle reaches of the Yangtze River was relatively stable, while that in the south coastal economic zone increased gradually, indicating that the overall differences in agricultural carbon emissions increased. Moreover, the Theil index in the southwest region and the south coast also increased, while those in the other economic zones had few changes for many years.

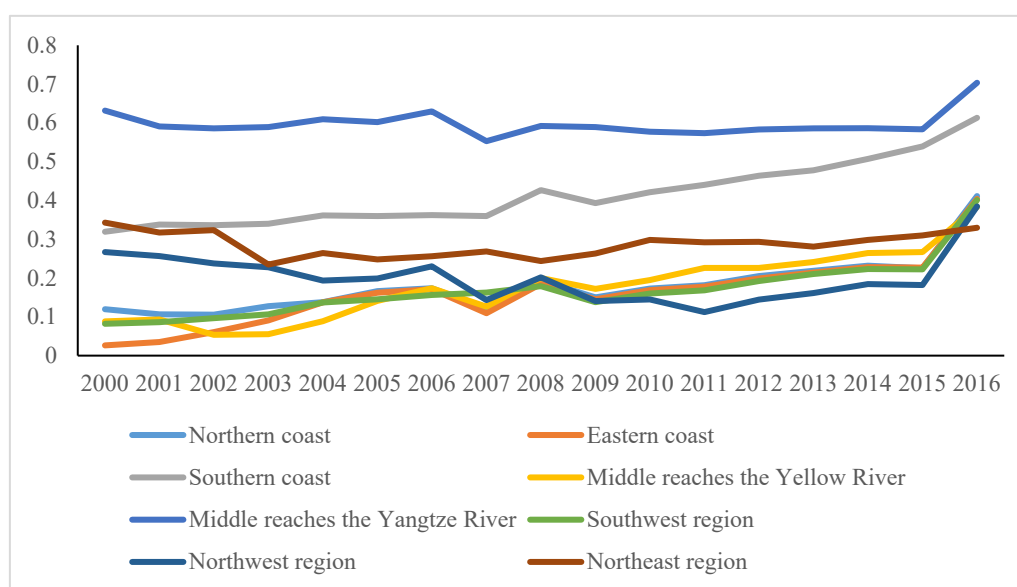


Figure 5. The Theil index of agricultural carbon emissions in eight economic zones.

The intra-regional differences of agricultural carbon emissions from 2000–2016 are summarized as follows:

The intra-regional differences of agricultural carbon emissions in the northern coastal region were relatively stable, with slight fluctuations in 2006 and 2009. It was generally stable, especially from 2009 to 2015, and then increased from 2016. The intra-regional differences of agricultural carbon emissions in the eastern coastal region declined gradually, and became the lowest among the eight economic zones from 2009. The trend of intra-regional differences of agricultural carbon emissions in the southern coastal region was consistent with that of the eastern coastal region, but with a lower speed. The peak of the intra-regional difference of agricultural carbon emissions in the middle reaches of the Yellow River appeared in 2008. The differences declined in 2019 and showed an upward trend from 2009 to 2016. The intra-regional differences of agricultural carbon emissions in the middle reaches of the Yangtze River were always the largest, and there was a slight fluctuation from 2006–2007. The intra-regional differences of agricultural carbon emissions in the southwest region increased from 2000 to 2005 and from 2008 to 2016, while they declined from 2005 to 2007. The intra-regional differences of agricultural carbon emissions in the northwest region and the northeast region from 2000 to 2016 were relatively stable.

Figure 6 shows radar charts of the changes of agricultural carbon emissions per capita in the eight economic zones in different years, measured by the variation coefficient method.

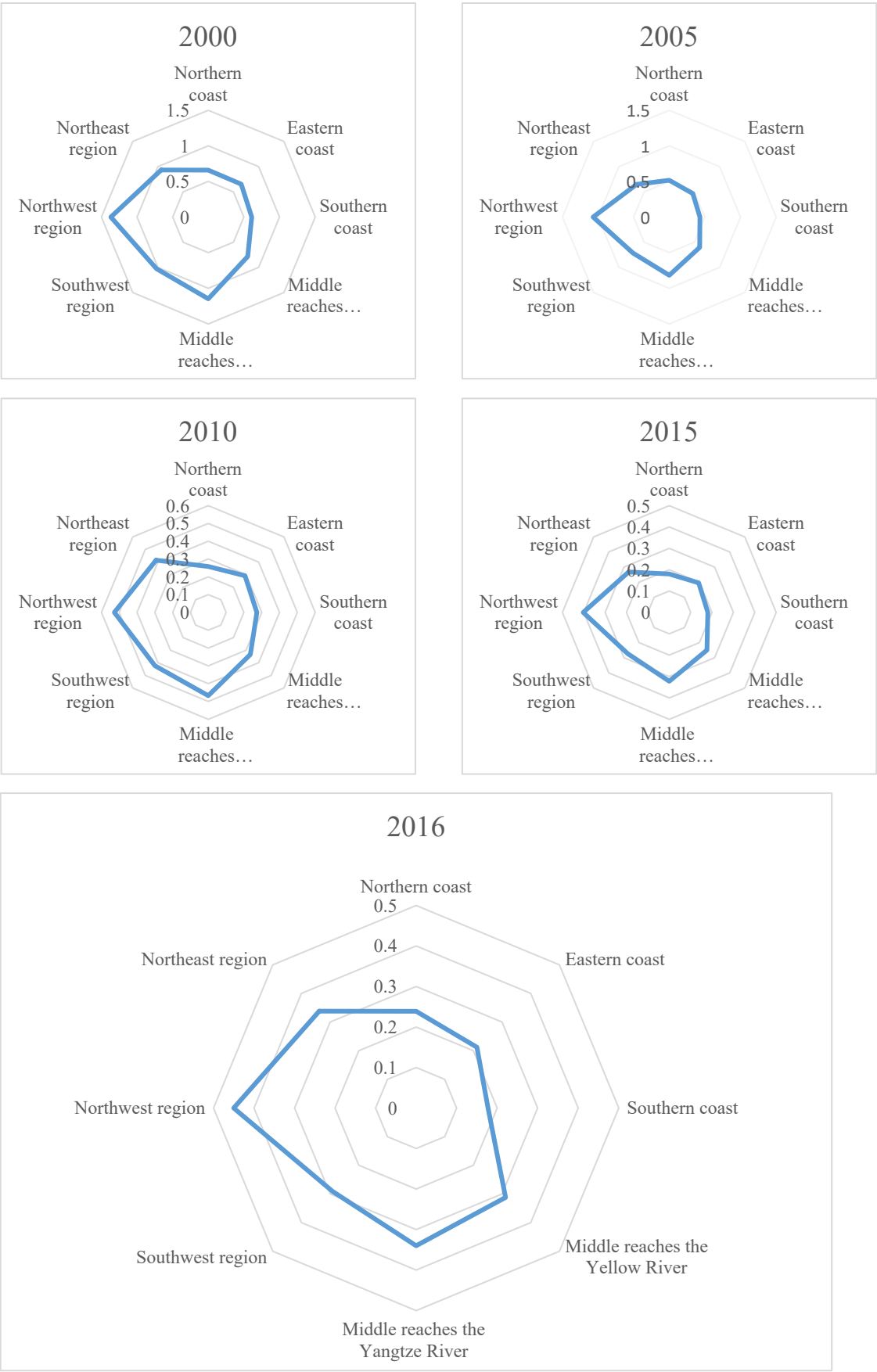


Figure 6. The intensities of agricultural carbon emissions per capita in eight economic zones.

Generally, the agricultural carbon emissions per capita in the eight economic zones all showed an uptrend from 2000 to 2016. According to the circle layers of the radar charts, the regions in outer layers have higher agricultural carbon emissions per capita. It can be seen from Figure 6 that in 2000 and 2015 the agricultural carbon emissions per capita in the northeast economic zone and the northwest economic zone were the highest, while in 2010 and 2016, the agricultural carbon emissions per capita in the northeast economic zone were the highest.

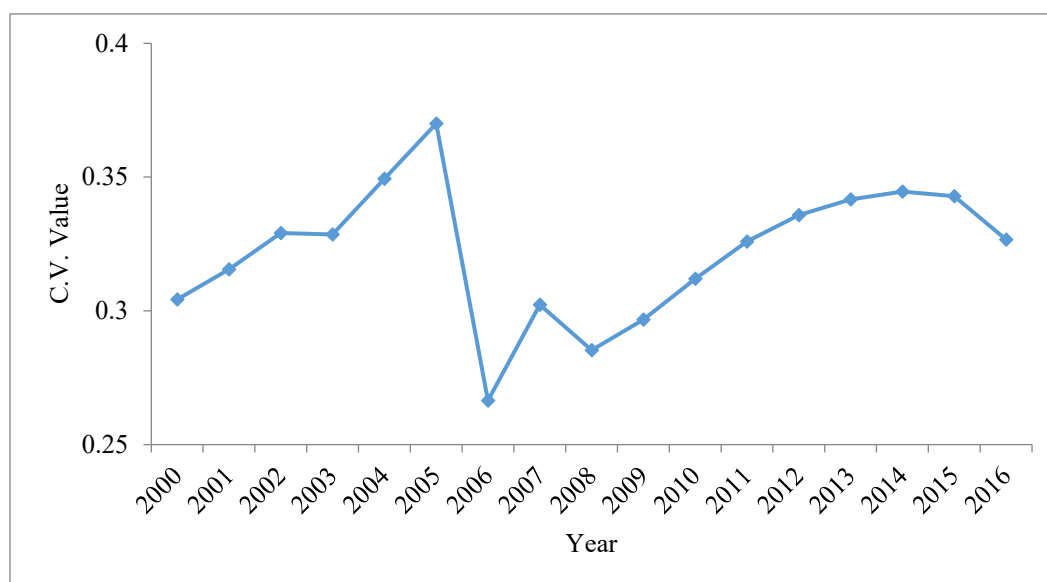


Figure 7. Coefficients of variation of agricultural carbon emissions in eight economic zones.

The coefficients of variation increased from 2000 to 2005 and declined significantly from 2006 (Figure 7). Regional differences in carbon emissions per capita increased from 2007 to 2014, and declined from 2015.

5. Policy Recommendations for the Reduction of Regional Agricultural Carbon Emissions

Based on the above research, this paper has constructed a matrix of total carbon emissions and the intensity of carbon emissions to analyze the regional policies for the reduction of agricultural carbon emissions in eight economic zones. The design of regional policy is a comprehensive and complex science, which needs classified considerations to ensure the pertinence of policy implementation.

The classified policy for the reduction of carbon emissions are important parts of China's national carbon emissions reduction policy. The classification of the intensity of carbon emissions and total agricultural carbon emissions are shown in Table 6.

Table 6. Classification of the intensity of carbon emissions and total agricultural carbon emissions.

Regional division	Total amount of agricultural carbon emissions	Intensity of carbon emissions
	(10,000 tons)	(ton/10,000 yuan)
Low	0–2000	0–0.4
Medium	2000–4000	0.4–0.8
High	>6000	>0.8

Therefore, there are nine types of combinations of emission and intensity, including low emission and low intensity (LE&LI), low emission and medium intensity (LE&MI), low emission and high intensity (LE&HI), medium emission and low intensity (ME&LI), medium emission and medium intensity (ME&MI), medium emission and high intensity (ME&HI); high emission and low intensity (HE&LI), high emission and medium intensity (HE&MI), high emission and high intensity (HE&HI). Agricultural production and livestock products are good outputs, while agricultural carbon emissions are bad outputs. The lower the intensity of agricultural carbon emissions is, the lower the carbon emissions of agricultural production per unit are. Therefore, low emission and low intensity (LE&LI) tends to be the best combination (Table 7).

Table 7. Carbon emissions in eight economic zones.

Year	Northern coast	Eastern coast	Southern coast	Middle reaches the Yellow River	Middle reaches the Yangtze River	Southwest region	Northwest region	Northeast region
2000	ME & MI	ME & MI	ME & MI	LE & MI	HE & HI	ME & HI	LE & HI	ME & HI
2001	ME&MI	ME & MI	LE & MI	LE & MI	HE & HI	ME & HI	LE & HI	ME & HI
2002	ME&MI	ME & MI	LE & MI	LE & MI	HE & HI	HE & HI	LE & HI	ME & HI
2003	ME&MI	ME & MI	LE & MI	LE & MI	HE & HI	HE & HI	LE & HI	ME & MI
2004	ME&MI	ME & MI	LE & MI	LE & MI	HE & HI	HE & MI	LE & HI	ME & MI
2005	ME&MI	ME & MI	LE & MI	LE & MI	HE & HI	HE & MI	LE & HI	ME & MI
2006	ME&MI	ME & MI	LE & MI	LE & MI	HE & HI	HE & MI	LE & HI	ME & MI
2007	ME&LI	ME&LI	LE & LI	LE & LI	HE & MI	HE & MI	LE & HI	ME & MI
2008	ME&LI	ME&LI	LE & LI	LE & LI	HE & MI	HE & MI	ME & HI	ME & MI
2009	ME&LI	ME&LI	LE & LI	LE & LI	HE & MI	HE & MI	ME & MI	ME & MI
2010	ME&LI	ME&LI	LE & LI	LE & LI	HE & MI	HE & MI	LE & MI	ME & MI
2011	ME&LI	ME&LI	LE & LI	LE & LI	HE & MI	HE & LI	LE & MI	ME & LI
2012	ME&LI	ME&LI	LE & LI	LE & LI	HE & LI	HE & LI	ME & MI	ME & LI
2013	ME&LI	ME&LI	LE & LI	LE & LI	HE & LI	HE & LI	ME & MI	ME & LI
2014	ME&LI	ME&LI	LE & LI	LE & LI	HE & LI	HE & LI	ME & MI	ME & LI
2015	ME&LI	ME&LI	LE & LI	LE & LI	HE & LI	HE & LI	ME & MI	ME & LI
2016	ME&LI	ME&LI	LE & LI	LE & MI	HE & LI	HE & LI	ME & MI	HE & LI

Note: Red-Yellow-Green, the agricultural carbon emissions and the intensity of agricultural carbon emissions decline gradually.  --HE&HI;  --ME&HI, HE&MI;  --HE&LI, LE&HI;  --ME&MI;  --ME&LI; LE&MI;  --LE&LI

Based on the concept of coordinated development in the eight economic zones, this paper proposes that corresponding policies for the reduction of agricultural carbon emissions should be adopted for different economic zones.

5.1. Agricultural Development in the Northern Coastal Economic Zone

The northern coastal economic zone includes the two cities of Beijing and Tianjin and the two provinces of Hebei and Shandong. The two provinces are important bases of agricultural production in China, especially Shandong province, which is also an important base of vegetable production in China. Moreover, Shandong also plays an important role in the development of modern agriculture. This region is generally characterized by a high level of openness and well-developed science and technology and transportation conditions. However, the integration process in this region is relatively slow as its agricultural products mainly support the Beijing area, which has hindered the establishment of a cooperation mechanism of carbon emission reduction among different provinces.

The agricultural carbon emissions in the northern coastal economic zone should be reduced and its intensity of agricultural carbon emissions should be controlled. Since leisure agriculture and picking agriculture in the suburbs of Beijing have been developed, Hebei and Shandong provinces can learn from its management technologies and methods to promote agricultural transformation. Furthermore, Shandong Province, as the largest exporter of agricultural products in China, should focus on the transformation of high-end and high value-added industries so as to realize the transformation and upgrading of industrial structure.

5.2. Agricultural Development in the Eastern Coastal Economic Zone

The development of the eastern coastal economic zone, which includes the city of Shanghai and the two provinces of Jiangsu and Zhejiang, has been promoted by China's reform and opening-up policy, and it has already become the center of China's modern industries. With 40 years of reform and opening up, the modern financial system in this region has been formed, and its agricultural input and output are already relatively high.

Therefore, the agricultural carbon emissions in this region should be reduced moderately. The high-end manufacturing industry can be a strong driving force for the development of agriculture in this region, which can also be accelerated by increasing the proportion of the tertiary industry; strengthening the development of logistics, consulting, and other industries as well as increasing brand awareness within the region.

5.3. Agricultural Development in the Southern Coastal Economic Zone

The southern coastal economic zone covers the city of Guangzhou and the two provinces of Fujian and Hainan. With a high level of opening up due to its location near to Hong Kong (HK), Macau, and Taiwan, advanced foreign technologies are usually adopted firstly in this region, and it is also the main production base of consumer durable goods (such as cotton cloth). The main disadvantages in this region are the environmental pollution and the relatively high cost of pollution treatment.

The total amount and intensity of carbon emissions in this region should be maintained at the current level. As the center of foreign trade in China, the transformation and upgrade of the traditional processing industry can be promoted by making full use of the regional capital market—importing foreign capital, introducing advanced experience, improving the existing industrial development system, and enhancing the role of the value added by the regional wholesale market.

5.4. Agricultural Development in the Middle Reaches of the Yellow River Economic Zone

The middle reaches of the Yellow River economic zone includes the autonomous region of Inner Mongolia and the provinces of Shanxi, Shaanxi, and Henan, which are all important inland provinces in China. The pattern and level of economic development in this region are significantly different from those in the three economic zones mentioned above. The natural resources in this region are relatively rich, but the ecological environment has been greatly affected by long-term extensive cultivation. With a low agricultural output and insufficient level of opening up in this region, this region has faced great pressure to upgrade the industrial structure.

Therefore, active measures should be taken to reduce the total amount and intensity of carbon emissions in this region. With the improvement of production efficiency and the introduction of advanced technologies, the agricultural industry chain can be extended at the same time by enhancing regional and intra-regional cooperation, making full use of agricultural raw materials, such as edible fungi, and establishing a national logistics transportation network.

5.5. Agricultural Development in the Middle Reaches of the Yangtze River Economic Zone

The middle reaches of the Yangtze River economic zone includes the provinces of Hubei, Hunan, Jiangxi, and Anhui. With sufficient water sources and a large population, this region has developed a relatively mature agricultural system. However, its degree of opening up needs to be further improved, and its agricultural industrial structure should be upgraded.

For this region, moderate measures should be taken to reduce the total amount and intensity of agricultural carbon emissions. As the agricultural carbon emissions in this region are the highest in China, the proportion of high-tech industries can be increased by introducing the concept of large-scale agriculture, with emphasis on the development of leisure agriculture, agricultural tourism, and the transformation of agricultural products, so as to fully develop the modern agriculture in this region.

5.6. Agricultural Development in the Southwest Economic Zone

The southwest economic zone includes the city of Chongqing; the provinces of Yunnan, Guizhou, Sichuan, and others; and the autonomous region of Guangxi. Restricted by geographical factors, the scale of agriculture in this region tends to be small, and the quality of soil is relatively poor. However, the forestry in this region has been well developed, which provides a good foundation for the development of tourism.

Therefore, the agricultural carbon emissions should be reduced moderately and the intensity of carbon emissions should be controlled. The degree of agricultural modernization in this region can be improved by enhancing the management of agricultural production and introducing modern agricultural industry systems, such as a picking industry.

5.7. Agricultural Development in the Northwest Economic Zone

The northwest economic zone includes the provinces of Gansu and Qinghai, and the autonomous regions of Ningxia, Tibet, and Xinjiang. This region is not only the largest base of deep processing for cotton, grain, and oil products but also an important energy base in China. The production of the primary industry accounts for a large proportion of the gross production in this region, and the conditions for agricultural development are relatively poor.

Therefore, the total amount and intensity of agricultural carbon emissions in this region should be maintained at the current level. Due to the strong light throughout the year, the proportion of fruit products in the agricultural market can be gradually increased with the overall agricultural carbon emissions unchanged, and industrial upgrading can be promoted by cotton production.

5.8. Agricultural Development in Northeast Economic Zone

The northeast economic zone, which includes Liaoning, Jilin, and Heilongjiang provinces, is characterized by good agricultural production conditions. In recent years, this region has faced the pressure of depleting resources and industrial structure upgrading.

The total agricultural carbon emissions in this region should be reduced moderately and the intensity should be controlled. Furthermore, with the experiences of resource transformation at home and abroad, taking the opportunity of establishing a national carbon emission market and the rich carbon storage in this region, the management and maintenance of agricultural land can be enhanced and the area of forestry can be increased.

6. Conclusions and Discussion

This paper measured the agricultural carbon emissions in China, and compared the regional differences of agricultural carbon emissions using the method of coefficient of variation and the Theil index by taking four regions and eight economic zones as research areas. The results showed that, in 2016, China's total carbon emissions were 272.022 million tons, which is 26.67% more than that in 2000, and the average annual increase was 1.67%. Among them, carbon emissions caused by agricultural land use, rice cultivation, and livestock and poultry were 110.5649 million tons, 70.193 million tons, and 91.2642 million tons, respectively, accounting for 40.64%, 25.8%, and 33.55% of agricultural carbon emissions. The total agricultural carbon emissions of the three aspects mentioned above all increased from 2000 to 2016. To be specific, carbon emissions from agricultural land use increased the fastest, from 73.9473 million tons to 110.5649 million tons, with an average annual increase of 3.09%. That means the increase of agricultural output in China depends greatly on the increase of agricultural material input. There were great fluctuations in the carbon emissions from rice cultivation, which increased slightly from 69.7028 million tons in 2000 to 70.193 million tons in 2016, with an average annual increase of 0.04%. Carbon emissions from rice cultivation are mainly affected by the scale and structure of rice cultivation. Carbon emissions from livestock and poultry farming increased from 71.1037 million tons in 2000 to 91.2642 million tons in 2016, with an average annual increase of 1.77%. Affected by the scale and structure of livestock and poultry farming, the change of carbon emissions from livestock and poultry farming can be divided into five periods: a period of continuous rising (2000–2005), a period of rapid declining (2006–2007), a period of rapid rising (2007–2008), a period of declining (2008–2009), and a period of steady growth (2009–2016). Agricultural carbon emissions per capita in eight economic zones all showed an uptrend from 2000 to 2016. In addition, in 2000 and 2015, the agricultural carbon emissions per capita in the northeast economic zone and the northwest economic zone were the highest, while in 2010 and 2016, only the agricultural carbon emissions per capita in the northeast economic zone were the highest. Based on the concept of coordinated development in the eight economic zones and their important positions in China's agricultural development, this paper proposes some policy recommendations for the reduction of agricultural carbon emissions. Compared with Tian's (2012) conclusions [32], in China, the intensity of agricultural carbon emissions declined from the west to the east (Figure 3), and in 2016, the intensity of agricultural carbon emissions showed a trend of northwest region > middle reaches the Yangtze River > northeast region > southwest region > northern Coast > eastern coast > southern coast, which is of strong similarity to previous literature.

Agricultural carbon emissions caused by straw burning and N_2O were not taken into consideration in this paper, as existing researches have shown different results for carbon emissions caused by N_2O . The regional differences of agricultural carbon emissions in this paper were only estimated on the basis of total carbon emissions and the intensity of carbon emissions. However, the efficiency of carbon emissions is also a very important indicator, which should be considered in further research.

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