agriculture

Article

Carbon Emissions from Agricultural Inputs in China over the Past Three Decades

Shixiong Song [1,2], Siyuan Zhao [1], Ye Zhang [1] and Yongxi Ma [1,2,*]

[1] School of Economics and Management, Zhejiang Sci-Tech University, Hangzhou 310018, China; songsx@zstu.edu.cn (S.S.); zhaosiyuan@mails.zstu.edu.cn (S.Z.); zhangye@mails.zstu.edu.cn (Y.Z.)
[2] Zhejiang Academy of Eco-Civilization, Zhejiang Sci-Tech University, Hangzhou 310018, China
* Correspondence: myx@zstu.edu.cn

Abstract: Global warming has become one of the major threats to the security of human survival, security, and sustainable development. Agricultural production has been widely suspected as one of the main sources of anthropogenic carbon emissions. Analyzing the changing characteristics and influencing factors of agricultural carbon emissions is of great significance for the mitigation of global climate change and the sustainable development in agriculture. Taking China, a large agricultural country, as an example, this study used the empirical model to quantify carbon emissions from agricultural inputs from 1991 to 2019, and analyzed the driving factors using ridge regression. We found that agricultural carbon emissions in China have been on the rise in the past 30 years, but at a markedly slower pace. From 2008 to 2019, the average annual growth rate of agricultural carbon emissions was 1.47%, down significantly from 2.92% between 1991 and 2007. The carbon emissions per unit of planting area showed an overall increasing trend, which grew from 179.35 t ce/km^2 to 246.26 t ce/km^2, with an average annual growth rate of 1.13%. The carbon emissions per unit of agricultural output mainly showed a decreasing trend, which decreased from 0.52 kg ce/CNY to 0.06 kg ce/CNY, with an average annual rate of change of −7.42%. China's agricultural carbon emissions were closely related to macro-policies. Fertilizer inputs, agricultural industry structure, and energy use intensity were significantly positively correlated with carbon emission intensity. The degree of urban feedback to rural areas, public investment in agriculture, and large-scale planting were significantly negatively correlated with carbon emission intensity, but the impacts of these factors had a "lag effect". In order to reduce carbon emissions from agriculture and promote development in green agriculture, we suggest that the government should further increase the degree of urban feedback to rural and public investment in the agricultural sector. In addition, large-scale agricultural production should be encouraged to increase resource efficiency and reduce carbon emissions.

Keywords: agricultural inputs; carbon emissions; driving mechanisms; ridge regression

check for updates

Citation: Song, S.; Zhao, S.; Zhang, Y.; Ma, Y. Carbon Emissions from Agricultural Inputs in China over the Past Three Decades. *Agriculture* **2023**, *13*, 919. https://doi.org/10.3390/agriculture13050919

Academic Editor: Mirna Velki

Received: 27 March 2023
Revised: 18 April 2023
Accepted: 20 April 2023
Published: 22 April 2023

1. Introduction

Global warming is one of the most serious challenges facing humanity today [1–3]. The average global CO_2 concentration reached a record high of 407.8 ppm in 2018 [4]. Human activities are increasing the concentration of greenhouse gasses, causing the temperature of Earth's surface to rise [5–7]. Global warming poses a major threat to human survival by reducing food production, changing agricultural production conditions, and increasing natural disasters [8–11]. According to the Fourth Assessment Report of the IPCC, carbon emissions from agriculture are the second largest contributor to global greenhouse gas emissions, accounting for approximately one third of total carbon emissions [12–14]. As a large agricultural country, China plays an important role in global food production, and its productivity growth has an important impact on global food security [15–18]. From FAO-STAT, China's grain output will account for 24.40% of the world's total in 2020, providing food security for about 20% of the world's population. However, compared with developed countries, China's agriculture still suffers from the over-input of production factors and an insufficient utilization of resources [19–22]. Agroecological practices will reduce carbon emissions from agriculture, which will help to develop green agriculture [23,24]. At present, the "high input and high emission" development model of China's agriculture has become the key to restricting sustainable development in agriculture [25–28]. Therefore, it is of great practical significance to analyze the changing trends of carbon emissions caused by the inputs of agricultural production and its influencing factors for reducing agricultural carbon emissions and promoting green and low-carbon development in agriculture.

Currently, many scholars have studied the changes in carbon emissions caused by the inputs of agricultural production in China. For example, Jin et al. [29] analyzed the changing characteristics of carbon emissions from China's agricultural sector from 1961 to 2018 and its emission reduction pathways. Chen et al. [30] analyzed the changing characteristics and influencing factors of China's agricultural carbon emissions from 2005 to 2013. Ma et al. [31] simulated the changes in carbon emissions in the production of seven major crops in China under different technology scenarios. Wang [32] used carbon emission coefficients to analyze the changes in carbon footprint due to agricultural inputs in China from 1991 to 2014. Overall, the existing studies have laid a good foundation for further research into the changes in carbon emissions brought by the inputs of agricultural production and its driving mechanisms, but there are still certain shortcomings. This is mainly reflected by two aspects: (1) There were relatively few studies on the changing characteristics of carbon emissions caused by the inputs of production, and the existing studies mainly focused on the agricultural sector to explore the changing characteristics of carbon emissions. (2) Research on the influencing factors of carbon emissions was relatively simple, and relatively few studies analyzed the influencing factors of carbon emissions according to time segments based on changing characteristics.

Based on this, this study intends to analyze the characteristics of changes in carbon emissions caused by the inputs of agricultural production and its influencing factors in China from 1991 to 2019. Firstly, we used the empirical model to quantify the carbon emissions of the inputs of agricultural production in China from 1991 to 2019. Secondly, we calculated the carbon emission intensity per unit area and per unit output separately. Finally, we used the ridge regression to analyze the influencing factors of carbon emissions according to their changing trends over time. This study effectively quantifies and analyzes the characteristics of the changes in carbon emissions from agricultural inputs and their driving mechanisms over the past 30 years in China, with a view to providing a scientific reference for reducing agricultural carbon emissions.

2. Materials and Methods

2.1. Study Area and Data

This paper took China as the study area. Due to the lack of agricultural input statistics, the study area did not include Hong Kong, Macao, and Taiwan. The research subject was the carbon emissions caused by the inputs of agricultural production. Over the past few decades, the inputs of agricultural production in China have shown a rapid growth trend, which has been accompanied by a significant increase in greenhouse gas emissions. For example, Zhang and Wang [19] showed that the share of carbon emissions caused by energy and agrochemicals in China's agricultural production showed an increasing trend from 1985 to 2011, from 28.02% to 43.66%. Jin et al. [29] found that carbon emissions from agricultural energy consumption in China increased from 0.03 to 23.70 billion tons between 1979 and 2018, an increase of 6.9 times; agricultural electricity consumption increased from 134 to 1004 million kilowatts, an increase of 6.5 times. Wang [32] found that carbon emissions from the inputs of agricultural production in China increased from 93.29 million t ce in 1991 to 158.93 million t ce in 2014, with an average annual growth rate of 2.9%, with fertilizer and electricity factor inputs being the main contributors.

The data used in this study mainly include agricultural chemical inputs and energy inputs, empirical coefficients of carbon emissions, and impact factors. Among them, agricultural chemical inputs such as nitrogen fertilizer, phosphate fertilizer, potash fertilizer, pesticides, and agro-film from 1991 to 2019 were obtained from the China Rural Statistical Yearbook in 2020 (https://data.cnki.net/trade/Yearbook/Single/N2020120306?zcode=Z009, accessed on 14 September 2022), and agricultural energy data such as on raw coal, coke, petrol, diesel, and electricity were obtained from the China Energy Statistical Yearbook in 2020 (https://data.cnki.net/Trade/yearbook/single/N2021050066?zcode=Z023, accessed on 14 September 2022). The carbon emission coefficients of different agricultural production factors were obtained via collating the available literature. Data on the impact factors such as the structure of the agricultural output value, public investment in agriculture, urbanization rate, degree of crop damage, and scale of industrial cultivation were obtained from the China Energy Statistical Yearbook, China Rural Statistical Yearbook, and China Population and Employment Statistical Yearbook in 2020 (https://data.cnki.net/trade/Year-book/Single/N2021020056?zcode=Z001, accessed on 14 September 2022).

2.2. Methods

① Quantifying Carbon Emissions from Agricultural Inputs

Referring to [33–35], we used the carbon emission coefficients to quantify carbon emissions from each input of agricultural production. The formula is as follows:

$$CE_t = \sum_i^n E_{i,t} \times F_i \times GWP_i \tag{1}$$

where CE_t is the carbon emissions from inputs of agricultural production in t year. $E_{i,t}$ is the input amounts of agricultural production factor i in t year. n is the type of agricultural production factor, including nitrogen fertilizer, phosphate fertilizer, potash fertilizer, pesticide, agro-film, raw coal, coke, gasoline, diesel, and electricity. F_i is the carbon emission coefficient of production factor i. GWP_i is the warming potential of greenhouse gas emissions from agricultural production factor i.

② Calculating Carbon Emission Intensity

Carbon emission intensity refers to the amount of carbon emissions per unit of agricultural output value or per unit of planting area, reflecting the costs and eco-efficiency of agricultural production systems [36]. According to [37–39], we chose carbon emissions per unit of planting area and carbon emissions per unit of agricultural output value to quantify the carbon emission intensity of the inputs of agricultural production in China, respectively. The formula is as follows:

$$CIP_t = CE_t / O_t \tag{2}$$

$$CIA_t = CE_t / A_t \tag{3}$$

where CIP_t is the carbon emission per unit of agricultural output value in t year. O_t is the total value of agricultural sector output in t year. CIA_t is the carbon emission per unit of planting area in t year. A_t is the total planting area in t year.

③ Analyzing the Driving Mechanisms of Carbon Emissions from Agricultural Inputs

Referring to [40,41], we chose fertilizer input structure, agricultural industry structure, investment in agriculture, energy use intensity, planting scale, the extent of disaster in agriculture, and urbanization rate as the explanatory variables (Table 1). Considering the possible covariance problem among the explanatory variables, we used ridge regression to analyze the relationships between carbon emissions from the inputs of agricultural production and explanatory variables. The formula is as follows:

$$CIP = \beta_0 + \sum_{i=1}^n \beta_i x_i + \varepsilon \tag{4}$$

where β_0 is the intercept of the multiple regression equation. x_i is the explanatory variable i. n is the number of explanatory variables. β_i is the partial regression coefficient of explanatory variable i. ε is the error, which is normally distributed.

Table 1. Quantification of explanatory variables.

Explanatory Variables	Quantitative Indicators	Descriptions
Fertilizer input structure	$\frac{\text{Nitrogen fertilizer usage}}{\text{Fertilizer usage}} \times 100\%$	There are significant direct and implicit carbon emissions in the process of nitrogen fertilizer production and use. The higher the proportion of nitrogen fertilizer use, the higher the agricultural carbon emission intensity [42].
Agricultural industry structure	$\frac{\text{Output value of the main crops}}{\text{Total output value of agriculture}} \times 100\%$	The higher the output value of the main crops (wheat, maize, and rice), the higher the agricultural carbon emission intensity [43].
Investment in agriculture	$\frac{\text{Agricultural investment from finance}}{\text{Total output value of agriculture}} \times 100\%$	The higher the level of investment in agriculture, the higher the production efficiency and the lower the carbon intensity [44].
Energy use intensity	$\frac{\text{Agricultural energy consumption}}{\text{Total output value of agriculture}} \times 100\%$	The higher the energy use intensity, the higher the agricultural carbon emission intensity [45].
Urbanization rate	$\frac{\text{Urban population}}{\text{Total population}} \times 100\%$	The higher the degree of urban feedback to rural areas, the lower the agricultural carbon emission intensity [46,47].
The extent of disaster	$\frac{\text{Area of affected crops}}{\text{Total area of planting}} \times 100\%$	Disasters will reduce yields, and then reduce agricultural output and increase the carbon emission intensity [48].
Planting scale	$\frac{\text{Total area of planting}}{\text{Rural population}} \times 100\%$	The scale effect will increase production and resource use efficiency, thereby reducing the intensity of agricultural carbon emissions [49,50].

3. Results

3.1. Carbon Emissions from Agricultural Inputs in China from 1991 to 2019

Carbon emissions from the inputs of agricultural production in China showed a significant increase trend between 1991 and 2019 (Figure 1). Carbon emissions increased from 214.65 million t ce in 1991 to 351.11 million t ce in 2019, with an annual growth rate of 1.77%. The changes can be broadly divided into two time periods: 1991–2007 and 2008–2019, respectively (Figure 1). From 1991 to 2007, carbon emissions showed rapid growth, from 214.65 million t ce to 340.23 million t ce, with an average annual growth rate of 2.92%. From 2008 to 2019, carbon emissions showed slow and declining growth rates, from 299.06 million t ce to 351.11 million t ce, with an average annual growth rate of 1.47% (Figure 1).

Carbon emissions from agricultural chemicals have been increasing and then decreasing over the past 30 years. From 1991 to 2014, carbon emissions from agrochemicals such as fertilizers, pesticides, and agricultural films have increased from 90.83 million t ce to 174.23 million t ce, with an average annual increase of 2.87%. Since 2014, carbon emissions from agrochemicals have been decreasing, from 174.23 million t ce to 145.74 million t ce in 2019, with an average annual decrease of 0.71%. Carbon emissions from agricultural energy showed an increasing trend, from 123.82 million t ce to 205.37 million t ce between 1991 and 2019, with an average annual increase of 1.82%.

There are significant differences in the contribution of each factor input to carbon emissions (Figure 2). Fertilizer and fuel were the main contributors to agricultural carbon emissions, accounting for more than 60%. The contributions of factor inputs such as electricity, agro-film, and pesticide showed an increasing trend from 1991 to 2019. The contribution rate of electricity increased from 21.98% to 30.45%, an annual increase of 1.17%. Agro-film's contribution rate increased from 5.68% to 13.03%, an annual increase of 3.01%. Pesticide's contribution rate increased from 6.45% to 7.17%, an annual increase of 0.38%. From 1991 to 2019, the contribution of fertilizer and fuel such as raw coal, coke, gasoline, and diesel showed a decreasing trend. The contribution of fuel inputs decreased from 35.71% to 28.05%, and that of fertilizer decreased from 30.18% to 21.30% (Figure 2).

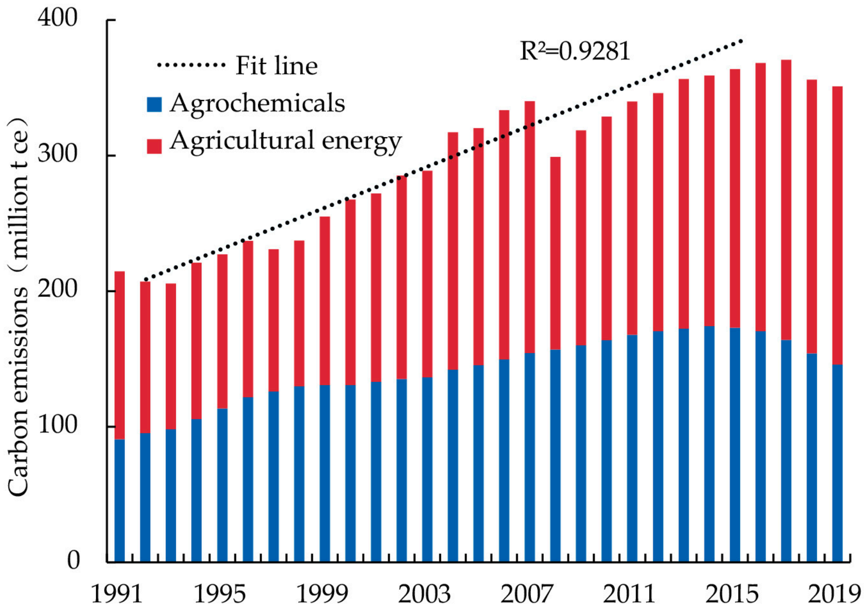

Figure 1. Carbon emissions from the inputs of agricultural production in China from 1991 to 2019.

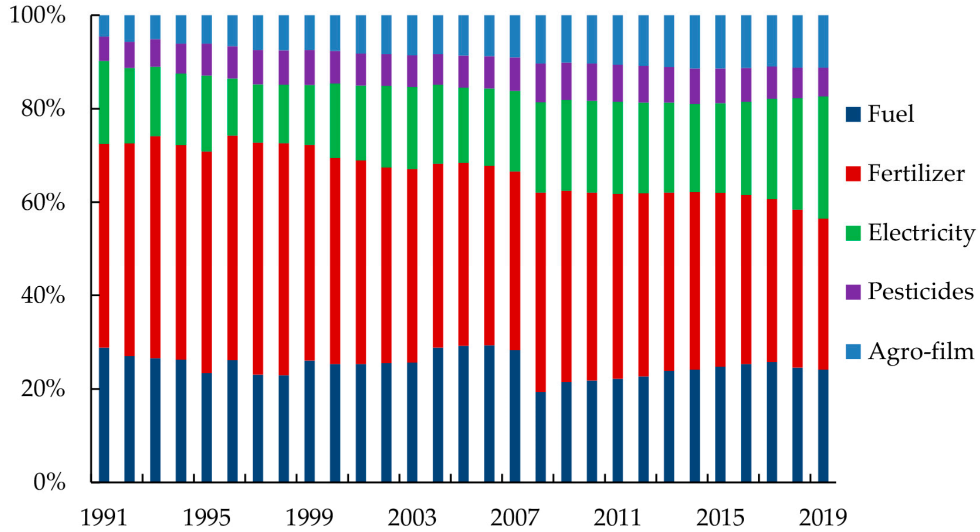

Figure 2. Contribution of different inputs to agricultural carbon emissions.

3.2. Carbon Emission Intensity

The carbon emissions per unit of planting area (CIA) have shown an overall increasing trend over the past 30 years. The CIA increased from 179.35 t ce/km^2 in 1991 to 246.26 t ce/km^2 in 2019, with an average annual growth rate of 1.13%. During 1991–2007, CIA grew rapidly from 179.35 t ce/km^2 to 266.31 t ce/km^2, an annual growth rate of 2.50%. There was a significant decrease after 2008, followed by a slow growth from 235.3 t ce/km^2 to 246.26 t ce/km^2, an annual growth rate of 0.41%. Between 1991 and 2019, there was little change in the area of arable land in China, and the changes in CIA indicated that the efficiency of agricultural resource utilization increased significantly from 2008 onwards.

The carbon emissions per unit of agricultural output (CIP) mainly showed a decreasing trend from 1991 to 2019. The CIP decreased from 0.52 kg ce/CNY in 1991 to 0.06 kg ce/CNY in 2019, with an average annual rate of change of −7.42% (Figure 3). From 1991 to 1998, CIP decreased rapidly, from 0.5 kg ce/CNY to 0.21 kg ce/CNY, a decrease of 11.66%. From 1999 to 2019, CIP showed a slow downward trend, from 0.22 to 0.06 kg ce/CNY, a decrease of 6.29%. Overall, the trend of CIP indicates that the ecological cost of agricultural production in China continues to decline and agriculture is geared toward high-quality development.

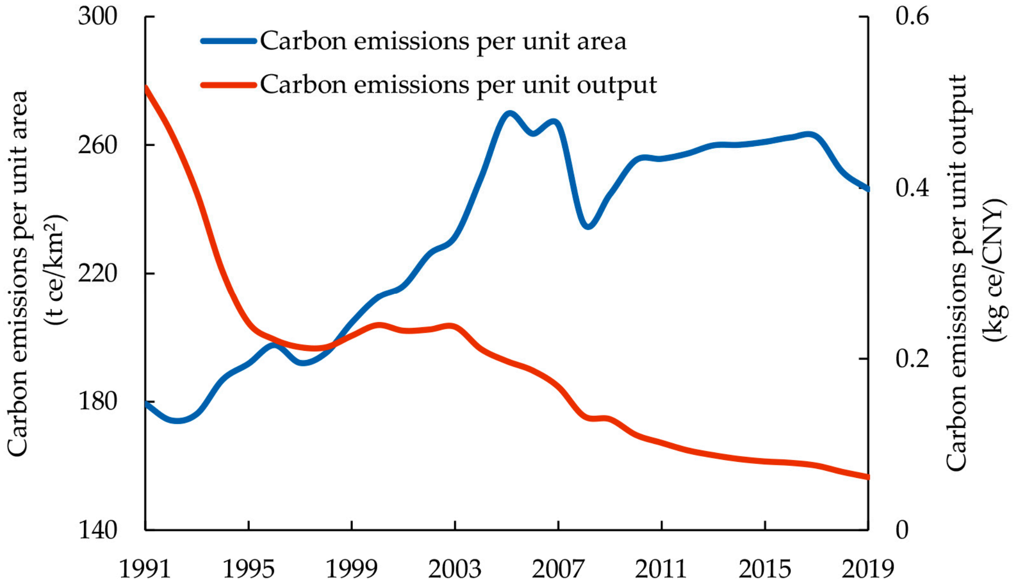

Figure 3. Carbon emission intensity.

3.3. The Driving Factors of Agricultural Carbon Emissions

There is a significant positive relationship between agricultural fertilizer input structure and carbon emissions per unit output. The partial regression coefficient of the agricultural fertilizer input structure from 1991 to 2019 was 0.0049 ($p < 0.001$). The standardized partial regression coefficient of the agricultural fertilizer input structure from 1991 to 2007 was 0.1432 and greater than 0.1196 from 2008 to 2019. This indicates that the agricultural fertilizer input structure had a greater impact on CIP in the period of 1991–2007 than in the period of 2008–2019 (Table 2). Nitrogen fertilizers produce a large amount of direct and implied carbon emissions during production and use. Nitrogen fertilizers account for a high proportion of fertilizers; so, a higher proportion of nitrogen fertilizer use will result in a higher carbon emission intensity.

The agricultural industry structure has a significant positive correlation with CIP. The partial regression coefficient of the agricultural industry structure from 1991 to 2019 was 0.0160 ($p < 0.001$). Major crops such as wheat, maize, and rice account for more than half of crop production; so, the higher their share, the higher the CIP. As with the agricultural fertilizer structure indicator, the structure of the agricultural industry had a greater impact on CIP in the period of 1991–2007 than in the period of 2008–2019 (Table 2).

The relationship between public investment in agriculture and CIP from 1991 to 2019 was not significant. However, there was a significant negative relationship in the period of 2008–2019, with a partial regression coefficient of −0.0008 ($p < 0.05$) (Table 2). This indicates that with an increase in China's financial investment in agriculture, the accumulation of agricultural production technologies to a certain extent would reduce agricultural carbon emissions.

There is a significant positive correlation between agricultural energy use intensity and CIP. The partial regression coefficient of agricultural energy use intensity from 1991 to 2019 was 0.2926 ($p < 0.001$), which is greater than other factors. The energy used in agricultural production is the main source of carbon emissions. The higher the energy use intensity, the higher the CIP. The relative importance of agricultural energy intensity to CIP was the highest between 1991 and 2007, at nearly 50% (Table 2).

Table 2. The results of ridge regression.

Periods	Explanatory Variables	Partial Regression Coefficients (Standard Error)	Standardized Partial Regression Coefficients	*p*-Value
1991–2019	Fertilizer input structure	0.0049 (0.0006)	0.1441	0.0000
	Agricultural industry structure	0.0160 (0.0014)	0.2632	0.0000
	Investment in agriculture	0.0012 (0.0011)	0.0272	0.3218
	Energy use intensity	0.2926 (0.0184)	0.3981	0.0000
	Urbanization rate	−0.0839 (0.0143)	−0.0838	0.0000
	The extent of disaster	0.0992 (0.0374)	0.0739	0.0150
	Planting scale	−0.0104 (0.0056)	−0.0403	0.0792
1991–2007	Fertilizer input structure	0.0055 (0.0014)	0.1432	0.0030
	Agricultural industry structure	0.0144 (0.0022)	0.2741	0.0001
	Investment in agriculture	0.0026 (0.0011)	0.0863	0.5633
	Energy use intensity	0.3340 (0.0291)	0.4955	0.0000
	Urbanization rate	−0.1032 (0.0275)	−0.0665	0.0045
	The extent of disaster	0.1548 (0.1309)	0.0597	0.2673
	Planting scale	−0.0063 (0.0242)	−0.0086	0.8010
2008–2019	Fertilizer input structure	0.0030 (0.0010)	0.1196	0.0437
	Agricultural industry structure	0.0154 (0.0028)	0.2074	0.0054
	Investment in agriculture	−0.0008 (0.0012)	−0.0386	0.0433
	Energy use intensity	0.2421 (0.0711)	0.1891	0.0272
	Urbanization rate	−0.0632 (0.0514)	−0.1442	0.0148
	The extent of disaster	0.0718 (0.0273)	0.1909	0.0582
	Planting scale	−0.0090 (0.0028)	−0.1238	0.0324

The urbanization rate has a significant negative correlation with CIP. The partial regression coefficient of the urbanization rate from 1991 to 2019 was −0.0839 ($p < 0.001$). As the urbanization rate increases, urban areas tend to help rural areas more, which can partly curb agricultural carbon emissions. The standardized partial regression coefficient of the urbanization rate increased from 6.65% between 1991 and 2007 to 14.42% between 2008 and 2019 (Table 2), indicating that urbanization has an increasing inhibiting effect on agricultural carbon emissions.

From 1991 to 2019, there was a significant positive correlation between the agricultural disaster level and CIP. In general, as the level of agricultural disaster increases and crop production decreases, but the planting area remains unchanged, CIP increases. The correlation between agricultural disaster level and CIP was not significant from 1991 to 2007 and 2008 to 2019 (Table 2).

From 1991 to 2019, planting scale had little correlation with CIP. However, the correlation between planting scale and CIP from 2008 to 2019 was −0.0090 ($p < 0.05$) (Table 2). This indicates that the scale effect of China's agriculture is becoming more evident and agricultural resource utilization is becoming more efficient, thus reducing the agricultural carbon emission intensity.

4. Discussion

4.1. Driving Mechanism of Agricultural Carbon Emissions in China

Macro policies are the dominant factors influencing agricultural carbon emissions. Trends in agricultural carbon emissions are closely related to China's agricultural policies. Our results from 1991 to 2019 show that the change in carbon emissions caused by agricultural inputs in China can be divided into rapid growth from 1991 to 2007 and slow growth from 2008 to 2019. In the first phase, China exempted non-compound fertilizer from value-added tax and implemented agricultural subsidies in 1994. In 2002, China promulgated the Rural Land Contract Law, which guarantees the interests of farmers and improves their motivation to produce. Since 2004, the Central Government Document No. 1 has been issued for five consecutive years to support agricultural development, proposing the policy of "Industry feeding agriculture and cities supporting agriculture". In 2006, China abolished agricultural taxes. These policies have greatly motivated farmers, resulting in a rapid increase in agricultural factor inputs and a rapid increase in agricultural carbon emissions between 1991 and 2007. The 2008 financial crisis led to a sharp increase in the price of agricultural inputs and the cost of production, leading farmers to reduce their agricultural inputs, resulting in a significant reduction in carbon emissions. In 2011, China introduced a series of green agriculture and eco-agriculture policies to support the use of high-efficiency fertilizers and low-residue pesticides. In 2015, China proposed green development and "zero growth" in fertilizer use. Our results show that there has been a significant decline in fertilizer inputs such as nitrogen, phosphate, and potash since 2015 (Figure 4). In 2016, the government proposed a reform plan for establishing a green and eco-oriented agricultural subsidy system (Figure 5). In the last stage, China proposed many policies for green and low-carbon development in agriculture, which have greatly improved the efficiency of agricultural resource use and have effectively alleviated agricultural carbon emissions. In general, changes in agricultural carbon emissions are closely related to macro-policies. Our findings are also consistent with Wang [32].

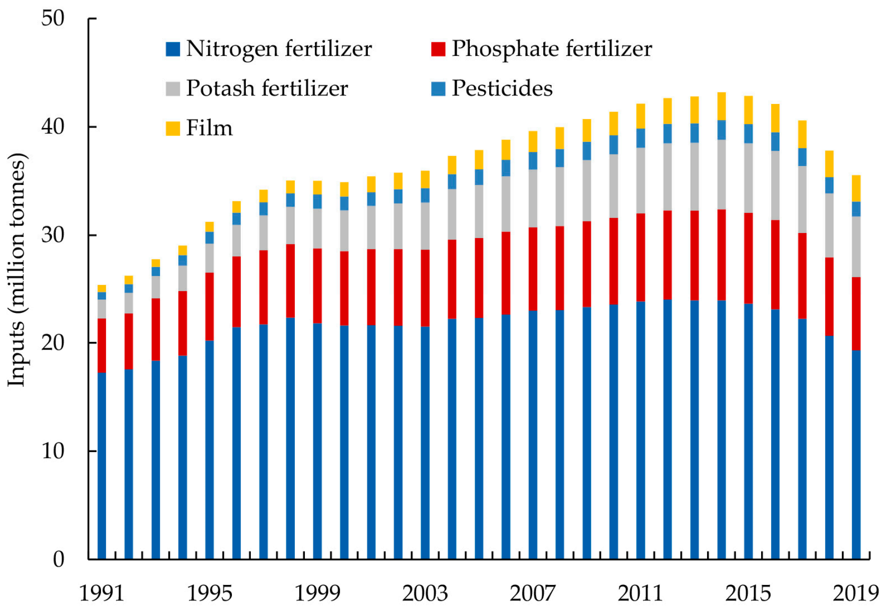

Figure 4. Agrochemical factor inputs.

Fertilizer inputs, agricultural industry structure, and energy use intensity contribute significantly to carbon emissions caused by agricultural production factor inputs in China. Our results show that energy and fertilizer have been the main contributors to carbon emissions from agriculture in China over the past 30 years (Figure 2). However, the contribution of energy and fertilizers, as well as the quantity of inputs, have been on a downward trend (Figure 4), which is also closely related to macro policies. This is in line with Wang [32] and Jin et al. [29], who also conclude that carbon emissions from energy and fertilizer are on a downward trend as national policies impact agricultural energy and fertilizer use. There was a significant negative correlation between the degree of urban feedback to rural areas and agricultural carbon emissions. Jiang et al. [51] and Zhao et al. [52] also showed that development in China's urbanization will improve the efficiency of agricultural resource use. This suggests that urban feedback to agriculture is an effective way to reduce agricultural carbon emissions. As China's socio-economic and urbanization continues to develop, the degree of urban feedback to rural areas should be further increased. In addition, some of the factors were not significant from 1991 to 2019, but were significant for part of the time period. For example, over the past decade, there has been a marked negative correlation between public investment in agriculture and CIP. On the one hand, China's public investment in agriculture has improved greatly in recent years. On the other hand, investment in technology, training, and production facilities in agriculture may have a "lag effect" and may need to accumulate to a certain extent before it can reduce agricultural carbon emissions more significantly. According to our study, public investment in agriculture should continue to increase in the future to further promote low-carbon development in agriculture.

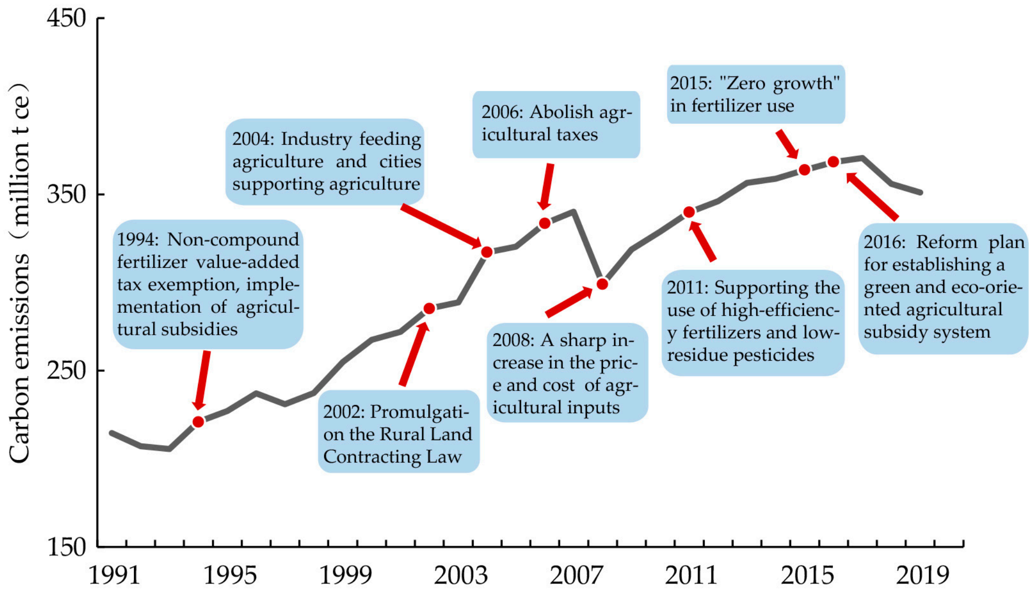

Figure 5. Agricultural policies and trends in carbon emissions from production factor inputs.

4.2. Policy Implications

Green and low-carbon agricultural development policies are critical for reducing carbon emissions from the agricultural sector. Over the past 30 years, China's agricultural policies have gradually shifted from focusing on production and mobilizing farmers' enthusiasm for production to focusing on efficiency and green production policies. At the same time, carbon emissions from the agricultural sector increased rapidly, then slowly, until they began to decline in recent years. After China introduced a zero-growth fertilizer program in 2015, fertilizer use dropped significantly, dramatically reducing carbon emissions from the agricultural sector. To meet China's 2030 carbon peak and 2060 carbon neutrality targets, the agricultural sector must continue to move resolutely toward green and low-carbon development, guided by macroeconomic policies.

Energy and fertilizer inputs have been major sources of carbon emissions from agriculture in China over the past 30 years, despite declining trends. Therefore, further improving the use efficiency of agricultural energy and fertilizer, and increasing the use of clean energy and organic fertilizer, will effectively reduce agricultural carbon emissions. Fertilizer use and agro-industrial structure have a significant positive correlation with agricultural carbon emissions; so, reducing nitrogen fertilizer use and grain production can also reduce agricultural carbon emissions. In addition, factors such as urbanization rates, public investment in agriculture, and planting scale have somewhat dampened agricultural carbon emissions. In order to reduce carbon emissions from agriculture, the government should further increase the degree of urban feedback to rural and public investment in the agricultural sector. Government should also encourage large-scale agricultural production to increase resource efficiency and thereby reduce agricultural carbon emissions.

4.3. Future Perspectives

This study has clearly described the impact of production factor inputs on agricultural carbon emissions in China in the past 30 years, and analyzed the influence factors by using ridge regression model, providing a scientific reference for development in low-carbon agriculture in China. However, there are some shortcomings in this study. For example, we only calculated the carbon emissions from key production factor inputs and did not consider all production factor inputs, such as organic fertilizers and agricultural irrigation. However, our study can represent most of the carbon emissions brought by agricultural factor inputs. In order to avoid the multicollinearity of the influencing factors, we used a ridge regression model to analyze the relationship between the influencing factors and agricultural carbon emissions linearly, but the actual agricultural input–output-emissions form an organic and complex system, which often has a complex nonlinear relationship. In the future, we can collect more data to comprehensively analyze agricultural carbon emissions from multiple factor inputs, and analyze the driving mechanisms of agricultural carbon emissions using complex system models such as system dynamics or machine learning to provide more detailed data support for green agriculture development.

5. Conclusions

In this study, we used the empirical model to quantify the carbon emissions from agricultural production factor inputs and carbon emission intensity, and analyzed the main drivers of agricultural carbon emissions in China by using the ridge regression model. We found that the overall trend of agricultural carbon emissions in China has increased in the past 30 years, but there have been differences in different periods. From 1991 to 2019, agricultural carbon emissions increased from 214.65 million t ce to 351.11 million t ce, with an annual growth rate of 1.77%. From 1991 to 2007, carbon emissions showed rapid growth, with an average annual growth rate of 2.92%. From 2008 to 2019, carbon emissions showed slow and declining growth rates, with an average annual growth rate of 1.47%. The carbon emissions per unit of planting area have shown an overall increasing trend over the past 30 years. During 1991–2019, CIA grew rapidly from 179.35 t ce/km^2 to 246.26 t ce/km^2, with an average annual growth rate of 1.13%. The carbon emissions per unit of agricultural output mainly showed a decreasing trend from 1991 to 2019. The CIP decreased from 0.52 kg ce/CNY to 0.06 kg ce/CNY, with an average annual rate of change of -7.42%. We found that China's agricultural carbon emissions were closely related to macro-policies. Fertilizer inputs, agricultural industry structure, and energy use intensity had a significant positive correlation with carbon emission intensity. The degree of urban feedback to rural areas, public investment in agriculture, and large-scale planting had a significant negative correlation with carbon emission intensity, but the impacts of these factors had a "lag effect". In order to reduce carbon emissions from agriculture in the short to medium term, we suggest that the government should further increase the degree of urban feedback to rural and public investment in the agricultural sector. In addition, large-scale agricultural production should be encouraged to increase resource efficiency and reduce carbon emissions. In the long run, the government should vigorously develop new energy technologies to reduce agricultural carbon emissions at the source and thus promote green and sustainable development in agriculture.

Author Contributions: Conceptualization, Y.M.; methodology, S.S., S.Z. and Y.Z.; writing—original draft preparation, S.S. and S.Z.; writing—review and editing, S.S. and Y.Z.; visualization, S.S.; project administration, Y.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant numbers 41961124004 and 71873125. It was also supported by the Science Foundation of Zhejiang Sci-Tech University (ZSTU) under grant no. 22092032-Y.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tang, Y.; Luan, X.; Sun, J.; Zhao, J.; Yin, Y.; Wang, Y.; Sun, S. Impact assessment of climate change and human activities on GHG emissions and agricultural water use. *Agric. For. Meteorol.* **2021**, *296*, 108218. [CrossRef]
2. Kay, J. Early models successfully predicted global warming. *Nature* **2020**, *578*, 45–46. [CrossRef] [PubMed]
3. Qiao, F.; Williams, J. Topic Modelling and Sentiment Analysis of Global Warming Tweets: Evidence from Big Data Analysis. *J. Organ. End User Comput.* **2022**, *34*, 1–18. [CrossRef]
4. WMO. The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2018. In *WMO Greenhouse Gas Bulletin*; WMO: Geneva, Switzerland, 2019; Volume 15. Available online: https://library.wmo.int/index.php?lvl=notice_display&id=21620#.ZCp-hHtBwrY (accessed on 5 April 2023).
5. Dai, X.; Wu, X.; Chen, Y.; He, Y.; Wang, F.; Liu, Y. Real Drivers and Spatial Characteristics of CO_2 Emissions from Animal Husbandry: A Regional Empirical Study of China. *Agriculture* **2022**, *12*, 510. [CrossRef]
6. Zhao, X.; Ma, X.; Chen, B.; Shang, Y.; Song, M. Challenges toward carbon neutrality in China: Strategies and countermeasures. *Resour. Conserv. Recycl.* **2022**, *176*, 105959. [CrossRef]
7. El-sharkawy, M. Global warming: Causes and impacts on agroecosystems productivity and food security with emphasis on cassava comparative advantage in the tropics/subtropics. *Photosynthetica* **2014**, *52*, 161–178. [CrossRef]
8. Lin, X.; Zhu, X.; Han, Y.; Geng, Z.; Liu, L. Economy and carbon dioxide emissions effects of energy structures in the world: Evidence based on SBM-DEA model. *Sci. Total Environ.* **2020**, *729*, 138947. [CrossRef]
9. Fan, S.; Cho, E.; Meng, T.; Rue, C. How to Prevent and Cope with Coincidence of Risks to the Global Food System. *Annu. Environ. Resour.* **2021**, *46*, 601–623. [CrossRef]
10. Panchasara, H.; Samrat, N.; Islam, N. Greenhouse Gas Emissions Trends and Mitigation Measures in Australian Agriculture Sector—A Review. *Agriculture* **2021**, *11*, 85. [CrossRef]
11. Bennetzen, E.; Smith, P.; Porter, J. Decoupling of greenhouse gas emissions from global agricultural production: 1970–2050. *Glob. Chang. Biol.* **2016**, *22*, 763–781. [CrossRef] [PubMed]
12. IPCC. *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007.
13. Madden, S.; Ryan, A.; Walsh, P. Exploratory Study on Modelling Agricultural Carbon Emissions in Ireland. *Agriculture* **2022**, *12*, 34. [CrossRef]
14. Li, S.; Zhu, Z.; Dai, Z.; Duan, J.; Wang, D.; Feng, Y. Temporal and Spatial Differentiation and Driving Factors of China's Agricultural Eco-Efficiency Considering Agricultural Carbon Sinks. *Agriculture* **2022**, *12*, 1726. [CrossRef]
15. Huang, J.; Hu, R.; Yi, H.; Sheng, Y.; Wang, J.; Bao, M.; Liu, X. Development Visions and Policies of China's Agriculture by 2050. *China Eng. Sci.* **2022**, *24*, 11–19. [CrossRef]
16. Huang, J.; Xie, W.; Sheng, Y.; Wang, X.; Wang, J.; Liu, C.; Hou, L. Global Agricultural Development Trends and Prospects for China's Agricultural Development in 2050. *China Eng. Sci.* **2022**, *24*, 29–37. [CrossRef]
17. Song, S.; Zhang, L.; Ma, Y. Evaluating the impacts of technological progress on agricultural energy consumption and carbon emissions based on multi-scenario analysis. *Environ. Sci. Pollut. Res.* **2022**, *30*, 16673–16686. [CrossRef] [PubMed]
18. Wang, J.; Zhang, Z.; Liu, Y. Spatial shifts in grain production increases in China and implications for food security. *Land Use Policy* **2018**, *74*, 204–213. [CrossRef]
19. Zhang, G.; Wang, S. The Structure, Efficiency and Determination Mechanism of Agricultural Carbon Emissions in China. *J. Agric. Econ.* **2014**, *35*, 18–26. [CrossRef]
20. Liu, D.; Zhu, X.; Wang, Y. China's agricultural green total factor productivity based on carbon emission: An analysis of evolution trend and influencing factors. *J. Clean. Prod.* **2021**, *278*, 123692. [CrossRef]
21. Li, Z.; Wu, X.; Wang, X.; Zhong, H.; Chen, J.; Ma, X. Measurement and Analysis of Contribution Rate for China Rice Input Factors via a Varying-Coefficient Production Function Model. *Agriculture* **2022**, *12*, 1431. [CrossRef]
22. Ye, X.; Cheng, Y.; Zhang, Y.; Wu, Z.; Li, Q.; Liu, C. Scenario Simulation, Main Paths and Policy Measures of Greenhouse Gas Emission Reduction of Agricultural Activities in China. *Issues Agric. Econ.* **2022**, *2*, 4–16. [CrossRef]
23. Kherif, O.; Seghouani, M.; Zemmouri, B.; Bouhenache, A.; Keskes, M.; Yacer-Nazih, R.; Ouaret, W.; Latati, M. Understanding the Response of Wheat-Chickpea Intercropping to Nitrogen Fertilization Using Agro-Ecological Competitive Indices under Contrasting Pedoclimatic Conditions. *Agronomy* **2021**, *11*, 1225. [CrossRef]
24. Latati, M.; Dokukin, P.; Aouiche, A.; Rebouh, N.; Takouachet, R.; Hafnaoui, E.; Hamdani, F.; Bacha, F.; Ounane, S. Species Interactions Improve Above-Ground Biomass and Land Use Efficiency in Intercropped Wheat and Chickpea under Low Soil Inputs. *Agronomy* **2019**, *9*, 765. [CrossRef]
25. 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] [PubMed]
26. Zhang, L.; Pang, J.; Chen, X.; Lu, Z. Carbon emissions, energy consumption and economic growth: Evidence from the agricultural sector of China's main grain-producing areas. *Sci. Total Environ.* **2019**, *665*, 1017–1025. [CrossRef] [PubMed]
27. Chen, S.; Yang, J.; Kang, X. Effect of Fiscal Expenditure for Supporting Agriculture on Agricultural Economic Efficiency inCentral China—A Case Study of Henan Province. *Agriculture* **2023**, *13*, 822. [CrossRef]

28. Yasmeen, R.; Tao, R.; Shah, W.; Padda, I.; Tang, C. The nexuses between carbon emissions, agriculture production efficiency, research and development, and government effectiveness: Evidence from major agriculture-producing countries. *Environ. Sci. Pollut. Res.* **2022**, *29*, 52133–52146. [CrossRef] [PubMed]
29. Jin, S.; Lin, Y.; Niu, K. Green transformation of agriculture driven by low carbon: Characteristics of China's agricultural carbon emissions and its emission reduction path. *Reform* **2021**, *5*, 29–37.
30. Chen, J.; Cheng, S.; Song, M. Changes in energy-related carbon dioxide emissions of the agricultural sector in China from 2005 to 2013. *Renew. Sustain. Energ. Rev.* **2018**, *94*, 748–761. [CrossRef]
31. Ma, Y.; Zhang, L.; Song, S.; Yu, S. Impacts of Energy Price on Agricultural Production, Energy Consumption, and Carbon Emission in China: A Price Endogenous Partial Equilibrium Model Analysis. *Sustainability* **2022**, *14*, 3002. [CrossRef]
32. Wang, X. Changes in CO_2 Emissions Induced by Agricultural Inputs in China over 1991–2014. *Sustainability* **2016**, *8*, 414. [CrossRef]
33. Chen, X.; Xu, X.; Lu, Z.; Zhang, W.; Yang, J.; Hou, Y.; Wang, X.; Zhou, S.; Li, Y.; Wu, L.; et al. Carbon footprint of a typical pomelo production region in China based on farm survey data. *J. Clean. Prod.* **2020**, *277*, 124041. [CrossRef]
34. Zhang, L.; Ruiz-Menjivar, J.; Tong, Q.; Zhang, J.; Yue, M. Examining the carbon footprint of rice production and consumption in Hubei, China: A life cycle assessment and uncertainty analysis approach. *J. Environ. Manag.* **2021**, *300*, 113698. [CrossRef]
35. 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]
36. Cheng, K.; Pan, G.; Smith, P.; Luo, T.; Li, L.; Zheng, J.; Zhang, X.; Han, X.; Yan, M. Carbon footprint of China's crop production-An estimation using agro-statistics data over 1993–2007. *Agric. Ecosyst. Environ.* **2011**, *142*, 231–237. [CrossRef]
37. Wang, Z.; Zhang, J.; Zhang, L. Reducing the carbon footprint per unit of economic benefit is a new method to accomplish low-carbon agriculture. A case study: Adjustment of the planting structure in Zhangbei County, China. *J. Sci. Food Agric.* **2019**, *99*, 4889–4897. [CrossRef] [PubMed]
38. Wang, Z.; Chen, J.; Mao, S.; Han, Y.; Chen, F.; Zhang, L.; Li, Y.; Li, C. Comparison of greenhouse gas emissions of chemical fertilizer types in China's crop production. *J. Clean. Prod.* **2017**, *141*, 1267–1274. [CrossRef]
39. Liu, C.; Cutforth, H.; Chai, Q.; Gan, Y. Farming tactics to reduce the carbon footprint of crop cultivation in semiarid areas. A review. *Agron. Sustain. Dev.* **2016**, *36*, 4. [CrossRef]
40. Xiong, C.; Chen, S.; Xu, L. Driving factors analysis of agricultural carbon emissions based on extended STIRPAT model of Jiangsu Province, China. *Growth Chang.* **2020**, *51*, 1401–1416. [CrossRef]
41. Huang, W.; Wu, F.; Han, W.; Li, Q.; Han, Y.; Wang, G.; Feng, L.; Li, X.; Yang, B.; Fan, Z.; et al. Carbon footprint of cotton production in China: Composition, spatiotemporal changes and driving factors. *Sci. Total Environ.* **2022**, *821*, 153407. [CrossRef]
42. Xu, B.; Lin, B. Factors Affecting CO_2 Emissions in China's Aagriculture Sector: Evidence from Geographically Weighted Regression Model. *Energy Policy* **2017**, *104*, 404–414. [CrossRef]
43. Tang, Y.; Chen, M. Impact Mechanism and Effect of Agricultural Land Transfer on Agricultural Carbon Emissions in China: Evidence from Mediating Effect Test and Panel Threshold Regression Model. *Sustainability* **2022**, *14*, 3014. [CrossRef]
44. 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]
45. Nabavi-Pelesaraei, A.; Abdi, R.; Rafiee, S.; Shamshirband, S.; Yousefinejad-Ostadkelayeh, M. Resource Management in Cropping Systems Using Artificial Intelligence Techniques: A Case Study of Orange Orchards in North of Iran. *Stoch. Environ. Res. Risk. Assess.* **2015**, *30*, 413–427. [CrossRef]
46. Wang, R.; Zhang, Y.; Zou, C. How does Agricultural Specialization Affect Carbon Emissions in China? *J. Clean. Prod.* **2022**, *370*, 133463. [CrossRef]
47. Wang, W.; Liu, L.; Liao, H.; Wei, Y. Impacts of Urbanization on Carbon Emissions: An Empirical Analysis from OECD Countries. *Energy Policy* **2021**, *151*, 112171. [CrossRef]
48. Liu, H.; Wen, S.; Wang, Z. Agricultural Production Agglomeration and Total Factor Carbon Productivity: Based on NDDF–MML Index Analysis. *China Agric. Econ. Rev.* **2022**, *14*, 709–740. [CrossRef]
49. You, L.; Spoor, M.; Ulimwengu, J.; Zhang, S. Land Use Change and Environmental Stress of Wheat, Rice and Corn Production in China. *China Econ. Rev.* **2011**, *22*, 461–473. [CrossRef]
50. Zhang, Y.; Long, H.; Li, Y.; Ge, D.; Tu, S. How does Off-farm Work Affect Chemical Fertilizer Application? Evidence from China's Mountainous and Plain Areas. *Land Use Policy* **2020**, *99*, 104848. [CrossRef]
51. Jiang, S.; Zhou, J.; Qiu, S. Digital Agriculture and Urbanization: Mechanism and Empirical Research. *Technol. Forecast. Soc. Chang.* **2022**, *180*, 121724. [CrossRef]
52. Zhao, Z.; Peng, P.; Zhang, F.; Wang, J.; Li, H. The Impact of the Urbanization Process on Agricultural Technical Efficiency in Northeast China. *Sustainability* **2022**, *14*, 2144. [CrossRef]