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Spatio-Temporal Evolution of Agricultural Carbon Emissions in China, 2000–2020

Xidong Zhang [1], Juan Zhang [2,*] and Chengbo Yang [3]

[1] Institute of Ecology and Sustainable Development, Shanghai Academy of Social Sciences, Shanghai 200020, China
[2] College of Philosophy, Law & Political Science, Shanghai Normal University, Shanghai 200234, China
[3] School of Mathematics, Jilin University, Changchun 130012, China
* Correspondence: zhangjuan1989@shnu.edu.cn

Abstract: Agricultural carbon mitigation is one of the most important components of China's carbon mitigation goals. This paper calculates China's agricultural carbon emissions (ACEs) from 2000 to 2020, studies the spatio-temporal evolution characteristics of China's ACEs, and aims to provide references for the development of China's ACEs reduction policies. The results show that the total ACEs in China presented an inverted "W" trend, with a slight increase of 2.81% in total. China's ACEs mainly came from livestock and poultry breeding and agricultural material inputs. Although the carbon emissions from rice cultivation and soil accounted for a relatively low proportion, they showed an uptrend of fluctuation during the study period. From a geographical point of view, ACEs in the regions of central China and western China were relatively high compared to those in eastern China. Carbon emissions decreased for crop farming and livestock and poultry breeding in most eastern provinces. Crop farming carbon emissions grew, while the emissions from livestock and poultry breeding declined in most of the central provinces. Carbon emissions increased for crop farming and livestock and poultry breeding in most western provinces. Therefore, the existing low-carbon agricultural policies should be optimized, crop farming technologies should be improved, and specific policies should be applied in the corresponding regions to support China's ACEs reduction.

Keywords: agriculture; carbon emissions; evolutionary characteristics

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1. Introduction

Carbon emissions are one of the most important factors contributing to climate change [1], consequently causing damage to the environment, production, and health [2–4]. Studies have shown that the global surface temperature will increase by an average of 1.8 °C to 4.0 °C over the next 100 years, and a 4 °C increase in the global temperature will lead to serious disasters [5]. The 2019 Climate Change Conference stated that the world must set a target to constrain global warming within 2 °C [6]. Controlling carbon emissions and building a low-carbon society have become a consensus of all countries around the world [7].

As one of the first signatories to the United Nations Framework Convention on Climate Change and the world's second largest economy, China has always been an active participant and supporter of global climate governance. In 2016, China signed the Paris Agreement to address climate change and reduce carbon emissions. Since the 18th National Congress of the CPC (Communist Party of China), the Central Committee of the CPC has attached great importance to the green and low-carbon development process of China. At the General Debate of the 75th Session of the United Nations General Assembly of 2020, President Xi proposed that China will strive to meet the emission peak of carbon dioxide by 2030 and achieve carbon neutrality by 2060. Now, China is actively taking actions and exploring ways to fulfil the commitment proposed by President Xi.

Scholars have studied the issue of carbon emissions, yet most of them focus on heavy-industry carbon emissions, which are an important source of carbon emissions [8,9].

Meanwhile, carbon emissions from agricultural production and land use account for a quarter of the total human carbon emissions [10]. Accounting for 17% of China's total carbon emissions, China's agricultural carbon emissions (ACEs) are one of the main sources of China's carbon emissions [11]. As the largest agricultural country of the world, China's ACEs account for 11–12% of the global ACEs [12] and are about twice those of the United States [13]. Therefore, reducing ACEs is an important way for China to achieve the goals of carbon peaking and carbon neutrality, which are of great significance for global ACEs reduction and climate change mitigation [14].

Given the importance of ACEs in reducing carbon emissions, investigating how to reduce ACEs has become a research hotspot for scholars. At present, research on ACEs mainly focuses on the aspects of ACEs sources, ACEs measurement, and the spatio-temporal characteristics of ACEs.

To reduce ACEs, the sources need to be identified. Greenhouse gases mainly include CH_4, N_2O, and CO_2. According to relevant studies, N_2O emissions mainly come from field burning, grazing, and animal manure, and CH_4 emissions are mainly released from livestock farming and rice cultivation, while CO_2 emissions mainly come from the production and use of agricultural machinery, fertilizers, and other chemical inputs [15,16]. Therefore, ACEs mainly come from agricultural production processes such as crop planting, input of agricultural material, livestock breeding, and agricultural waste treatment [17,18]. Scholars have carried out research on crop farming, and its carbon emissions are measured from the perspectives of fertilizers, pesticides, irrigation, etc. [19]. ACEs have also been estimated in terms of agricultural waste, livestock and poultry intestinal fermentation and manure emissions, rice cultivation, and straw burning [20–22].

Upon the identification of ACEs sources, researchers conduct ACEs measurement. Currently, ACEs are generally estimated according to Volume 4 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [23]. In a previous study, the authors constructed an ACEs measurement indicator system based on four dimensions, namely, fertilizer, pesticide, agricultural irrigation, and seed cultivation, and took the United States as an example to calculate ACEs [24]. Others believe that ACEs mainly come from abnormal treatment of agricultural waste, livestock and poultry breeding, agricultural energy utilization, rice cultivation, and other sources. Based on all of this, a detailed indicator system has been constructed to measure ACEs in the United States [21]. There are also scholars who only measured and analyzed carbon emissions from the perspective of agricultural land use [25,26].

In recent years, the number of studies on the measurement of greenhouse gas emissions from China's agriculture has gradually increased. Some scholars have measured China's ACEs, but their selection of carbon sources was relatively simple, merely focusing on agricultural material input and agricultural land use [27]. Similarly, various studies have been carried out from a solo perspective of carbon resources on the measurement and analysis of ACEs, such as carbon emissions from agricultural land use [28,29], from livestock and poultry breeding [30–32], and from fishery production [33–35]. Scholars have also comprehensively measured China's ACEs from a more comprehensive perspective, which covers the main sectors of agricultural production (i.e., planting and animal husbandry), and specific carbon sources include agricultural material inputs, crop farming, and livestock and poultry breeding [36–42].

By calculating the total amount of ACEs, scholars have further studied the regional differences and spatio-temporal evolution characteristics of ACEs. The basic research results show that the total volume of China's ACEs has witnessed an increasing trend, and China's ACEs show an obvious spatial correlation [39,43], but their growth rate has gradually slowed down [44], and ACEs per capita show an uptrend [45]. The carbon emission intensity of agricultural production in China shows a downward trend. The Global Moran I index indicates that China's carbon emission intensity of agricultural production presents a clear trend of spatial aggregation. Additionally, the overall pattern of ACEs intensity shows a pattern of increasing differentiation from east to west [38].

In general, previous research on ACEs in China has made a lot of achievements. However, there are still some deficiencies in the previous research, which can be categorized as follows: First, updated data are unavailable for calculating China's ACEs in recent years. Second, the time span of the studies is short; thus, it cannot reflect the long-term changes in ACEs in China. Third, research on the evolution of regional ACEs is insufficient, and the evolution characteristics of ACEs in different regions cannot be identified clearly. Based on this, this paper adopts the standardized accounting method of ACEs, and synthetically calculates the spatial–temporal characteristics of ACEs in China from 2000 to 2020 considering four dimensions: rice cultivation, soil, input of agricultural materials, and livestock and poultry breeding. Furthermore, this paper studies the dynamic evolution characteristics of ACEs in different regions, finally drawing the conclusions.

This paper deepens the understanding of China's ACEs structure and brings value to the rational optimization of the agricultural structure, as well as support for achieving China's goal of carbon peaking in the agriculture sector. The scientific measurement and analysis of the spatio-temporal characteristics of ACEs lay the foundation for the development and optimization of China's ACEs reduction policies.

2. Method and Data

2.1. ACEs Accounting Method

Based on the research results of the IPCC, coefficient measurement is used for the modeling of ACEs accounting in this paper, as shown below:

$$C_e = C_{eh} \cdot \mu_h + C_{en} \cdot \mu_n + C_{ec} \cdot \mu_c \tag{1}$$

$$C_{eh} = \sum\nolimits_{i=1}^{n} (S_{hi} \cdot \alpha_{hi}) + \sum\nolimits_{i=1}^{m} (D_{hi} \cdot \beta_{hi}) \tag{2}$$

$$C_{en} = \sum\nolimits_{i=1}^{n} (S_{ni} \cdot \alpha_{ni}) + \sum\nolimits_{i=1}^{m} (D_{ni} \cdot \gamma_{ni}) \tag{3}$$

$$C_{ec} = \sum\nolimits_{i=1}^{o} (S_{ci} \cdot \delta_{ci}) \tag{4}$$

where C_e is agricultural carbon emissions, C_{eh} is the total agricultural CH_4 emissions, C_{en} is the total agricultural N_2O emissions, C_{ec} is the total amount of carbon emissions from agricultural materials, μ_h is the CO_2 equivalent coefficient converted from CH_4, μ_n is the CO_2 equivalent coefficient converted from N_2O, μ_c is the CO_2 equivalent coefficient converted from C, S_{hi} is the seeded area of the i^{th} type of crop, which is featured with α_{hi} as the CH_4 emission coefficient per unit area, D_{hi} is the annual mean number of the i^{th} type of livestock and poultry, which is featured with β_{hi} as the CH_4 emission coefficient, S_{ni} is the seeded area of the i^{th} type of principal N_2O emission crop, which is featured with α_{ni} as the annual background N_2O emission flux per unit area, D_{ni} is the annual mean number of the i^{th} type of livestock and poultry, which is featured with γ_{ni} as the N_2O emission coefficient, and S_{ci} is the i^{th} type of agricultural material, which is featured with δ_{ci} as C emission coefficient.

2.2. Carbon Emissions from Rice Cultivation

Considering that the anaerobic respiration process is weak in dryland ecosystems, rice cultivation is the main emission source of CH_4; therefore, only CH_4 emissions from rice are considered when calculating the CH_4 emissions from crop growth. In addition, the CH_4 emission rate from rice cultivation is affected by rice varieties, climatic conditions, and soil and hydrological conditions. With reference to previous studies, the CH_4 emission coefficients from rice cultivation in various regions of China are shown in Table 1 [36,45].

Table 1. CH_4 emission coefficients from rice cultivation in different regions of China (g/m^2).

Region	Early Rice	Late Rice	Semilate Rice	Region	Early Rice	Late Rice	Semilate Rice
Beijing	0	0	13.23	Hubei	17.51	39	58.17
Tianjin	0	0	11.34	Hunan	14.71	34.1	56.28
Hebei	0	0	15.33	Guangdong	15.05	51.6	57.02
Shanxi	0	0	6.62	Guangxi	12.41	49.1	47.78
Inner Mongolia	0	0	8.93	Hainan	13.43	49.4	52.29
Liaoning	0	0	9.24	Chongqing	6.55	18.5	25.73
Jilin	0	0	5.57	Sichuan	6.55	18.5	25.73
Heilongjiang	0	0	8.31	Guizhou	5.1	21	22.05
Shanghai	12.41	27.5	53.87	Yunnan	2.38	7.6	7.25
Jiangsu	16.07	27.6	53.55	Tibet	0	0	6.83
Zhejiang	14.37	34.5	57.96	Shanxi	0	0	12.51
Anhui	16.75	27.6	51.24	Gansu	0	0	6.83
Fujian	7.74	52.6	43.47	Qinghai	0	0	0
Jiangxi	15.47	45.8	65.42	Ningxia	0	0	7.35
Shandong	0	0	21	Xinjiang	0	0	10.5
Henan	0	0	17.85				

2.3. Carbon Emissions from Soil

The accounting of soil carbon emissions mainly accounts for N_2O emissions during the growth of crops. Crops mainly include rice, wheat (spring wheat, winter wheat), soybean, corn, vegetables, and other dryland crops. N_2O emission factors for crops are obtained mainly from previous studies [36], as shown in Table 2.

Table 2. The N_2O coefficient of each crop (kg/hm^2).

	Rice	Spring Wheat	Winter Wheat	Soybean	Corn	Vegetables	Other Dryland Crops
Coefficient	0.24	0.4	1.75	2.29	2.53	4.94	0.95

2.4. Carbon Emissions from Agricultural Materials

The input categories of agricultural materials mainly include fertilizer, pesticides, agricultural films, diesel oil, agricultural irrigation area, and plowing. Among them, fertilizer, pesticides, agricultural plastic films, diesel fuel, and agricultural irrigation area correspond to the actual situation of the year; plowing data use the actual planting area of crops to replace from the corresponding year. The carbon emission coefficients for various agricultural inputs are obtained mainly from previous studies [12,43,46–58], as shown in Table 3.

Table 3. Carbon emission coefficients from agricultural materials.

	Coefficient		Coefficient
Fertilizer	0.8956 kg C/kg	Diesel Fuel	0.5927 kg C/kg
Pesticides	4.9341 kg C/kg	Plowing	312.6 kg C/km^2
Agricultural Plastic Films	5.18 kg C/kg	Irrigation	266.48 kg C/km^2

2.5. Carbon Emissions from Livestock and Poultry

The carbon emissions accounting of animal husbandry mainly includes two aspects: one is animal gastrointestinal fermentation and CH_4 emissions, and the other is N_2O emissions. Livestock and poultry varieties mainly include cows, buffaloes, cattle, horses, donkeys, mules, camels, pigs, sheep, rabbits, and poultry. The carbon emission coefficients for livestock and poultry are obtained mainly from previous studies [36,59–61], as shown in Table 4.

Table 4. Carbon emission coefficients for each animal (kg/unit/year).

	Coefficient of CH_4		Coefficient of N_2O		Coefficient of CH_4		Coefficient of N_2O
	Intestinal Fermentation	**Fecal Discharge**	**Fecal Discharge**		**Intestinal Fermentation**	**Fecal Discharge**	**Fecal Discharge**
Cows	68	16	1	Horses	18	1.64	1.39
Buffaloes	55	2	1.34	Pigs	1	3.5	0.53
Cattle	47.8	1	1.39	Sheep	5	0.16	0.33
Mules	10	0.9	1.39	Rabbits	0.254	0.08	0.02
Camels	46	1.92	1.39	Poultry	-	0.02	0.02
Donkeys	10	0.9	1.39				

2.6. Data Sources

The data of sown area of crops, agricultural materials, and livestock and poultry are mainly derived from the "China Agricultural Yearbook", "China Rural Statistical Yearbook", "China Statistical Yearbook", and "China Animal Husbandry and Veterinary Yearbook".

3. Results

Based on the above accounting method for ACEs, this paper estimates China's ACEs from 2000 to 2020 and analyzes the characteristics of the spatio-temporal variation and dynamic evolution. It is worth noting that this paper focuses on ACEs from the Chinese mainland, excluding the regions of Hong Kong, Macao, and Taiwan.

3.1. Analysis of the Spatio-Temporal Characteristics of ACEs

Figure 1 shows the variation in the total carbon emissions, and Table 5 displays the structural changes in ACEs in China from 2000 to 2020. It should be noted that the ACEs units mentioned in this paper are all CO_2 equivalents. The conversion coefficients between different greenhouse gases refer to the IPCC report, which shows that the greenhouse effect of 1 $kgCH_4$ is equivalent to that of 25 $kgCO_2$, the greenhouse effect of 1 kgN_2O is equivalent to that of 298 $kgCO_2$, and the carbon equivalent of 1 $kgCO_2$ is 0.2727 kgC [54].

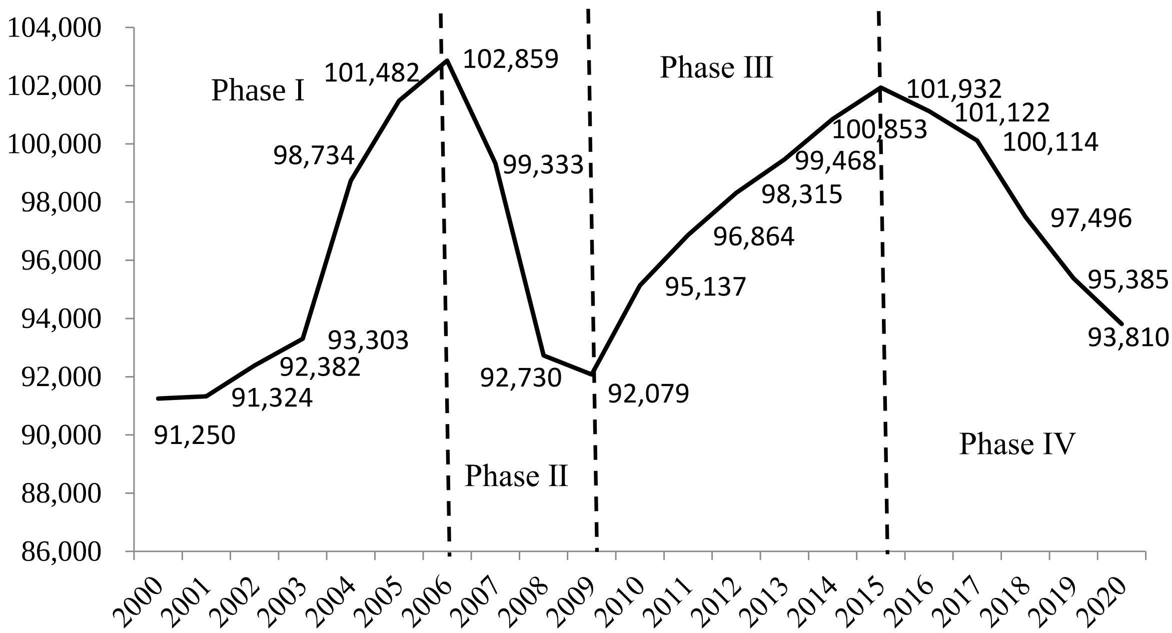


Figure 1. China's agricultural carbon emissions (ACEs) from 2000 to 2020 (10^4 t).

Table 5. Sources of ACEs in China from 2000 to 2020 (10^4 t).

	Rice Cultivation	Soil	Agricultural Materials	Livestock and Poultry Breeding		Rice Cultivation	Soil	Agricultural Materials	Livestock and Poultry Breeding
2000	23,449	7648	21,757	38,396	2011	23,569	8884	31,044	33,367
2001	22,620	7807	22,491	38,407	2012	23,501	9259	31,801	33,754
2002	22,486	7913	23,040	38,943	2013	23,534	9245	32,346	34,343
2003	21,404	7907	23,561	40,431	2014	23,553	9402	32,847	35,051
2004	22,909	7923	25,111	42,790	2015	23,622	9555	32,982	35,773
2005	23,307	8102	26,010	44,063	2016	23,610	9315	32,605	35,592
2006	23,466	8178	26,884	44,331	2017	24,708	9533	31,851	34,023
2007	23,082	8115	28,014	40,121	2018	24,624	9602	30,580	32,689
2008	23,290	8296	28,384	32,759	2019	24,419	9730	29,299	31,938
2009	23,465	8554	29,292	30,768	2020	23,660	9909	28,436	31,806
2010	23,522	8721	30,215	32,679					

In 2020, China's ACEs amounted to 93,810 ten thousand tons, with an increase of 2.81% compared to those in 2000. ACEs originating from rice cultivation, soil, agricultural materials, and livestock and poultry breeding corresponded to amounts of 23,660 ten thousand tons, 9909 ten thousand tons, 28,436 ten thousand tons, and 31,806 ten thousand tons, with proportions of 25.22%, 10.56%, 30.31%, and 33.9%, respectively. In general, the trend of China's ACEs from 2000 to 2020 appeared to fall after rising, and then it repeated this trend again in four phases with a tendency of an inverted "W".

The first phase, from 2000 to 2006, can be split into two stages. ACEs witnessed small growth from 2000 to 2003, and then a rapid growth emerged from 2003 to 2006. In general, ACEs increased to 102,859 ten thousand tons, with an increase rate of 12.72% compared to 2000. The ascent rates of rice cultivation, soil, agricultural materials, and livestock and poultry breeding increased by 0.07%, 6.92%, 23.57%, and 15.46%, respectively. The continuous increase in agricultural material investment and the scale expansion of livestock and poultry breeding acted as key drivers for the huge growth in ACEs during this phase.

Phase II began in 2006 and ended in 2009. In this phase, ACEs experienced a rapid decline to 92,079 ten thousand tons in 2009, with a descent rate of 10.48% compared to 2006. Specifically, carbon emitted from soil and agricultural materials increased by 4.60% and 8.96%, respectively, and the amount remained unchanged for rice cultivation, yet it declined by 30.60% for livestock and poultry breeding. The shrinkage of the breeding scale and industrial structure optimization of animal husbandry played key roles in this decline.

Phase III, from 2009 to 2015, achieved steady-state growth in ACEs. China's ACEs were 101,932 ten thousand tons in 2015, with a growth rate of 10.7% compared to 2009. Carbon emitted from rice cultivation, soil, agricultural materials, and livestock and poultry breeding increased by 0.67%, 11.71%, 12.60%, and 16.27%, respectively. Unlike the scenario of rapid growth in phase I, the growth rate of ACEs appeared to be more balanced in phase III. The scale expansion of crop farming, agricultural materials, and livestock and poultry breeding turned out to be the key driver of such emission growth during this phase.

Phase IV, from 2015 to 2020, achieved a steady-state decline in ACEs. China's ACEs were 93,810 ten thousand tons in 2020, with a decrease rate of 7.97% compared to 2015. Carbon emitted from rice cultivation and soil increased by 0.16% and 3.70%, while it decreased by 13.78% and 11.09%, respectively, for agricultural materials and livestock and poultry breeding. The policy of the "fertilizer and pesticide reduction" campaign has played a positive role in China's ACEs reduction since 2015, and has worked particularly well for the carbon emission reduction of agricultural materials. Such an outstanding achievement can largely be attributed to the relevant national strategy, the continuous decline in agricultural materials, and the sharp shrinkage of the large livestock inventory.

Among the various emission sources, ACEs from livestock and poultry breeding declined, while for other sources, they increased in 2020 compared to 2000. Among all the growing carbon resources, emissions from agricultural materials accounted for the largest proportion and growth rate. Carbon emissions from agricultural materials experienced the trend of "falling after rising" from 2000 to 2020. Specifically, agricultural materials witnessed continuous growth in carbon emissions from 2000 to 2015, with a growth rate of 51.60% in 2015 compared to 2000; then, carbon emissions from agricultural materials showed a downward trend year by year, driven by the national growing emphasis on the green development of agriculture, and the campaign for fertilizer and pesticide reduction, from 2015 to 2020. ACEs from agricultural materials dropped by 13.78% in 2020 compared to 2015. ACEs from rice cultivation were second only to those from agricultural materials, and they maintained a steady growth trend from 2000 to 2020, with a growth rate of 0.90%. The volume of ACEs from soil occupied the lowest position among all the carbon sources and showed an uptrend, generally increasing by 29.55% unilaterally; even fluctuations were spotted during the survey, yet the range of such fluctuations remained narrow. By contrast, ACEs from livestock and poultry breeding declined stepwise during the survey, with an accumulative drop of 17.16%; from the perspective of development, they endured a "rapid decline after steady growth" in phase I (2000–2009), followed by a "gentle decline after gentle growth" in phase II (2009–2020). It can be found that the carbon emitted from livestock and poultry breeding was lower in phase II than that in phase I, and ACEs showed a trend of declining stepwise during the whole period of the study.

3.2. Analysis of the Spatial Variation Characteristics of ACEs

According to the level of regional economic development, China is divided into the eastern, central, and western regions: the eastern region includes Beijing, Tianjin, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong; the central region covers Hebei, Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hunan, Hubei, and Hainan; the western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. Figure 2 displays the variation in ACEs in the eastern, central, and western regions. The central and western regions contributed most of the ACEs in China; this is aligned with China's overall ACEs trend, which features a reversed "W" tendency. Meanwhile, the ACEs trend showed a wave-like decrease in the eastern region. More recently, from 2015 to 2020, ACEs declined in the eastern, central, and western agricultural regions by 14.26%, 7.58%, and 5.96%, respectively. During the period of this study, ACEs declined by 14.26% in the eastern region, while they increased by 7.58% and 5.96% in the central and western regions from 2000 to 2020.

In the five maps from 2000 to 2020 in Figure 3, from a time-span point of view, the color deepens gradually in the central and western regions, while it becomes shallow in the eastern region, indicating the changes in China's ACEs on a regional scale. Within the maldistribution of ACEs in each province, the central region ranks top, followed by the western region, while the eastern region remains at the bottom from 2000 to 2020. As observed through the color change over the years, it is found that ACEs sustained a high level in certain provinces, and a lock-in effect of carbon emissions may have been developed. The map also reveals the provinces with the highest ACEs, including Shandong, Henan, Hunan, Hubei, Sichuan, Jiangsu, Anhui, and Jiangxi, with ACEs above 4000 ten thousand tons. By contrast, emissions from Beijing, Tianjin, Shanghai, Hainan, and Ningxia were relatively low. Considerable differences in carbon emissions existed in different provinces, and the significant gap in resource endowment among the provinces was a major contributor to such differences. Traditional major agricultural provinces such as Shandong, Henan, Hunan, Hubei, and Sichuan possess superior conditions in terms of agricultural production, which means there are developed crop farming and livestock and poultry breeding industries in these places.

According to Figure 4, ACEs presented various degrees of change among the eastern, central, and western agricultural regions in China. Eastern China possesses a developed economy, which is mainly based on the secondary and tertiary industries, yet it mainly relies on transfer from other regions or import for agricultural products. ACEs grew in

Liaoning alone in eastern China, whereas the rest of the provinces and cities experienced a wave-like decline in emissions. Among these areas, a large decline in ACEs occurred in Beijing, Shanghai, and Zhejiang, decreasing by 72.54%, 48.38%, and 32.18%. A gentle decline occurred in Shandong, Fujian, Guangdong, Tianjin, and Jiangsu, with decline rates of 23.16%, 22.71%, 21.60%, 16.99%, and 5.71%, respectively. Central China is a leading agricultural production base with distinctive features in different areas. Heilongjiang and Jilin are important national grain production bases in the northeast, while Hainan concentrates on tropical agriculture development as per its geographical location. From 2000 to 2020, ACEs declined in Hebei, Hainan, Henan, and Shanxi, and such a descent was particularly obvious in Hebei and Hainan, with descent rates of 21.47% and 19.90%. Meanwhile, the descent in Henan and Shanxi appeared to be comparatively small, with descent rates of 9.78% and 5.55%. ACEs increased in the rest of the region, especially in Heilongjiang, where the rate of ACEs increased to 57.92%; the rates of ACEs in Jilin, Jiangxi, Hunan, Hubei, and Anhui were 23.60%, 18.54%, 13.00%, 12.86%, and 2.63%, respectively.

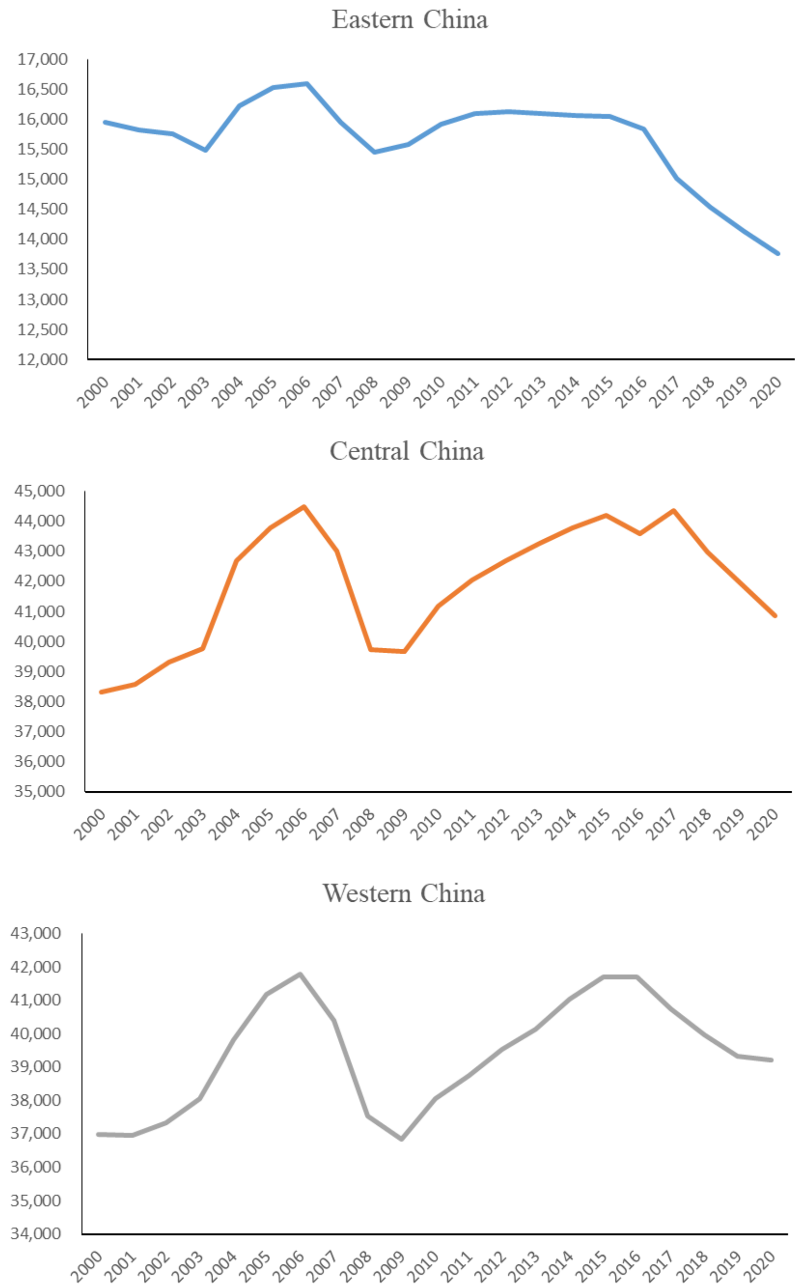


Figure 2. Regional ACEs from 2000 to 2020 (10^4 t).

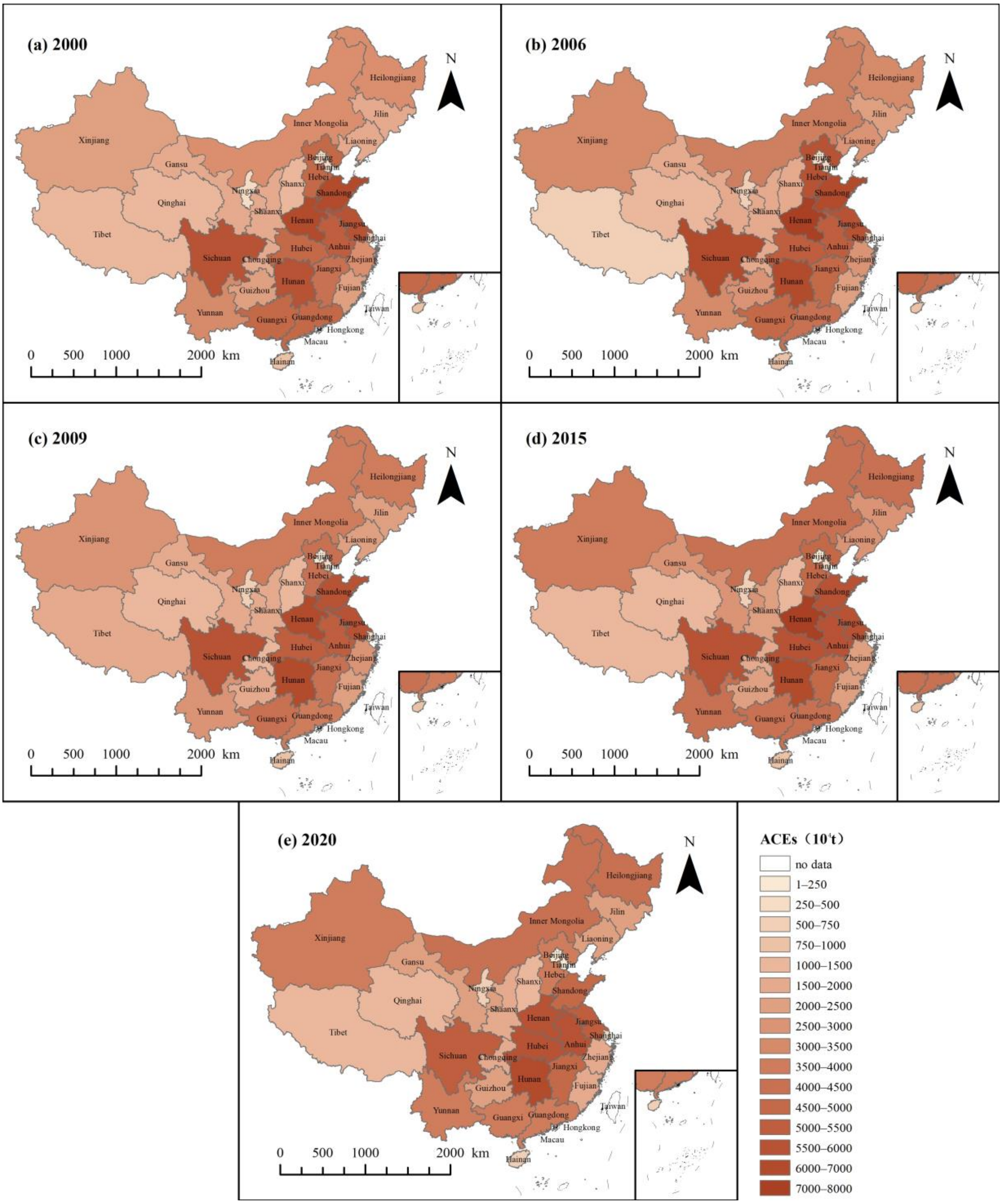
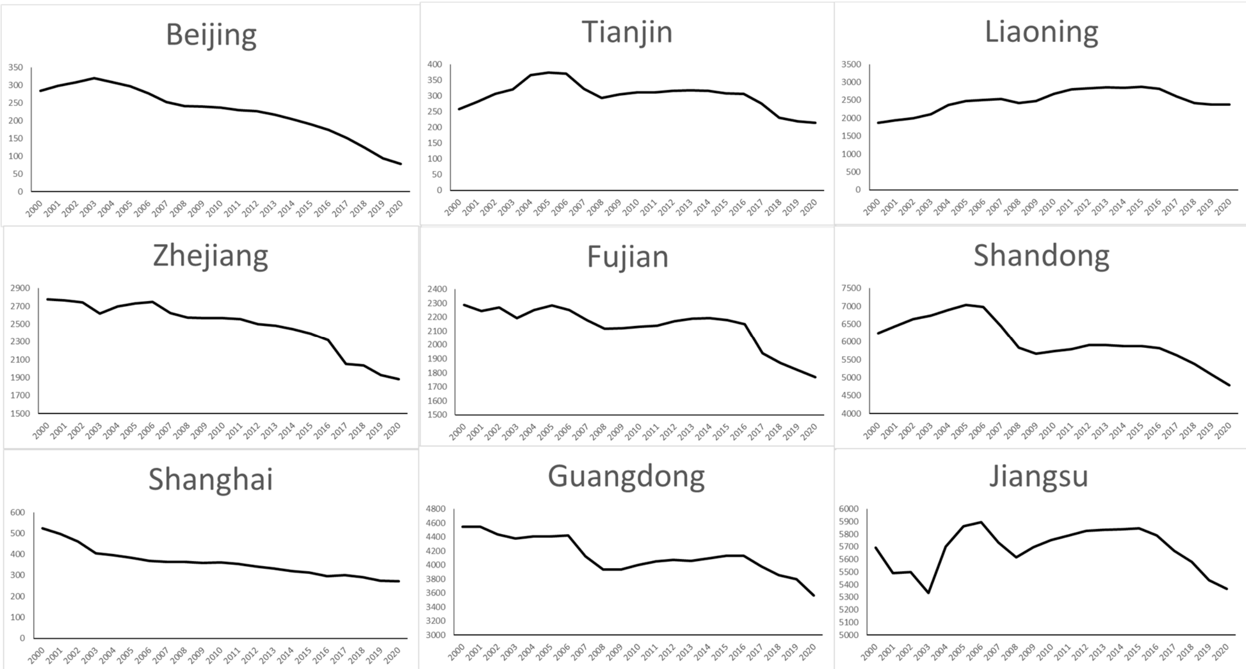
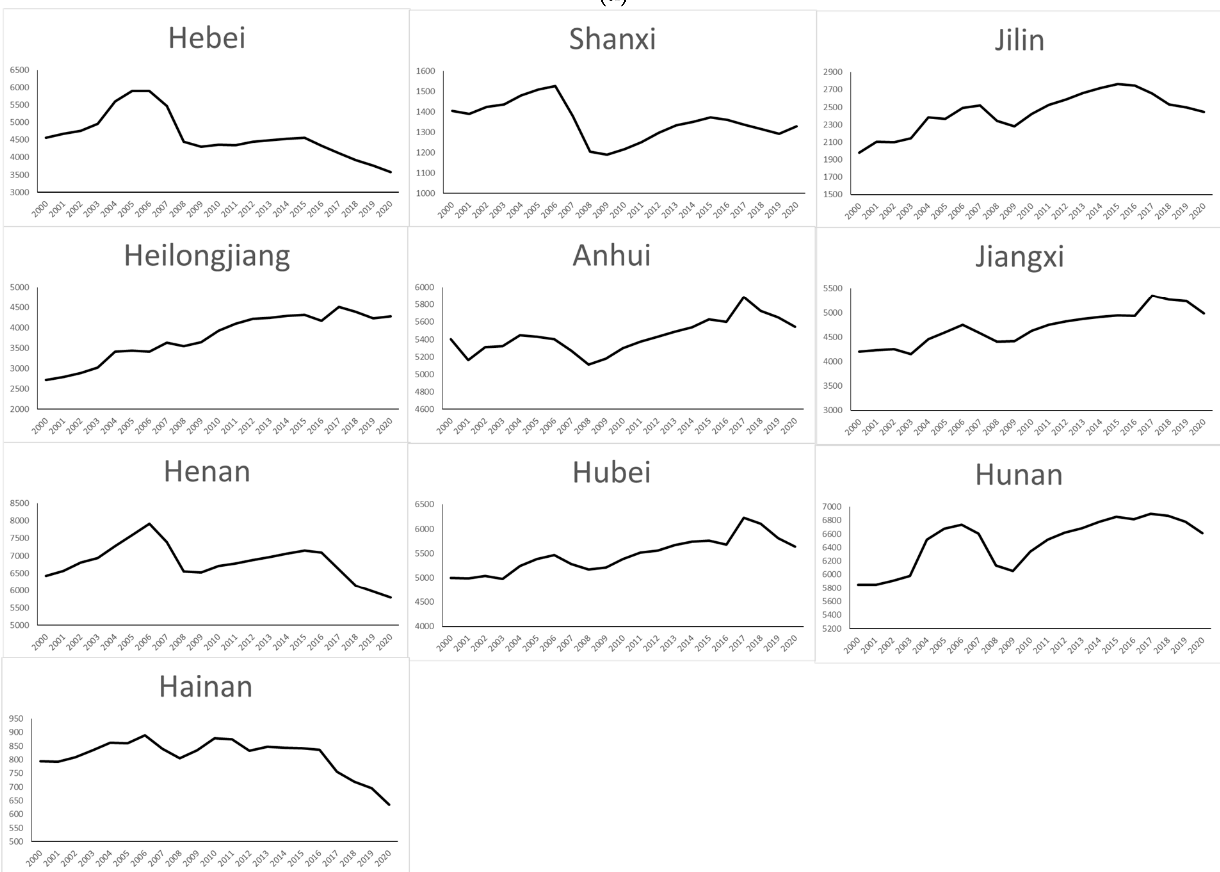


Figure 3. Spatial changes in ACEs in China from 2000 to 2020.

Under the background of a backward economy and a nationwide demand gap in agricultural products, agriculture has developed rapidly in western China, and ACEs have grown accordingly. ACEs decreased by 24.15%, 8.29%, 2.14%, and 2.09% in Guangxi, Sichuan, Chongqing, and Guizhou from 2000 to 2020. ACEs increased in the rest of the region, especially in Ningxia, Inner Mongolia, Xinjiang, and Gansu, with sharp increase rates of 82.84%, 74.25%, 59.62%, and 45.29% compared to the gentle increase rates of 26.88%, 19.96%, 16.65%, and 12.64% in Yunnan, Qinghai, Shanxi, and Tibet.

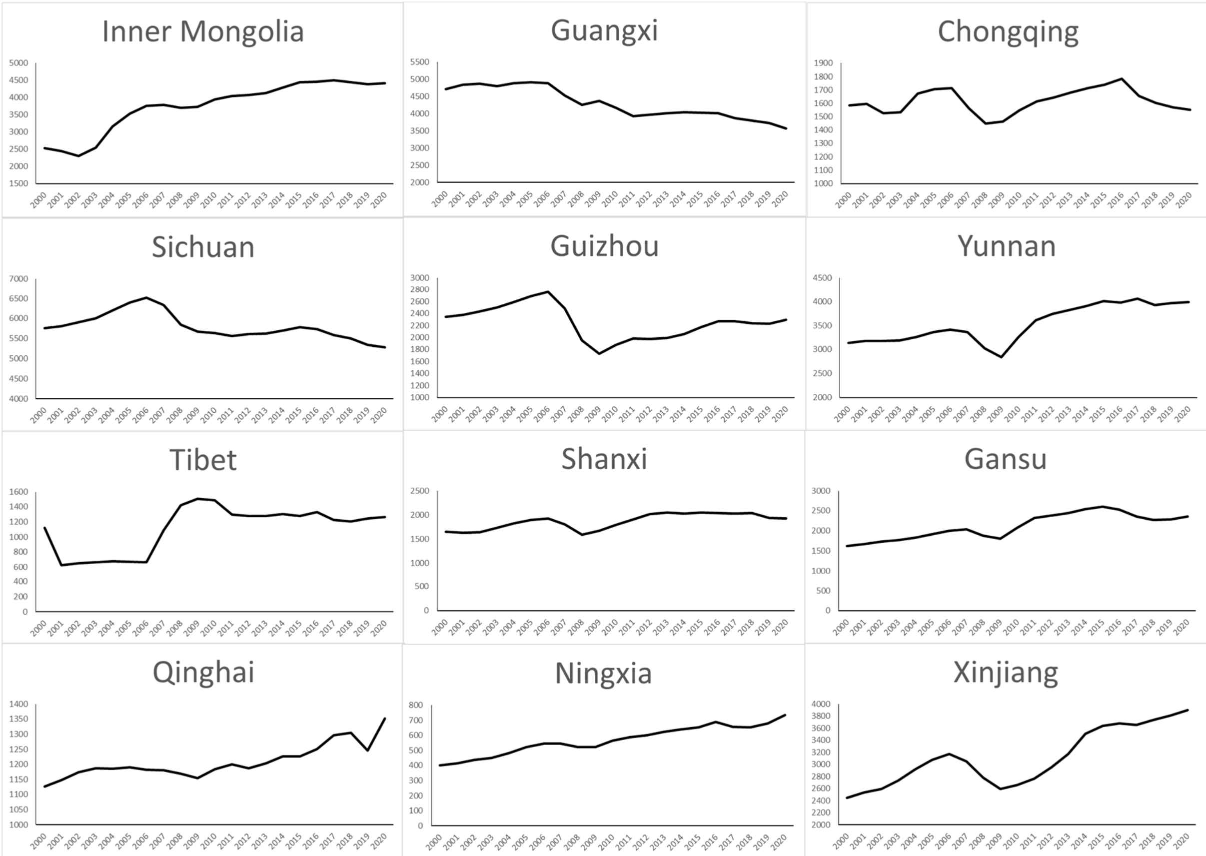


(**a**)



(**b**)

Figure 4. *Cont*.



(**c**)

Figure 4. ACEs in 31 provinces of China from 2000 to 2020. (**a**) ACEs in eastern China from 2000 to 2020 (10^4 t). (**b**) ACEs in central China from 2000 to 2020 (10^4 t). (**c**) ACEs in western China from 2000 to 2020 (10^4 t).

Overall, in accordance with Table 6, significant changes took place in the ACEs structure from 2000 to 2020. In the eastern provinces, except for Liaoning, ACEs as well as the tendency of emission proportions showed a wave-like decline. The opposite occurred in the central and western regions, where carbon emissions as well as the carbon emission proportions increased in most provinces. The results in Table 6 show that the boundary of the carbon emission proportion is 4%, above which brings the provinces into the top 12 of China's ACEs ranking table. It is worth noting that the carbon emission proportions in Guangdong, Hebei, and Guangxi accounted for over 4% of the total national emissions all year round before the figures dropped below 4% in 2020. The three provinces belong to the eastern, central, and western regions, respectively. Conversely, the carbon emission proportions in Heilongjiang, Inner Mongolia, Yunnan, and Xinjiang accounted for less than 4% before the figures exceeded 4% in 2020; Heilongjiang belongs to the central region, while the other three provinces belong to the western region.

From the perspective of the regional ACEs ranking, the top 12 provinces for carbon emissions in 2000 were Henan, Shandong, Hunan, Sichuan, Jiangsu, Anhui, Hubei, Guangxi, Hebei, Guangdong, Jiangxi, and Yunnan, while the top 12 provinces in 2020 changed to Hunan, Henan, Hubei, Anhui, Jiangsu, Sichuan, Jiangxi, Shandong, Inner Mongolia, Heilongjiang, Yunnan, and Xinjiang, in that order. The eastern provinces fell down the rankings for ACEs: for instance, Shandong and Guangdong fell from 2nd and 10th in 2000 to 8th and 15th in 2020, respectively, accompanied by a province number drop from 3 to 2 in the top 12. There were six provinces from the central region in the top 12 in 2000 and 2020, and the rankings were further promoted in 2020 compared to those in 2000. The western provinces rose in the rankings for ACEs: for instance, the rankings of Inner

Mongolia, Yunnan, and Xinjiang rose from 15th, 12th, and 16th in 2000 to 9th, 11th, and 12th in 2020, respectively, accompanied by a province number increase from 2 to 3 in the top 12; meanwhile, Guangxi fell from 8th in 2000 to 13th in 2020.

Therefore, in view of the time variation in the regional differences, ACEs have declined in the eastern region while increasing in the central and western regions.

Table 6. The proportions of ACEs accounted for by China's provinces across years (units: %).

	2000	2006	2009	2015	2020		2000	2006	2009	2015	2020
Beijing	0.31	0.27	0.26	0.19	0.08	Hubei	5.47	5.32	5.66	5.65	6.01
Tianjin	0.28	0.36	0.33	0.30	0.23	Hunan	6.41	6.55	6.58	6.72	7.04
Hebei	4.99	5.73	4.68	4.48	3.81	Guangdong	4.98	4.30	4.27	4.05	3.80
Shanxi	1.54	1.49	1.29	1.35	1.42	Guangxi	5.16	4.75	4.74	3.96	3.81
Inner Mongolia	2.77	3.66	4.06	4.37	4.70	Hainan	0.87	0.86	0.91	0.83	0.68
Liaoning	2.04	2.44	2.69	2.81	2.54	Chongqing	1.74	1.67	1.59	1.70	1.65
Jilin	2.17	2.42	2.48	2.71	2.61	Sichuan	6.32	6.34	6.17	5.67	5.63
Heilongjiang	2.97	3.32	3.97	4.23	4.57	Guizhou	2.57	2.68	1.88	2.13	2.45
Shanghai	0.58	0.36	0.39	0.31	0.29	Yunnan	3.44	3.31	3.09	3.93	4.25
Jiangsu	6.24	5.73	6.19	5.73	5.72	Tibet	1.23	0.64	1.64	1.25	1.35
Zhejiang	3.04	2.67	2.79	2.35	2.01	Shanxi	1.81	1.87	1.81	2.01	2.05
Anhui	5.92	5.25	5.63	5.52	5.91	Gansu	1.78	1.94	1.96	2.55	2.51
Fujian	2.51	2.19	2.31	2.14	1.89	Qinghai	1.24	1.15	1.25	1.20	1.44
Jiangxi	4.61	4.62	4.80	4.85	5.31	Ningxia	0.44	0.53	0.57	0.64	0.78
Shandong	6.84	6.79	6.15	5.77	5.11	Xinjiang	2.68	3.09	2.81	3.57	4.16
Henan	7.05	7.70	7.08	7.02	6.18						

3.3. Analysis of the Dynamic Evolution Characteristics of ACEs

There are significant differences in agricultural resources and industrial structure in the 31 provinces of China's mainland, and the obvious diversity in the carbon emission structure causes an impact on the changes in local carbon emissions. This triggers our thinking on the following:

What are the dynamic evolution characteristics of ACEs in different regions of China, and what is the major source of the increase or decrease in carbon emissions in these regions? This paper combines the four categories of ACEs sources into two groups: The first group constitutes crop farming, which includes rice cultivation, soil, and agricultural materials. The second group is livestock and poultry breeding. Hereby, based on the differences in the sources of ACEs in 2020 and 2000 (Table 7), the 31 provinces are divided into 4 types, as shown in Figure 5.

(1) Scale-up type of ACEs: This type corresponds to ACEs that grew in both crop farming and livestock and poultry breeding, and regions of this type included Inner Mongolia, Liaoning, Heilongjiang, Yunnan, Tibet, Gansu, Qinghai, Ningxia, and Xinjiang. For areas above the 45° line, carbon emissions from livestock and poultry breeding played a dominant role in the growth in carbon emissions; specifically, the carbon emission proportions from livestock and poultry breeding accounted for 92.51%, 85.74%, 65.50%, and 50.47% of the total increased carbon emissions in Qinghai, Tibet, Ningxia, and Inner Mongolia, respectively. Despite Inner Mongolia having the lowest increment rate, it had the maximum absolute increment value. Moreover, there was significant growth in crop farming carbon emissions, and agricultural material carbon emissions contributed the largest increment for such growth in Inner Mongolia. Below the 45° line, carbon emissions from crop farming played a dominant role in the growth in carbon emissions; specifically, the carbon emission proportions from crop farming accounted for 87.48%, 76.29%, 75.72%, 52.33%, and 51.81% of the total carbon emission increment in Heilongjiang, Xinjiang, Yunnan, Liaoning, and Gansu, respectively. Carbon emissions from agricultural materials were a critical contributor to the growth in crop farming emissions, with the specific increment rates accounting for 89.30%, 83.45%, 74.66%, and 61.55% of the total emission increment in Xinjian, Gansu, Liaoning, and Yunnan. Heilongjiang holds a unique position

because of its more balanced emission growth from agricultural materials, rice cultivation, and soil, each accounting for 41.09%, 34.25%, and 24.65% of the growth in the total crop farming carbon emissions.

Table 7. Regional differences in ACEs between 2020 and 2000 (10^4 t).

	Livestock Breeding	Crop Farming			
		Total	Rice Cultivation	Soil	Agricultural Materials
Beijing	−110.13	−95.5	−4.6	−27.8	−63.11
Tianjin	4.6	−48.28	5.1	−12.01	−41.37
Hebei	−925.16	−52.89	−24.99	−24.65	−3.25
Shanxi	−217.65	139.72	−0.35	12.9	127.17
Inner Mongolia	948.43	930.91	9.49	234.38	687.04
Liaoning	247.9	272.09	7.09	61.85	203.14
Jilin	−216.13	683.06	35.14	114.04	533.88
Heilongjiang	196.66	1374.52	470.83	338.87	564.82
Shanghai	−80.88	−172.67	−89.2	−14.79	−68.68
Jiangsu	−320.46	−4.99	5.81	56.12	−66.92
Zhejiang	−154.09	−739.73	−761.4	4.19	17.48
Anhui	−799.85	941.14	570.81	75.89	294.44
Fujian	−91.15	−429.11	−446.02	−16.78	33.69
Jiangxi	−107.51	887.67	807.67	15.8	64.2
Shandong	−1264.95	−179.83	−33.76	29.44	−175.5
Henan	−1838.09	1208.96	70.29	220.96	917.71
Hubei	−299.5	942.1	774.03	83.45	84.61
Hunan	−179.64	939.6	535.61	107.68	296.31
Guangdong	−540.2	−441.85	−684.14	29.26	213.03
Guangxi	−1121.39	−15.07	−537.06	97.68	424.31
Hainan	−155.33	−3.12	−144.8	10.31	131.37
Chongqing	−123.56	88.73	−75.72	45.73	118.72
Sichuan	−530	52.1	−162.7	127.75	87.05
Guizhou	−267.7	218.86	−46.81	175.48	90.19
Yunnan	204.91	639.05	−45.73	263.32	421.46
Tibet	121.16	20.14	−0.02	3.6	16.56
Shanxi	−95.54	370.8	−12.42	29.97	353.25
Gansu	353.94	380.6	−0.65	63.09	318.16
Qinghai	207.84	16.82	0	9.48	7.34
Ningxia	218.46	115.06	−2.92	25.42	92.57
Xinjiang	345.44	1111.48	−8.01	119.77	999.72

(2) Scale-up for livestock and poultry breeding—scale-down for crop farming: This type corresponds to ACEs that grew in livestock and poultry breeding but dropped in crop farming. The main area of this type was Tianjin, which is located below the 45° line, with greater decreased emissions from crop farming compared to the increased emissions from livestock and poultry breeding. Moreover, the decline in emissions from crop farming was mainly due to the reduction in agricultural materials, which accounted for 77.50% of the total carbon emission drop in crop farming in Tianjin.

(3) Scale-down type of ACEs: This type corresponds to ACEs that declined in both crop farming and livestock and poultry breeding, and regions of this type included Beijing, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi, and Hainan. Above the 45° line, carbon emissions from crop farming played a dominant role in the decrease in carbon emissions in regions such as Shanghai, Zhejiang, and Fujian. Furthermore, the reduction in carbon emissions from rice cultivation dominated the emission reduction in all three regions; in particular, the decline in rice cultivation carbon emissions accounted for 83.17% and 80.52% of the total ACEs in Zhejiang and Fujian. Below the 45° line, carbon emissions from livestock and poultry breeding played a dominant role in the decrease in carbon emissions in Beijing, Hebei, Jiangsu, Shandong, Guangxi, and Hainan; specifically, the rapid drop in livestock and poultry breeding carbon emissions accounted

for 94.59%, 85.80%, 82.72%, and 67.62% of the decline in total carbon emissions in Hebei, Shandong, Jiangsu, and Guangxi, while it accounted for only 53.56% and 51.75% of the total descent in Beijing and Hainan. Despite the location of Guangdong below the 45° line, it is worth noting that the carbon emission proportion from livestock and poultry breeding only accounted for 44.12% of the total carbon emission reduction, because the whole decline in crop farming carbon emissions was derived from the decrease in rice cultivation's carbon emissions, which accounted for 55.88% of the total carbon emission reduction; moreover, there was a slight emission increase from soil and agricultural materials. Therefore, the decline in crop farming carbon emissions played a dominant role, with the reduction in rice cultivation carbon emissions being a major contributor in Guangdong.

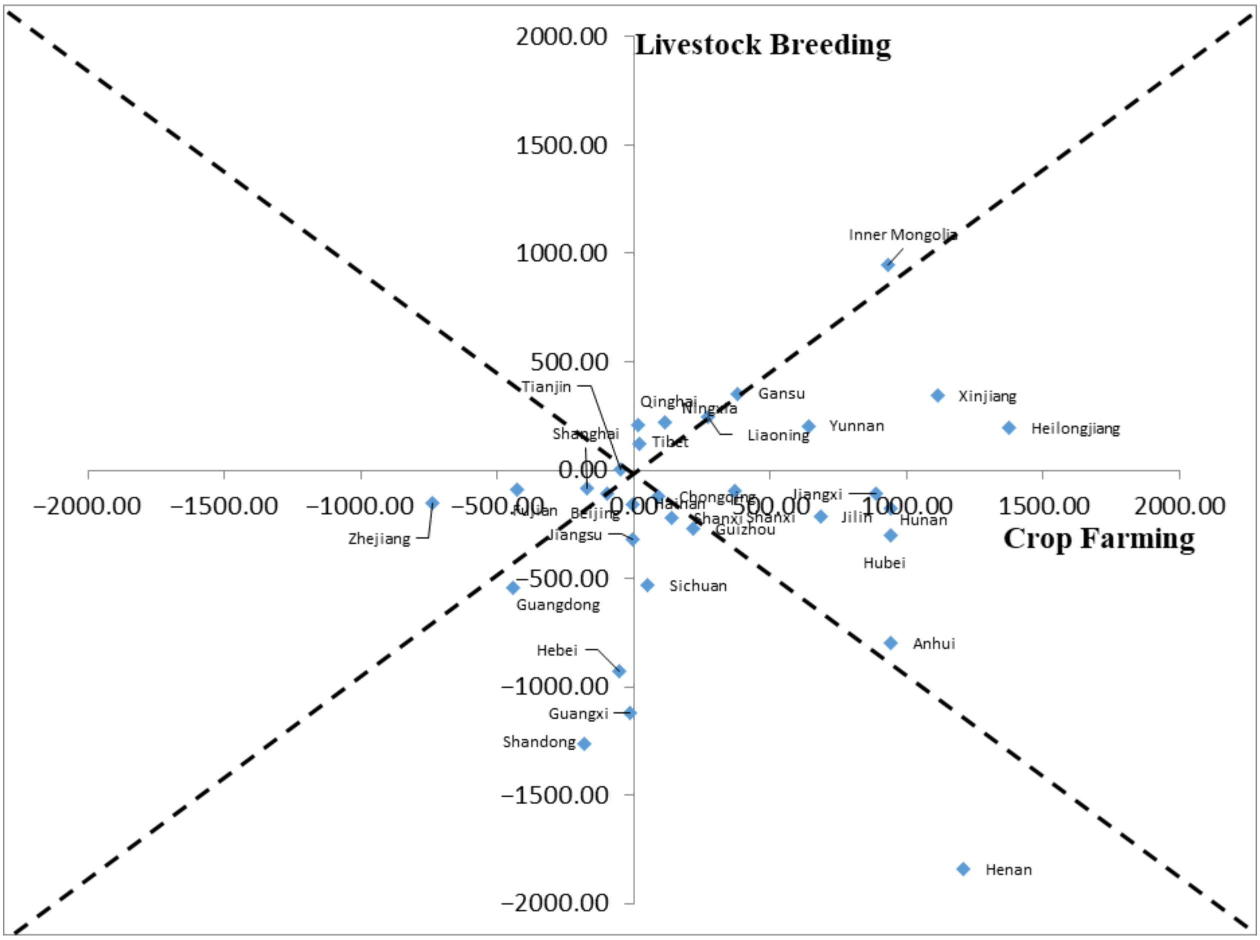


Figure 5. Area type division (10^4 t).

(4) Scale-up for crop farming–scale-down for livestock and poultry breeding: This type corresponds to ACEs that grew in crop farming but declined in livestock and poultry breeding, and regions of this type included Shanxi, Jilin, Anhui, Jiangxi, Henan, Hubei, Hunan, Chongqing, Sichuan, Guizhou, and Shanxi. Above the 45° line, the increment in the growth in carbon emissions from crop farming is greater than the decrement in the reduction in emissions from livestock and poultry breeding, meaning that the total ACEs tended to grow in these regions, including Hunan, Jilin, Anhui, Jiangxi, Hubei, and Shanxi. Specifically, the growth in carbon emissions from crop farming was mainly derived from the increase in agricultural material emissions, and such an increase accounted for 78.16% and 92.18% of the growth in total crop farming emissions in Jilin and Shanxi. Rice cultivation carbon emissions experienced the most growth in emissions from crop farming, accounting for 90.99%, 82.16%, 60.65%, and 57.00% of the growth in total crop farming carbon emissions in Jiangxi, Hubei, Anhui, and Hunan. Below the 45° line, the increment

in the growth in carbon emissions from crop farming is less than the decrement in the reduction in emissions from livestock and poultry breeding; thus, the total ACEs tended to decrease in these regions, including Shanxi, Henan, Chongqing, Sichuan, and Guizhou. Shanxi, Chongqing, and Guizhou are close to the 45° line, and the ACEs decreased slightly, while the reduction was greater in Henan and Sichuan since they are far away from the 45° line. Especially in Henan, a large decrease in carbon emissions from livestock and poultry breeding occurred, while large growth occurred in crop farming. Despite the slight decrease in total carbon emissions, a significant change occurred in the ACEs structure. Specifically, livestock and poultry breeding carbon emissions dropped from 55.50% to 29.83% from 2000 to 2020; oppositely, crop farming emissions soared to 70.17% from 44.5% during the same period.

In light of Table 8, ACEs in the eastern region evolved into the scale-down type for seven provinces and cities in total, and the reduction in rice cultivation emissions played the primary role in Shanghai, Zhejiang, Fujian, and Guangdong; meanwhile, in Beijing, Jiangsu, and Shandong, the primary role was played by the decrease in livestock and poultry breeding carbon emissions. The central region contains three types of ACEs: The first type, scale-up for crop farming–scale-down for livestock and poultry breeding, applied to all seven provinces and cities. The reduction in rice cultivation carbon emissions was the main feature of carbon emissions in Jiangxi, Hubei, Anhui, and Hunan, while the reduction in livestock and poultry breeding carbon emissions led the way in Shanxi and Henan, and the decrease in agricultural material carbon emissions played a similar role in Jilin. The second type is the scale-down type of carbon emissions, where the reduction in livestock and poultry breeding carbon emissions led the way in Hebei and Hainan. The third type is the scale-up type of carbon emissions, where the decrease in agricultural material emissions played the dominant role in Heilongjiang. ACEs in the western region evolved into two types for seven provinces and cities in total: The first type is the scale-up type of carbon emissions, where the reduction in livestock and poultry breeding carbon emissions dominated the contribution in Qinghai, Tibet, Ningxia, and Inner Mongolia, while the reduction in agricultural material carbon emissions led the way in Xinjiang, Yunnan, and Gansu. The second type is scale-up for crop farming–scale-down for livestock and poultry breeding, where the scale of emissions decreased in Chongqing, Sichuan, and Guizhou mainly due to the decrease in livestock and poultry breeding carbon emissions, yet emissions increased in Shanxi because of the growth in agricultural material carbon emissions.

Table 8. Evolution of ACEs in China's provinces from 2000 to 2020.

	Livestock and Poultry Industry Dominates	**Crop Farming Dominates**	
		Agricultural Inputs Dominate	**Rice Cultivation Dominates**
Scale-up type	Qinghai, Tibet, Ningxia, Inner Mongolia	Heilongjiang, Xinjiang, Yunnan, Liaoning, Gansu	
Scale-up for livestock and poultry breeding—scale-down for crop farming	Tianjin		
Scale-down type	Beijing, Hebei, Jiangsu, Shandong, Guangxi, Hainan		Shanghai, Zhejiang, Fujian, Guangdong
Scale-up for crop farming–scale-down for livestock and poultry breeding	Shanxi, Henan, Chongqing, Sichuan, Guizhou	Jilin, Shanxi	Jiangxi, Hubei, Anhui, Hunan

4. Discussion

Agriculture is a source of greenhouse gas emissions, and the agriculture industry is vulnerable to climate change [62]. China is a large agricultural country and generates a large amount of greenhouse gases from agricultural production processes. Previous studies on China's ACEs are insufficient, especially on China's updated ACEs conditions and ACEs evolution characteristics. Based on this, this paper uses the ACEs accounting method to calculate China's ACEs from 2000 to 2020 and analyzes their spatio-temporal evolution characteristics.

From a temporal perspective, China's total ACEs during the study period were shown to fall after rising and then repeat this trend in the four phases studied, with a tendency of an inverted "W". China's total ACEs increased from 912.5 million tons in 2000 to 938.1 million tons in 2020, an increase of 2.81%. Two studies on China's ACEs from 2000 to 2016 and from 1997 to 2016 showed that the total amount of China's ACEs increased during the study period [43,63]. From the perspective of the ACEs structure, China's ACEs are mainly from livestock and poultry breeding and agricultural material inputs [64]. Meanwhile, different results obtained from other studies show that China's ACEs are mainly from the livestock and poultry, rice cultivation, and agricultural energy sectors [44]. In the past two decades, China's carbon emissions from livestock and poultry breeding have declined, and the carbon emissions from rice cultivation and soil have continued to increase, while the carbon emissions from agricultural material inputs increased before 2015 but have been declining since 2015 [44,65]. The above conclusion is basically consistent with the research results of this paper; however, this paper uses the latest data to analyze the newest changes in China's ACEs and finds that China's ACEs declined from 2015 to 2020. However, in general, China's total ACEs have increased in the past two decades, mainly due to the increase in agricultural material inputs, such as the usage of chemical fertilizers in agricultural production [12]. These factors have directly or indirectly promoted the growth of China's total ACEs. China's ACEs showed an inverted "W" trend during this research period. This paper analyzes the reasons for the decline in China's ACEs since 2015 from three dimensions. First, in recent years, the Chinese government has optimized relevant laws and regulations at the institutional level and put forward the strategy of developing "resource-saving and environmentally friendly agriculture" and reducing the input of agricultural materials, especially the usage of fertilizers and pesticides [51,66]. Second, the education level of farmers has improved. Farmers have changed their behaviors in the process of agricultural production and paid more attention to the environmental impact caused by agricultural production [67,68]. Third, ACEs have been reduced as a result of all the measures of the development of green agriculture and low-carbon production technologies, the upgrading of agricultural machinery, intensive agricultural production, and the development of agricultural resource recycling [51,69].

From a spatial perspective, China's ACEs mainly come from the central and western regions, while the ACEs in the eastern region account for a small proportion. Other studies show that China's ACE intensity presents a gradient increase in the spatial change pattern from east to west [38,39], which is consistent with the research results of this paper, to a certain extent. The total ACEs and carbon emissions of each carbon source in China's main grain production areas are significantly higher than those in grain sales areas and balanced production–marketing areas [44]. The calculation of China's ACEs in this paper also shows that the top-ranking regions in carbon emissions are basically the main grain-producing regions. Different from previous studies, this paper finds that ACEs have increased significantly in Yunnan and Xinjiang, which have been balanced areas of grain production and marketing in recent years, even exceeding some major grain-producing provinces, such as Jilin, Liaoning, and Hebei. Two factors cause such regional differences in ACEs. The first is the natural factor. China's vast territory and diverse climate lead to large differences in agricultural production among the regions, which also means that there are great differences in ACEs. Though modern transportation and logistics break the regional barrier for regional agricultural cooperation, this is only applicable to general agriculture [68,70]. However, agricultural production such as crop cultivation and livestock and poultry breeding is vulnerable to natural conditions, which severely constrain regional agricultural cooperation [71]. The second is the economic factor. Overall, the level of China's regional economic development shows a stepped feature of "high in the east, followed by the central region and lowest in the west". Compared with the less developed regions, the developed regions have higher environmental awareness and acceptance of agricultural green, low-carbon technologies, as well as a lower ACEs intensity [72].

Based on the evolution characteristics of regional ACEs, this paper finds that carbon emissions from both planting and livestock and poultry breeding decreased in most of the eastern provinces, while they grew in most of the western regions. Carbon emissions from planting increased, while emissions from livestock and poultry breeding decreased in most of the central provinces. From 2010 to 2019, the methane emissions in Henan decreased by 2.31% due to the reduction in the free-range livestock and poultry breeding scale. The increase in carbon emissions from livestock and poultry breeding in Inner Mongolia was the main reason for its ACE growth. The large rice-planting area contributes high methane emissions in Hunan [73]. Research on the ACEs of Jilin Province from 1998 to 2018 shows that the carbon emissions of livestock and poultry breeding decreased, while those of planting showed the opposite trend [74]. Although the above research does not comprehensively analyze the dynamic evolution of China's ACEs in different provinces, some of the obtained results verify the evolution characteristics of China's ACEs analyzed in this paper. There are three reasons for the dynamic evolution of China's ACEs. First, developed areas enjoy higher rural financial efficiency and advanced agricultural technology, which have an effect of the inhibition of ACEs [75]. Meanwhile, the conditions in undeveloped areas are exactly the opposite. Second, in recent years, the country has advocated intensive agricultural development and the removal of free-range livestock and poultry households from rural places such as villages. The decrease in free-range livestock and poultry farming has been accompanied by a significant drop in carbon emissions from livestock and poultry breeding in Henan, Shandong, Hebei, and other major livestock and poultry breeding provinces [73]. Third, agriculture holds a different status in different places. For example, Beijing, Tianjin, Shanghai, and other regions, which take the secondary and tertiary industries as their top goals of development, are the sales places of agricultural products [44]. They pay more attention to the quality of agricultural development rather than the scale. In Inner Mongolia, Xinjiang, Gansu, Qinghai, and other provinces with better natural conditions suitable for livestock and poultry breeding, the carbon emissions from livestock and poultry breeding have increased. The status of agriculture among different regions determines the evolution of regional ACEs, to a certain extent.

This paper studies the spatio-temporal evolution characteristics of ACEs in China and brings value to the current research of this topic, yet there are still some limitations. Firstly, this paper does not analyze the characteristics of ACEs in Hong Kong, Macao, and Taiwan due to the difficulty of data collection. Secondly, it studies the temporal and spatial characteristics of China's ACEs without a comprehensive analysis of the factors affecting the evolution of China's ACEs. Therefore, it is highly encouraged to carry out metrical research on the influencing factors of China's ACEs and the identification of the key factors affecting China's ACEs in future work.

5. Conclusions and Policy Implications

5.1. Conclusions

The main conclusions of this paper include four aspects. First, China's total ACEs showed an inverted "W" trend from 2000 to 2020, and the total carbon emissions have declined significantly since 2015. Second, China's ACEs mainly came from livestock and poultry breeding and agricultural material inputs. Although the carbon emissions from the cultivation of rice and other crops were relatively low, they increased from 2000 to 2020. Third, the proportion of ACEs in the central and western regions was relatively high, while that in the eastern region was relatively low. Fourth, in the eastern region, the main evolution characteristics of ACEs were of the scale-down type, while scale-up for crop farming–scale-down for livestock and poultry breeding applied to the central region, and the scale-down type of carbon emissions suited the western region well.

5.2. Policy Implications

According to the findings of this study, the following policy implications are suggested to reduce the ACEs of China.

First, we should continue to implement and further strengthen the existing agricultural low-carbon policies. In recent years, China's ACEs have continually declined under the influence of low-carbon agricultural policies. It is suggested to continue to accelerate the agricultural industrial agglomeration and promote the recycling of agricultural resources on the basis of the original low-carbon agricultural policy; to actively take measures for the guidance of various agricultural production activities such as crop farming and livestock and poultry breeding; and to strengthen the recycling and utilization of crop and livestock and poultry breeding waste. Specifically, crop straw can be used to produce biomass fuel, and livestock and poultry manure can be used to produce organic fertilizer for the improvement of agricultural resource recycling and utilization and optimization of the low-carbon agricultural production system.

Second, we should continue to escalate the development of crop farming technology and reduce crop carbon emissions. In particular, it is suggested to enhance farmers' awareness of low-carbon environmental protection with the support of investment, policy, and platform construction from the government for the development of a scientific low-carbon agricultural production mode. It is also suggested to upgrade the low-carbon agricultural planting technology, to improve the ability of crop carbon sequestration via scientific research, to develop low-carbon planting technology, and to enhance the cooperation between researchers and farmers in order to popularize the low-carbon agricultural planting technology.

Third, ACEs reduction policies should be developed according to local conditions, especially for the regions with high ACEs. It is suggested to transition to low-carbon agriculture, to strengthen the large-scale operation of livestock and poultry breeding, to reduce the input of energy, pesticides, fertilizers, and other agricultural materials, and to improve the ability of straw and livestock manure to return to the field as well as the efficiency of resource utilization. For regions with low ACEs, the agricultural production structure should be further optimized. In addition, low-carbon and high-value-added agriculture such as leisure agriculture, ecological agriculture, and organic agriculture should be developed.

Fourth, we should formulate ACEs reduction policies according to the types of ACEs evolution in different regions. There are differences in the dynamic evolution of regional ACEs. The government should pay attention to the areas where ACEs have increased rapidly in recent years, especially in the central and western provinces. The government should also strengthen the financial investment and technical support in the provinces in the central and western regions and improve the awareness of low-carbon environmental protection and the level of agricultural production while restraining the rapid growth of ACEs in the central and western provinces.

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References

1. Bai, Y.; Deng, X.; Gibson, J.; Zhao, Z.; Xu, H. How does urbanization affect residential CO_2 emissions? An analysis on urban agglomerations of China. *J. Clean. Prod.* **2019**, *209*, 876–885. [CrossRef]
2. Chen, J.; Li, C.; Ristovski, Z.; Milic, A.; Gu, Y.; Islam, M.S.; Wang, S.; Hao, J.; Zhang, H.; He, C. A review of biomass burning: Emissions and impacts on air quality, health and climate in China. *Sci. Total Environ.* **2016**, *579*, 1000–1034. [CrossRef] [PubMed]
3. Elahi, E.; Khalid, Z.; Tauni, M.Z.; Zhang, H.; Xing, L. Extreme weather events risk to crop-production and the adaptation of innovative management strategies to mitigate the risk: A retrospective survey of rural punjab, pakistan. *Technovation* **2021**, *4*, 102255. [CrossRef]
4. Elahi, E.; Khalid, Z. Estimating smart energy inputs packages using hybrid optimization technique to mitigate environmental emissions of commercial fish farms. *Appl. Energy* **2022**, *326*, 119602. [CrossRef]
5. Wu, H.Y.; He, Y.Q.; Chen, R. Assessment of agricultural carbon emission performance and stochastic convergence in China using SBM-Undesirable model and panel unit root test. *Chin. J. Eco-Agric.* **2017**, *25*, 1381–1391.
6. Asadnabizadeh, M. Development of UN framework convention on climate change negotiations under COP25: Article 6 of the Paris Agreement perspective. *Open Political Sci.* **2019**, *2*, 113–119. [CrossRef]
7. Guo, X.; Zhang, L.M.; Hu, R.G.; Song, M.W. Influencing factor decomposition of planting carbon emission in central China. *Resour. Environ. Yangtze Basin* **2016**, *25*, 695–701.
8. Xu, B.; Chen, J.B. How to achieve a low-carbon transition in the heavy industry? A nonlinear perspective. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110708. [CrossRef]
9. Xu, B. How to efficiently reduce the carbon intensity of the heavy industry in China? Using quantile regression approach. *Int. J. Environ. Res. Public Health* **2022**, *19*, 12865. [CrossRef]
10. Laborde, D.; Mamun, A.; Martin, W.; Piñeiro, V.; Vos, R. Agricultural subsidies and global greenhouse gas emissions. *Nat. Commun.* **2021**, *12*, 2601. [CrossRef]
11. Guan, D.; Hubacek, K.; Weber, C.L.; Peters, G.P.; Reiner, D.M. The drivers of Chinese CO_2 emissions from 1980 to 2030. *Glob. Environ. Chang.* **2008**, *18*, 626–634. [CrossRef]
12. Guo, L.; Zhao, S.; Song, Y.; Tang, M.; Li, H. Green finance, chemical fertilizer use and carbon emissions from agricultural production. *Agriculture* **2022**, *12*, 313. [CrossRef]
13. Bai, Y.; Deng, X.; Jiang, S.; Zhao, Z.; Miao, Y. Relationship between climate change and low-carbon agricultural production: A case study in Hebei Province. *China. Ecol. Indic.* **2018**, *105*, 438–447. [CrossRef]
14. Veelen, B.V. Cash cows? Assembling low-carbon agriculture through green finance. *Geoforum* **2021**, *118*, 130–139. [CrossRef]
15. Lal, R. Carbon management in agricultural soils. *Mitig. Adapt. Strat. Glob. Chang* **2006**, *12*, 303–322. [CrossRef]
16. Gao, M.; Song, H. Dynamic changes and spatial agglomeration analysis of the Chinese agricultural carbon emissions per-formance. *Econ. Geogr.* **2015**, *35*, 142–148.
17. Liu, J.; Diamond, J. China's environment in a globalizing world. *Nature* **2005**, *435*, 1179–1186. [CrossRef]
18. Xiong, C.; Chen, S.; Yang, D. Selecting counties to participate in agricultural carbon compensation in China. *Pol. J. Environ. Stud.* **2019**, *28*, 1443–1449. [CrossRef]
19. Nurse, J.; Basher, D.; Bone, A.; Bird, W. An ecological approach to promoting population mental health and well-being—A response to the challenge of climate change. *Perspect. Public Health* **2010**, *130*, 27–33. [CrossRef]
20. Goldstein, B.; Hauschild, M.Z.; Fernandez, J.; Birkved, M. Testing the environmental performance of urban agriculture as a food supply in northern climates. *J. Clean. Prod.* **2016**, *135*, 984–994. [CrossRef]
21. Johnson, M.F.; Franzluebbers, A.J.; Weyers, S.L. Agricultural opportunities to mitigate greenhouse gas emissions. *Environ. Pollut.* **2007**, *150*, 107–124. [CrossRef]
22. Holland, S.P.; Hughes, J.E.; Knittel, C.R.; Parker, N. Unintended consequences of transportation carbon policies: Land-use, emissions, and innovation. *Energy J.* **2015**, *36*, 35–74.
23. Hiraishi, T.; Krug, T.; Tanabe, K.; Srivastava, N.; Baasansuren, J.; Fukuda, M.; Troxler, T.G. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*; IPCC: Georgia Batumi, Switzerland, 2014.
24. West, T.O.; Marland, G. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agric. Ecosyst. Environ.* **2002**, *91*, 217–232.
25. Stocker, B.D.; Yu, Z.; Massa, C.; Joos, F. Holocene peatland and ice-core data constraints on the timing and magnitude of CO2 emissions from past land use. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 1492–1497. [PubMed]
26. Venterea, R.T.; Halvorson, A.D.; Kitchen, N.; Liebig, M.; Cavigelli, M.A.; Del Grosso, S.J.; Motavalli, P.P.; Nelson, K.A.; Spokas, K.A.; Singh, B.; et al. Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. *Front. Ecol. Environ.* **2012**, *10*, 562–570. [CrossRef]
27. Li, B.; Zhang, J.; Li, H. Research on spatial-temporal characteristics and affecting factors decomposition of agricultural carbon emission in China. *China Popul. Resour. Environ.* **2011**, *21*, 80–86.

28. You, H.; Wu, C. Analysis of carbon emission efficiency and optimization of low carbon for agricultural land intensive use. *Trans. Chin. Soc. Agric. Eng.* **2014**, *30*, 224–234.
29. Li, J. Research on Characteristics and Driving Factors of Agricultural Land Carbon Emission in Provinces of Minorities in China. *China Popul. Resour. Environ.* **2012**, *22*, 42–47.
30. Yang, T.; Li, F.; Du, M.; Wang, Y.; Sun, Z. Measuring pollutant emissions of cattle breeding and its spatial-temporal variation in China. *J. Environ. Manag.* **2021**, *299*, 113615. [CrossRef]
31. Wei, S.; Bai, Z.; Chadwick, D.; Hou, Y.; Qin, W.; Zhao, Z.; Jiang, R.; Ma, L. Greenhouse gas and ammonia emissions and mitigation options from livestock production in peri-urban agriculture: Beijing–A case study. *J. Clean. Prod.* **2018**, *178*, 515–525. [CrossRef]
32. Liu, Y.; Liu, J.; Wu, W. Spatiotemporal dynamics of greenhouse gases emissions from livestock and poultry in Beijing area during 1978–2009. *Chin. J. Eco-Agric.* **2013**, *21*, 891–897. [CrossRef]
33. Chen, X.; Di, Q.; Hou, Z.; Yu, Z. Measurement of carbon emissions from marine fisheries and system dynamics simulation analysis: China's northern marine economic zone case. *Mar. Policy* **2022**, *145*, 105279. [CrossRef]
34. Liu, G.; Xu, Y.; Ge, W.; Yang, X.; Su, X.; Shen, B.; Ran, Q. How can marine fishery enable low carbon development in China? Based on system dynamics simulation analysis. *Ocean Coast. Manag.* **2021**, *231*, 106382. [CrossRef]
35. Shao, G.; Kong, H.; Yu, J.; Li, C. Decomposition of driving factors of carbon emissions from China's marine fisheries based on LMDI method. *J. Agrotech. Econ.* **2015**, *6*, 119–128.
36. Min, J.; Hu, H. Calculation of greenhouse gases emission from agricultural production in China. *China Popul. Resour. Environ.* **2012**, *22*, 21–27.
37. Tian, Y.; Wu, H. Research on Fairness of Agricultural Carbon Emissions in China's Major Grain Producing Areas from the Perspective of Industrial Structure. *J. Agric. Econ.* **2020**, *1*, 45–55.
38. Pang, J.; Li, H.; Lu, C.; Lu, C.; Chen, X. Regional differences and dynamic evolution of carbon emission intensity of agriculture production in China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 7541. [CrossRef]
39. Liu, M.; Yang, L. Spatial pattern of China's agricultural carbon emission performance. *Ecol. Indic.* **2021**, *133*, 108345. [CrossRef]
40. Zang, D.; Hu, Z.; Yang, Y.; He, S. Research on the relationship between agricultural carbon emission intensity, agricultural economic development and agricultural trade in China. *Sustainability* **2022**, *14*, 11694. [CrossRef]
41. Zhu, Y.; Huo, C. The impact of agricultural production efficiency on agricultural carbon emissions in China. *Energies* **2022**, *15*, 4464. [CrossRef]
42. Han, H.; Zhong, Z.; Guo, Y.; Xi, F.; Liu, S. Coupling and decoupling effects of agricultural carbon emissions in China and their driving factors. *Environ. Sci. Pollut. Res.* **2018**, *25*, 25280–25293. [CrossRef]
43. Huang, X.; Xu, X.; Wang, Q.; Zhang, L.; Gao, X.; Chen, L. Assessment of agricultural carbon emissions and their spatiotemporal changes in China, 1997–2016. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3105. [CrossRef]
44. Wen, S.; Hu, Y.; Liu, H. Measurement and Spatial–Temporal Characteristics of Agricultural Carbon Emission in China: An Internal Structural Perspective. *Agriculture* **2022**, *12*, 1749. [CrossRef]
45. Wang, G.; Liao, M.; Jiang, J. Research on Agricultural Carbon Emissions and Regional Carbon Emissions Reduction Strategies in China. *Sustainability* **2022**, *12*, 2627. [CrossRef]
46. Yang, S.; Li, Y.; Yan, S. An empirical analysis of the decoupling relationship between agricultural carbon emission and economic growth in Jilin province. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *392*, 062101.
47. Sun, Q. Ecological agriculture development and spatial and temporal characteristics of carbon emissions of land use. *Appl. Ecol. Environ. Res.* **2019**, *17*, 11045–11053. [CrossRef]
48. Liu, X.; Yu, Y.; Luan, S. Empirical study on the decomposition of carbon emission factors in agricultural energy consumption. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *252*, 042045. [CrossRef]
49. Chen, Y.; Li, M.; Su, K.; Li, X. Spatial-temporal characteristics of the driving factors of agricultural carbon emissions: Empirical evidence from Fujian, China. *Energies* **2019**, *12*, 3102. [CrossRef]
50. Zhang, L.; Pang, J.; Chen, X.; Lu, Z. Carbon emissions, energy consumption and economic growth: Evidence from the ag-ricultural sector of China's main grain-producing areas. *Sci. Total Environ.* **2019**, *665*, 1017–1025. [CrossRef]
51. Chen, X.; Shuai, C.; Wu, Y.; Zhang, Y. Analysis on the carbon emission peaks of China's industrial, building, transport, and agricultural sectors. *Sci. Total Environ.* **2020**, *709*, 135768. [CrossRef]
52. Akiyama, H.; Yan, X.; Yagi, K. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: Meta-analysis. *Glob. Chang. Biol.* **2010**, *16*, 1837–1846. [CrossRef]
53. Balsalobre-Lorente, D.; Driha, O.M.; Bekun, F.V.; Osundina, O. Do agricultural activities induce carbon emissions? The BRICS experience. *Environ. Sci. Pollut. Res.* **2019**, *26*, 25218–25234. [CrossRef]
54. Intergovernmental Panel on Climate Change. Special Report on Climate Change and Land. In Proceedings of the Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 2–6 August 2019; IPCC: Georgia Batumi, Switzerland, 2019.
55. Frank, S.; Havlik, P.; Stehfest, E.; Van Meijl, H.; Witzke, P.; Pérez-Domínguez, I.; Van Dijk, M.; Doelman, J.C.; Fellmann, T.; Koopman, J.F.L.; et al. Agricultural non-CO_2 emission reduction potential in the context of the 1.5 °C target. *Nat. Clim. Chang.* **2018**, *9*, 66–72. [CrossRef]
56. Wang, J.; Rothausen, S.G.S.A.; Conway, D.; Zhang, L.; Xiong, W.; Holman, I.P.; Li, Y. China's water-energy nexus: Green-house-gas emissions from groundwater use for agriculture. *Environ. Res. Lett.* **2012**, *7*, 014035. [CrossRef]

57. Dumortier, J.; Hayes, D.J.; Carriquiry, M.; Dong, F.; Du, X.; Elobeid, A.; Tokgoz, S.; Fabiosa, J.F. Sensitivity of carbon emission estimates from indirect land-use change. *Appl. Econ. Perspect. Policy* **2011**, *33*, 428–448. [CrossRef]
58. De Souza, J.P.; Bortolon, E.S.O.; Bortolon, L.; De Camargo, F.P.; Conceição, W.S.S.; Lima, A.D.O.; Vezzani, F.M. Carbon dioxide emissions in agricultural systems in the Brazilian Savanna. *J. Agric. Sci.* **2019**, *11*, 242. [CrossRef]
59. Zhou, J.; Jiang, M.; Chen, G. Estimation of methane and nitrous oxide emission from livestock and poultry in China during 1949–2003. *Energy Policy* **2007**, *35*, 3759–3767. [CrossRef]
60. Khalil, M.; Shearer, M.; Rasmussen, R. Methane sources in China: Historical and current emissions. *Chemosphere* **1993**, *26*, 127–142. [CrossRef]
61. Yamaji, K.; Ohara, T.; Akimoto, H. A country-specific, high-resolution emission inventory for methane from livestock in Asia in 2000. *Atmos. Environ.* **2003**, *37*, 4393–4406. [CrossRef]
62. Qiao, H.; Zheng, F.; Jiang, H.; Dong, K. The greenhouse effect of the agriculture economic growth-renewable energy nexus: Evidence from G20 countries. *Sci. Total Environ.* **2019**, *671*, 722–731. [CrossRef]
63. Wang, Z.P. Estimation of nitrous oxide emission of farmland in China. *Rural Eco-Environ.* **1997**, *13*, 51–55.
64. Tian, Y.; Yin, M. Re-evaluation of China's agricultural carbon emissions: Basic status, dynamic evolution and spatial spillover effects. *Chin. Rural. Econ.* **2022**, *3*, 104–127.
65. Yang, H.; Wang, X.; Bin, P. Agriculture carbon-emission reduction and changing factors behind agricultural eco-efficiency growth in China. *J. Clean. Prod.* **2022**, *334*, 130193. [CrossRef]
66. Liao, Y.; Wei, Y. Rural social justice construction since the 18th National Congress of the Communist Party of China. *J. Agro-For. Econ. Manag.* **2019**, *18*, 702–708.
67. Xu, H.; Huang, X.; Zhong, T.; Chen, Z.; Yu, J. Chinese land policies and farmers' adoption of organic fertilizer for saline soils. *Land Use Policy* **2014**, *38*, 541–549. [CrossRef]
68. Xu, J.; Huang, D.; He, Z.; Zhu, Y. Research on the structural features and influential factors of the spatial network of China's regional ecological efficiency spillover. *Sustainability* **2020**, *12*, 3137. [CrossRef]
69. Shen, J.; Zhu, Q.; Jiao, X.; Ying, H.; Wang, H.; Wen, X.; Xu, W.; Li, T.; Cong, W.; Liu, X.; et al. Agriculture green development: A model for China and the World. *Front. Agric. Sci. Eng.* **2020**, *7*, 5–13. [CrossRef]
70. Zheng, D.; Hao, S.; Sun, C.; Lyu, L. Spatial correlation and convergence analysis of eco-efficiency in China. *Sustainability* **2019**, *11*, 2490. [CrossRef]
71. Guan, X.; Zhang, J.; Wu, X.; Cheng, L. The shadow prices of carbon emissions in China's planting industry. *Sustainability* **2018**, *10*, 753. [CrossRef]
72. Li, Z.; Li, J. The influence mechanism and spatial effect of carbon emission intensity in the agricultural sustainable supply: Evidence from China's grain production. *Environ. Sci. Pollut. Res.* **2022**, *29*, 44442–44460. [CrossRef]
73. Wang, G.; Liu, P.; Hu, J.; Zhang, F. Spatiotemporal Patterns and influencing factors of agriculture methane emissions in China. *Agriculture* **2022**, *12*, 1573. [CrossRef]
74. Guo, H.; Fan, B.; Pan, C. Study on mechanisms underlying changes in agricultural carbon emissions: Acase in Jilin Province, China, 1998–2018. *Int. J. Environ. Res. Public Health* **2021**, *18*, 919. [CrossRef]
75. Huang, H.; Zhu, N. Rural financial efficiency, agricultural technological progress and agricultural carbon emissions: Evidence from China. *Nat. Environ. Poll. Technol.* **2022**, *21*, 61–69. [CrossRef]