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Original Research

Understanding the Carbon Footprint of Chinese Agriculture: An Analysis of Consumption-Driven Environmental Impact

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Abstract

Agriculture is the link between sustainable development and human nutrition and health. Increasing carbon emissions from agriculture threaten ecosystems and human living conditions. However, the level of agricultural emissions in China and uncertainties in the global supply chain limit the implementation of more sustainable agricultural policies in China. This paper aims to assess the environmental impacts of Chinese agriculture from the perspective of consumption carbon emissions. This paper adopts a multi-regional environmental input-output model, uses the global supply chain to identify major trade partners and key industries, and estimates China's domestic agricultural carbon emissions from the perspective of intermediate product input industries. Then, from the perspective of the country (region) and intermediate product input industry, we estimate the embodied carbon of China's agriculture in international trade. Finally, based on the structural decomposition analysis, we factor out the changes in carbon emissions embodied in Chinese agriculture from the demand and supply sides. The findings underscore that energy supply, crop cultivation, livestock farming, machinery and equipment manufacturing, food production, and electrical equipment manufacturing are the primary drivers behind the growth in carbon emissions. According to the SDA decomposition results of the global supply chain, the major partners of China's agricultural sector, which are also the top ten carbon emission sources, can be roughly divided into four categories: developed countries with a long geographical distance from China, BRIC countries, Asian neighbors and Taiwan region. The results of the factor decomposition analysis reveal that the surge in carbon emissions is primarily attributable to increased demand and decreased production emission efficiency. In contrast, advancements in industry-wide technology play a key role in reducing carbon emissions. Conclusively, this study provides scientific basis and policy recommendations for formulating

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sustainable agricultural development strategies and protecting the ecological environment, which is expected to provide an important reference for solving the problem of global climate change.

Keywords: agriculture, low-carbon development, input-output model, structural decomposition analysis, embodied carbon

Introduction

In the current context of global sustainable development, agriculture, as an important economic pillar and a key component of the ecosystem, bears the important responsibility of maintaining ecological balance and achieving economic sustainability. As the largest agricultural country, China's agricultural economy has grown steadily. The primary industry's added value represents 7.12% of GDP in 2023, up 4.1% from the previous year. The total grain output exceeded 650 million tons for eight straight years, up 1.3% from the preceding year [1]. In 2001, China's agricultural import and export trade was less than $30 billion, and in 2023, agricultural import and export trade was $333.04 billion [2]. However, rapid economic expansion and environmental degradation often coincide [3]. From the perspective of the rapid development of the agricultural economy and global trade, environmental hazards have also increased, further confirming this view [4, 5]. Consumer carbon emissions from Chinese agriculture are increasingly becoming one of the key issues constraining sustainable development.

According to the Food and Agriculture Organization of the United Nations (FAO), agriculture generates about 17% of global greenhouse gas (GHG) emissions. When food production and other related activities are considered, the share rises to 21%-37%, making it the second largest source of global GHG emissions. Agri-food systems generated 21% of the world's carbon emissions, 53% of methane emissions, and 78% of nitrous oxide emissions in terms of individual GHGs in 2019. Between 1990 and 2019, while emissions from the global agri-food system increased by 16%, its share of total emissions declined from 40% to 31%, and emissions per capita also fell from 2.7 tonnes of carbon dioxide to 2.1 tonnes. When China's carbon emissions spiked in the early 2000s, there was a distinct downward trend in the proportion of agricultural greenhouse gases released, which afterward stayed at 7%-8%. Despite this, maintaining grain output at more than 650 million tons is required to achieve the agricultural development aim of assuring fundamental self-reliance in grains and complete safety in food rations. As a result, more energy, farm machinery, fertilizers, and pesticides will be invested in agriculture, resulting in more GHG emissions [6-8].

A high-quality ecological environment is recognized as a critical component of sustainable economic development. Numerous studies have confirmed that the degree of improvement in environmental quality heavily depends on the degree of reduction in carbon emissions. Organization for Economic Cooperation and Development figures show that agricultural carbon emissions' overall volume and structural percentage differ significantly across countries and regions. As a proportion of total volume, China's agricultural carbon emissions are consistently greater than those in Europe and the United States. If we ignore the carbon emissions of agriculture-related industries in the global supply chain and the differences in production patterns, it won't be easy to achieve the development goal of low-carbon agriculture. Since China acceded to the World Trade Organization (WTO) in 2001, the country has become increasingly dependent on imports of some high-quality and organic high-end agricultural products while gradually increasing the import demand for some intermediate inputs [9, 10]. According to the data of the FAO report, China's agricultural products imports $234.11 billion in 2023, down 0.3% year on year. It is undeniable that agriculture, as the primary industry, provides raw materials for food processing, furniture processing, and other related manufacturing industries downstream of the supply chain, in addition to direct sales of agricultural products [11], which plays a crucial role in achieving global food security. However, as geographic distances have grown due to increased global trade, transportation-related GHG emissions have progressively increased [12]. The concept of "food miles" has led to a wave of research. It is used to assess the energy consumption, carbon footprint, and other environmental impacts of food generated during transportation.

There is a major dilemma in promoting low-carbon agriculture in China since the environmental impact of Chinese agriculture on the global agricultural supply chain is not clear. On the one hand, China entered a period of decoupling food security and carbon emissions in 2003. The amount of grain produced has increased quickly, whereas the agricultural carbon emissions and the carbon intensity per unit of grain production have progressively decreased. On the other hand, China's large population base leads to the consumption of more agricultural by-products. Regarding emissions reduction from farming, China's plantation production has a large GHG emissions base and lacks disruptive key technologies to increase production and reduce emissions [13]. In terms of emissions reduction from the breeding industry, compared with developed countries, China's livestock and poultry farming is large and in a stage of transformation and upgrading. Comparing China's agricultural sector to that of developed countries, there is a significant disparity between its output level and reproductive efficiency, and the GHG emission factor per animal unit is considerable.

Meanwhile, China's agricultural imports are diversified to include developing and developed countries. The energy consumption efficiency of these agricultural trading partners likewise varies greatly. Some people have already achieved the energy transition and possess cutting-edge technologies for reducing emissions. Therefore, it is difficult to define whether China should increase its agricultural imports or consume more domestic products. However, environmental pressure requires China to adopt a firm path of low-carbon agriculture, which is not only influenced by the traditional concept of self-sufficiency but also by the upgrading of consumers' food consumption structures [14].

Existing studies mainly assess the impact of agriculture on climate change from two perspectives. Most academics will evaluate the direct emissions inside the agricultural sector, which is the most common evaluation perspective. It directly assesses the carbon dioxide produced by agricultural manufacturing. For example, Ji et al. (2024) [15] estimated agricultural carbon emissions from data on fertilizers, agricultural films, pesticides, and diesel fuel for agricultural machinery, revealing the key determinants of China's agricultural carbon emissions from within the agricultural sector. Some scholars have also focused on the study of implied carbon emissions in domestic supply chains based on a production perspective [16] or from a global perspective to determine the decoupling of energy consumption from agricultural economic growth [17]. Further, some scholars have analyzed the spatial and temporal differences in carbon footprint intensity and the factors influencing it in 31 provinces in China from 1997 to 2019 from the perspective of agricultural carbon sinks [18].

Based on the research status, this paper focuses on assessing the environmental impacts of Chinese agriculture along the global supply chain. The main contributions of this paper are as follows:

(1) Traditional studies have mainly focused on carbon emissions in the domestic agricultural production process, often ignoring the hidden carbon emissions transmitted in the global trade chain [15, 18]. The first contribution of this paper is to assess the hidden carbon emissions of Chinese agriculture in international trade from the perspective of the global supply chain, which broadens the horizon of traditional studies. Specifically, the article examines the carbon emissions generated during the production, processing, and transportation of agricultural products exported from China. Although these emissions do not occur directly within China, they are closely related to Chinese agricultural activities. The study not only focuses on domestic carbon emissions but also integrates the impacts of transnational carbon emissions, thus providing a more comprehensive framework for assessing the environmental impacts of Chinese agriculture. This contribution fills the gap in the existing literature on assessing agricultural carbon emissions in the context of global trade and provides a new perspective on international trade policy and carbon emissions governance.

(2) The second important contribution of this paper is to assess agricultural carbon emissions from a consumer-side perspective, emphasizing the impact of consumer demand on carbon emissions. Traditional carbon footprint assessment focuses on the production side, analyzing the direct carbon emissions generated during agricultural production, such as energy consumption, fertilizer, and pesticide use. In contrast, the consumption side of carbon emissions focuses on the carbon emissions of agricultural products in cross-border transportation, processing, and packaging. Especially in the context of globalized trade, the consumer demand for export products not only increases carbon emissions in the producing countries but also may transfer carbon emissions to the consuming countries. Through this perspective, this paper bridges the gap of traditional studies and reveals the distribution and transfer of carbon emissions in cross-border trade. It suggests that certain countries indirectly increase carbon emissions by importing Chinese agricultural products, further highlighting the profound impact of Chinese agriculture on the global environment.

(3) Existing studies usually focus on internal factors of agriculture, such as technology, socio-economic conditions, and natural factors [16, 18], and less on the impact of global supply chains and international trade on carbon emissions. The third contribution of this paper is to comprehensively analyze the impact of external factors such as domestic production conditions, international market demand, and import and export structure on carbon emissions from the perspective of international trade. The paper reveals the mechanism of domestic and international trade structure on carbon emissions through a multi-regional environmental input-output model, combined with sub-regional and sub-intermediate product input industry analysis. In particular, this paper reveals the complex interrelationship between international trade and China's agricultural carbon emissions by comparing the impacts of factors such as place of production, consumer market, and input selection on changes in agricultural carbon emissions. This provides a valuable theoretical basis for optimizing carbon emission management in global supply chains.

(4) This paper analyzes the supply and demand factors of China's agricultural carbon emissions from a macro perspective. It is found that changes in the structure of domestic and foreign final demand trade have differential impacts on changes in China's agricultural carbon emissions. In contrast, the impact of trade involving domestic and foreign intermediate product inputs is observed to increase carbon emissions. This finding challenges some of the existing views and provides new perspectives to understand the complex impacts of changes in global supply chains and trade

patterns on China's agricultural carbon emissions, highlighting their critical role.

The following is how the paper is set up: The methodology and data sources are the main topics of section 2. The results are displayed in section 3. Section 4 examines the results as mentioned above. The conclusions of this study are summarized in section 5, and implications are provided for the advancement of low-carbon agriculture in China.

Methods and Data Sources

Analysis of the Applicability of Research Methods

The Input-Output model (IOA), due to its low implementation cost, is widely used to analyze potential linkages in macro and micro-economies. Environmental Input-Output Analysis (EIO), which incorporates environmental and energy accounts, was created to investigate how production and consumption affect the environment. EIO studies environmental issues caused by final demand in a particular industry, such as carbon and water footprints. With the rise of this research method, some scholars have proposed to use the Multi-Regional Environmentally Expanded Input-output (MREEIO) model to study the relationship between the role of carbon emissions on a global scale.

With the establishment of global input-output databases, such as WIOD and EXIOBASE, studying the international carbon emissions caused by national trade is feasible. Currently, the Single-Region Input-Output model (SRIO) is frequently used to examine how a particular industry affects the environment [14, 19, 20], but this method is more suitable for studying the domestic level environmental impact issues. For studying global environmental impact issues, the Multi-Regional Input-Output (MRIO) model is more appropriate. Because it integrates the production technology, intermediate product input, and final product consumption of different countries into the same research framework, it has a better simulation effect.

Furthermore, there are two main estimation mechanisms to evaluate carbon emissions, which are calculated from the production side and the consumption side, respectively. There are production-based accounting (PBA) and consumption-based accounting (CBA). The biggest difference between the two is accounting for indirect carbon emissions. PBA mainly assesses carbon emissions directly generated in the production process, while CBA assesses both direct and indirect carbon emissions. The Intergovernmental Panel on Climate Change (IPCC) promotes PBA because it believes greenhouse gas producers should be held accountable for environmental protection [21]. In contrast, the CBA abandons the principle of production responsibility. The idea is that regardless of the source of the product, the consumer should bear the responsibility for carbon emissions since he or she enjoys the actual utility brought by the product [22, 23]. According to the consumption perspective, some academics have recently investigated the carbon emissions of the food sector, service sector, and building sector [24-27]. However, few researchers have examined the agriculture sector's carbon emissions from the consumption standpoint.

Moreover, input-output analysis methods are widely used in academia to study climate change. Radwan et al. (2022a) [28] used input-output tables to analyze changes in energy use in Egypt's overall economy from 1972 to 2014. A structural decomposition analysis of the resulting carbon dioxide drivers follows this. Lin and Guan (2023) [29] used an MRIO model to identify the main trading partners and cooperating industries of China's food sector, from which they accounted for the carbon footprint and further decomposed the drivers of the change in carbon footprint. Through input-output analysis, Jiang et al. (2022) [30] calculated the carbon dioxide emissions of the Chinese building industry. Additionally, it has been emphasized that food and farming production are the key contributors to the rise in GHGs in China [31]. Academics have widely utilized input-output modeling to evaluate how a particular industry affects the environment. However, studies on carbon emissions in the agricultural sector are scarce and mostly restricted to domestic supply chains. In this study, we consider carbon emissions from both the domestic and global agriculture supply chains.

There are two main research methods in academia for assessing the influencing factors of inter-annual changes in carbon emissions: index decomposition analysis (IDA) and structural decomposition analysis (SDA). Among them, SDA must use input-output tables. The differences between the two include the following: first, IDA can only study the direct effects, while SDA can also analyze the indirect impacts of determinants. Second, SDA can break down more drivers but requires higher-quality data. Of course, SDA also has an obvious problem in that the decomposition is not unique, and the average of two polar decompositions is encouraged to solve this problem [32].

In conclusion, this study will employ an MREEIO model to evaluate Chinese agriculture's consumption-based carbon footprint within the international supply chain. The SDA model will also be used to explore further the variables affecting changes in carbon emissions.

Consumption-Based Multi-Regional Input-Output Model (MRIO)

This research attempts to assess the effect of agriculture on environmental change from the consumption perspective, concentrating on carbon emissions brought on by changes in final demand. The MRIO model thus better meets the requirements of the study goal. The formula for implicit carbon emissions depending on consumption is:

$$C = e(I - A)^{-1}Y \tag{1}$$

Where C represents the carbon emissions implicit in global trade; e represents the row vector of carbon emission intensity per unit, with the economic meaning of the ratio of carbon emissions per unit to production per unit. A represents the matrix of intermediate product input demand. The diagonal sub-matrix represents domestic demand for intermediate goods inputs, and the off-diagonal matrix represents foreign demand for intermediate goods inputs, which is imports. Setting the demand for the non-agricultural sector in Y to zero, Y represents the final demand for the agricultural sector. $L = e(I - A)^{-1}$ is the Leontief inverse matrix. In this case, to explore the carbon emissions from the agricultural sector in a certain region, the final demand from the non-agricultural sector in the region is set to zero. In addition, to achieve a detailed decomposition of carbon emission sources, the row vector of carbon emission intensity e is diagonalized. The results will give the emissions caused by each industry in each region due to the final demand in our region of interest. By aggregating the results by region or industry, supply chain analysis can be performed at the regional and industry level.

Structural Decomposition Analysis (SDA)

SDA helps to explore the direct and indirect effects of determinants. The most popular drivers in SDA are the energy intensity effect, population growth effect, technological progress effect, and ultimate demand structure change effect [33-35]. In this article, trade-related aspects must be considered to examine the consumption-based carbon footprint of Chinese agriculture in the worldwide supply chain. To further differentiate the influence of domestic and international trade on variations in carbon emission levels. In this paper, we distinguish the domestic implied carbon C_{dom} and foreign implied carbon C_{for} by setting the foreign element or domestic element of the carbon emission intensity e determinant to zero, so the decomposition of the consumption-based carbon emission of Chinese agriculture can be rewritten as follows:

$$C_{dom} = e_{dom}(I - T \otimes H)^{-1}(F \otimes B)\hat{d} \tag{2}$$

$$C_{for} = e_{for}(I - T \otimes H)^{-1}(F \otimes B)\hat{d}\hat{p} \tag{3}$$

The prior L and Y can be further broken down into the ultimate demand trade structural change effect and the intermediate product input trade effect. ⊗ known as the Hadamard product, which mathematically means element-by-element multiplication. The Leontief inverse matrix L is decomposed into two drivers: T represents the effect of input trade in intermediate products, and H refers to the influence of overall technological change in production. Final demand Y is further decomposed into four drivers. Where B represents the ultimate demand change effect, F represents the ultimate demand trade effect, D represents the per capita ultimate demand change effect, and P represents the population change effect. The D and P determinants are also to be diagonalized.

Of course, the consumption-based carbon emissions change ΔC can also be written as the sum of the various drivers, where ΔQ is the carbon emissions intensity effect. This is shown below:

$$\Delta C = \Delta Q + \Delta T + \Delta H + \Delta F + \Delta B + \Delta D + \Delta H \tag{4}$$

Based on previous research experience, the results of polar decomposition have incomparable advantages, and the calculation results are very close to the ideal decomposition results. The two polar decomposition types proposed by Dietzenbacher and Los in 1998 are averaged in this study. The final decomposition results are shown in Appendix B.

Data Sources

One need for using the MRIO model is having access to high-quality global data. The World Input-Output Database (WIOD) provided the information used in this study. This database contains macroeconomic datasets for 56 industries, 44 countries or regions, and provides corresponding environmental accounts and carbon emissions. Additionally, we chose this database since it only offers equivalent global IO tables for our structural decomposition analysis. In addition, the carbon emission data collected by WIOD based on the residence principle is more in line with the research objective of this paper.

WIOD is based on available data officially published by statistical agencies. The high-quality database broadly represents countries and regions that account for more than 85% of global GDP. However, due to data availability, the latest published version, 2016, only includes input-output data tables from 2000 to 2014. Before 2014, most countries had not paid fundamental attention to carbon emissions. Quantifying the sources of carbon emissions from China's agriculture in global trade, with little policy intervention, is critical to achieving effective carbon emission reductions. By clearly presenting carbon emissions from all aspects of agriculture, it can provide data to support the development of emission reduction strategies, help address environmental risks, and reduce production costs while not being time-bound[29, 36, 37]. This quantitative approach marks the first steps in reducing carbon emissions in agriculture and its upstream and downstream businesses and avoids 'false reductions' following policy interventions.

For data matching, Corsatea et al. (2000) [38] carbon emission data covering the years 2000-2014 will be used. The United Nations Framework Convention on Climate Change, NAMEA-Air, and the energy accounting of WIOD comprise the three primary parts of the carbon emission of the WIOD database. Moreover, the World Bank provides the population database. In addition, to avoid the influence of monetary inflation and other occurrences in various years on the estimation results of carbon emissions, it is necessary to make full use of the input-output tables of the previous year's prices and the current prices provided by the WIOD database. Suppose only the previous year's price of the last year of the sub-period is subtracted from the current price of the first year. There will be residual price changes, and the estimation results will be seriously biased. In this paper, to eliminate the price effect, the correct approach should derive the volume change for each year separately and add up the years to get the volume change for the sub-period.

Trends in China's Agricultural Carbon Emissions

Empirical Results

The first part of this essay looks at the sectoral and regional origins of China's agricultural consumption-based carbon emissions. The top 10 sectors and countries/regions in terms of carbon emissions from agriculture in China are shown in Tables 1 and 2. From the perspective of industry, electricity supply, crop and animal industry, machinery and equipment manufacturing, furniture manufacturing, and food manufacturing are the primary carbon source industries for agriculture in China. Machinery and equipment maintenance, mining, electrical equipment manufacturing, fisheries and aquaculture, and accommodation and food services also rank among the top ten sources of emissions. Further analysis of China's agricultural carbon source sectors is shown in Table 1, which divides the study's temporal frame into four sub-periods.

Before 2004, carbon emissions from Chinese agriculture increased quickly. Since then, except for 2010, carbon emissions from Chinese agriculture began to decline steadily. Among these, the crop and animal industries have emerged as China's agriculture's major carbon emissions reduction source. In terms of the top ten sources of carbon dioxide emissions from China's agriculture, the electricity supply steadily overtook the crop and animal industry to rank first in carbon emissions. Of course, it was the primary contributor. From 2000 to 2014, the agricultural and animal industries always placed second in carbon emissions; it is the second largest source of emissions. Fisheries and aquaculture were tenth in carbon emissions from 2000 to 2003, but since then, they have progressively improved to ninth. In addition to the main contributors to Chinese agriculture, other industries, including the production of machinery and equipment, the production of food, and the production of electrical equipment, have consistently grown at exceptionally high rates in carbon emissions. In contrast, machinery and equipment repair, furniture manufacturing, mining, accommodation, and food services emissions have gradually declined, and this has helped the agriculture sector reduce its carbon emissions between 2004 and 2014.

Table 2. Sources of imported carbon emissions from China's agriculture from a regional perspective.

Country/ Region	Value (Mt)	Country/ Region	Value (Mt)
RUS	18.67	IND	11.04
TWN (CHN)	17.79	AUS	6.43
USA	15.02	IDN	5.72
KOR	13.81	BRA	5.47
JPN	12.08	CAN	4.57

Using the global supply chain as a starting point, five countries, including Brazil, the United States, Australia, Canada, and India, lead to a relatively high carbon emissions growth rate in China's agriculture, as shown in Table 2. By separating the study period into four sub-periods, more details may be discovered in Appendix Table A2. In the early stage, Russia was the importer with the most significant increase in China's agricultural consumption-based carbon emissions. Subsequently, Taiwan and the United States successively surpassed Russia as the regions with the largest share of the change in carbon emissions from China's agricultural imports. China's agricultural import carbon emission sources mainly come from industrialized nations such as the United States, Russia, Japan, Australia, South Korea, and Canada. As global demand for China's agriculture

Table 1. Sources of agricultural carbon emissions in China from an industry perspective.

Industry	Value (Mt)	Industry	Value (Mt)
Electricity supply, etc.	1159.67	Repair and installation of machinery and equipment	91.74
Crop and animal industry	817.69	Mining and quarrying	80.31
Chemical industry	390.68	Manufacture of electrical equipment	60.62
Manufacture of furniture; other manufacturing	107.77	Fishing and aquaculture	48.77
Food manufacturing, etc.	96.29	Accommodation and food service activities	37.14

Table 3. China's agricultural import carbon emission sources from the perspective of region and industry.

Industry	Country/Region	Value (Mt)
Electricity supply, etc.	RUS	7.68
Chemical industry	TWN	6.95
Electricity supply, etc.	TWN	5.39
Chemical industry	KOR	4.71
Mining and quarrying	IND	4.24
Electricity supply, etc.	USA	3.68
Chemical industry	JPN	3.57
Chemical industry	RUS	3.27
Electricity supply, etc.	KOR	3.26
Electricity supply, etc.	IND	3.21
Chemical industry	USA	3.04
Crop and animal industry	USA	2.82
Mining and quarrying	RUS	2.66
Crop and animal industry	BRA	2.54
Electricity supply, etc.	JPN	2.47
Manufacture of basic metals	JPN	2.33
Electricity supply, etc.	AUS	2.28

increases, developing countries such as Brazil, India, and Indonesia have also become importers of China's agricultural carbon emissions.

The decomposition of Chinese agricultural carbon sources will be carried out in regional and industrial dimensions to examine further whether industries or goods contribute to the rise in carbon emissions from Chinese agriculture. According to Table 3, among the top ten trading partners, Russia, South Korea, and Taiwan generate carbon emissions from the electricity supply and chemical product manufacturing sectors. In contrast, the US and India's carbon emissions to Chinese agriculture are concentrated in the electricity supply sector, with India also involved in the mining sector. In comparison, Japan has concentrated on chemical product manufacturing, metal manufacturing, and electricity supply. Data through sub-periods show that the US and Brazil's crop and animal industries also ranked among the top ten sources of emissions from 2010-2014. Appendix Table A3 provides more comprehensive information.

Discussion of Research Results

The previous section reveals domestic agricultural production and its hidden contribution to global carbon emissions through an in-depth analysis of carbon emissions from Chinese agriculture and its upstream and downstream supply chains. In particular, the transfer of carbon emissions under the framework of global supply chains is addressed. The study not only focuses on the traditional sources of carbon emissions during domestic agricultural production but also looks at the carbon emissions from the production, processing, and transportation of exported agricultural products. Thus, it broadens the horizon of carbon emission assessment and provides a new theoretical basis and practical direction for policymaking and global climate change governance.

First, from the analysis of carbon emission sources in China's agricultural sector, electricity supply, planting and animal husbandry, manufacturing of machinery and equipment, food manufacturing, and electrical equipment manufacturing are the main sources of carbon emissions. With the comprehensive advancement of agricultural mechanization, China's agricultural production has been gradually industrialized, with the comprehensive mechanization rate of plowing, planting, and harvesting reaching 72.03%. Among them, the rates of mechanized plowing, sowing, and harvesting reached 86.42%, 60.22%, and 64.66%, respectively, reflecting the development of Chinese agriculture in a more energy-intensive direction. The spread of mechanization has significantly improved agricultural productivity, but it has also led to an increase in energy consumption. In particular, the reliance on coal as the main energy source has led to a continuing upward trend in carbon emissions from the agricultural sector. As mentioned in this paper, the huge demand for energy in agriculture and its upstream and downstream industries (e.g., electricity supply, machinery and equipment manufacturing, and food manufacturing) further complicates the issue of carbon emissions. This must be considered alongside the impacts of energy mix and industrial transformation.

In particular, the plantation and livestock industries, which have traditionally been the "mainstay" of agricultural carbon emissions, remain the most significant sources of emissions. In the plantation industry, methane emissions from paddy fields, nitrous oxide emissions from the use of nitrogen fertilizers, and field incineration all have a significant impact on total carbon emissions. The popularity and use of chemical fertilizers in agriculture have dramatically increased crop yields, but it has also brought about tremendous environmental pressure. Taking nitrogen fertilizer as an example, its production and use generate a large amount of the greenhouse gas nitrous oxide. The greenhouse effect of this gas is 300 times stronger than that of carbon dioxide, further exacerbating the risk of climate warming.

In the livestock sector, methane emissions from animal feeding, especially from the intestinal tract of livestock, and the disposal of manure during the farming process have become important sources of carbon emissions. Although the farming industry has the potential to reduce emissions to a certain extent by improving feed and upgrading management, the demand for energy in large-scale farming still leads to an increase in carbon emissions. In addition, the carbon emissions from feed production, transportation, and energy consumption of farming facilities should not be ignored. Therefore, the reduction of carbon emissions from agriculture not only needs to focus on the innovation of production technology but also emphasizes the synergistic reduction of carbon emissions in the upstream and downstream links of the industrial chain.

By further analyzing the results of the decomposition of domestic supply chains, this paper reveals the changing roles of several industries in agricultural carbon emissions. In particular, the changing trend of carbon emissions in related industries such as machinery and equipment manufacturing, furniture manufacturing, mining, and accommodation and food services reflects part of the effectiveness of China's economic green transformation. The negative growth in carbon emissions in the maintenance of the machinery and equipment sector suggests that energy efficiency in this sector has improved with the increase in agricultural mechanization. Meanwhile, the decline in carbon emissions from the mining sector indicates that resource-intensive industries are gradually realizing energy efficiency improvements, providing important support for China's green economic development. The decline in carbon emissions from these sectors signals the growing role of energy restructuring and technological innovation in promoting the green transformation of agriculture in China.

However, it is worth noting that the growth in carbon emissions remains significant in certain agriculture-related sectors, such as aquaculture and food manufacturing. The steady increase in carbon emissions from aquaculture, in particular, reflects the high emissions characteristic of the farming model. Whether it is freshwater pond aquaculture or factory farming, manure discharge, feed use, and expansion of farming areas during aquaculture will bring about high carbon emissions. The negative impacts of aquaculture on the environment are exacerbated by over-farming and irrational environmental management. Therefore, how to promote an environmentally friendly aquaculture model while safeguarding the needs of agricultural production has become a challenge in future agricultural emissions reduction policies.

In the food manufacturing sector, China, as one of the world's largest food industries and food trading countries, has been experiencing a high rate of growth in carbon emissions. The agricultural sector provides a large amount of raw materials, while food processing is the "hardest hit" area in terms of carbon emissions. The carbon intensity of the food industry is high, especially in the processing, packaging, transportation, and other aspects of energy consumption. As China's food industry continues to grow and the volume of international trade increases, the problem of carbon emissions in this industry is becoming more and more prominent. Therefore, promoting the green transformation of the food processing industry, adopting low-carbon technologies, and optimizing energy use efficiency are important ways to reduce overall agricultural carbon emissions.

To summarize, this section provides a new perspective on the carbon emissions of Chinese agriculture from the perspective of global supply chains. In particular, it provides a more comprehensive assessment of the impact of Chinese agriculture on the global environment after taking into account the implied carbon emissions from cross-border trade. The study shows that carbon emissions from Chinese agriculture not only originate from the domestic production process but are also transferred to other countries and regions through the international trade chain. The globalization of agricultural production has not only changed the spatial distribution of carbon emissions but also made transnational carbon emission governance more and more complicated. Therefore, when formulating agricultural carbon emission policies in the future, it is necessary to take into account the carbon emission factors in the global trade chain.

Analysis of Driving Factors at the Macro Level

Drivers of Consumption-Based Carbon Emission Changes in Chinese Agriculture

As mentioned, Chinese agriculture is moving towards high energy consumption and carbon inputs. The increase in fossil fuels inevitably brings greenhouse gas emissions, and low-carbon agriculture should be seen as a necessary path to develop modern agriculture. From the global agricultural supply chain perspective, the exponential growth of consumer demand for farm products, the development of industrialized agriculture, and the rise of international trade are all likely to increase the carbon footprint of Chinese agriculture. Therefore, based on the SDA model, this paper factorizes the implied carbon emission changes in Chinese agriculture. We further analyze the impact of changes in final demand for agricultural products (B), production emission efficiency (E), population growth (P), rising final individual demand for agricultural products (D), structural changes in last demand trade (F), general production technology advancement (H), and trading patterns of intermediate inputs (T) on the implied carbon emissions of Chinese agriculture. Table 4 and Fig. 1 display the findings of the decomposition based on factors in the local supply chain.

Since 2003, the country has entered a period of decoupling between food security and carbon emissions. As living standards have improved, consumption patterns have shifted from a cereal-based diet to meat and other value-added products such as cereal protein, vegetables, fruits, and nuts, with a relative reduction in demand for bulk commodities. According to the decomposition results of the domestic supply chain structure, the change in final demand (B) leads to

Table 4. Results of decomposition of domestic supply chain structure (Mt).

Influence factor	2000-2003	2003-2006	2006-2010	2010-2014	2000-2014
Changes in final demand	-2.88	-18.32	-8.71	-48.21	-78.13
Final demand per capita	-18.32	-0.48	5.25	6.84	4.51
Emission efficiency of production	15.95	18.51	8.64	14.36	57.46
Trade structure of final demand	-0.66	-0.71	-1.79	-0.84	-4.00
Advances in production technology	-53.61	-82.89	-81.60	-49.16	-267.26
Increase in population	53.46	72.55	76.79	53.22	256.03
Trading of inputs of intermediate products	4.04	3.54	3.58	3.62	14.79

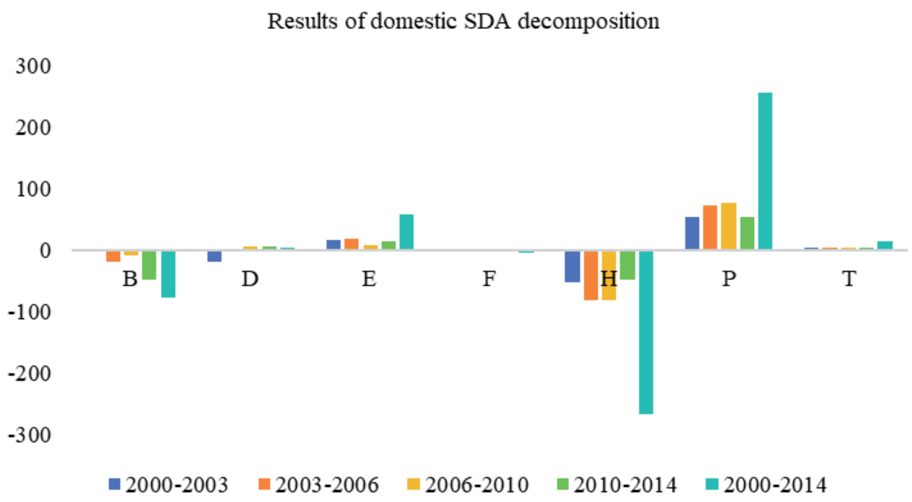

Fig. 1. Decomposition results of domestic SDA
Note: B represents the effect of change in final demand; D represents the effect of change in per capita final demand; E reflects the impact of changing domestic production's emission efficiency; F represents the effect of change in trade structure of the final domestic market; H reflects the impact of change in domestic production technology; P reflects the impact of change in domestic population, and T reflects the impact of trade in domestic intermediate goods inputs.

changes in the consumption structure. Gradually increasing the consumption of animal foods such as poultry meat, eggs, milk, and fish with a low integrated carbon conversion coefficient leads to a moderating trend in agricultural carbon emissions. For each demand (D), the rising demand for agricultural products raises carbon emissions [31]. The increase in carbon emissions is driven by domestic production's emission efficiency (E). Influenced by the traditional concept of self-sufficiency, the population scale effect (P) from domestic population growth has driven an increase in consumption-based carbon emissions from domestic agriculture. It is also the main reason for the increase in China's agricultural carbon emissions from 2000 to 2014. This stems from the fact that an increase in population, driven by per capita final demand (D), triggers an increase in total consumption demand, leading to rising carbon emissions.

In contrast, the structure of domestic ultimate demand trade (F) led to decreased carbon emissions. In terms of overall production technology progress (H), technological advances are conducive to improving production efficiency, optimizing production structures, and reducing energy consumption per unit, thereby reducing carbon emissions. Lower carbon emissions are primarily attributable to advancements in production technology. Regarding the domestic trade effect of intermediate inputs (T), the trade structure of intermediate agricultural inputs in China is moving towards high pollution and energy consumption. Therefore, it accelerates the increase of implied carbon emissions in Chinese agriculture.

Further factor decomposition of foreign carbon emission changes based on foreign supply chains. This makes it easier to comprehend the effects of the ultimate demand trade structure (F) and intermediate product input trading effects (T) on the implied carbon emissions of Chinese agriculture internationally. Table 5 and Fig. 2 display the results. For trade in intermediate product inputs (T), domestic inputs of intermediate products are gradually able to meet increased consumer demand, driven by substitution effects, leading to more minor changes in demand for foreign intermediate products. The impact of intermediate goods input

Table 5. Results of the decomposition of foreign supply chain structure (Mt).

	2000-2003	2003-2006	2006-2010	2010-2014	2000-2014
Changes in final demand	-0.84	-2.43	0.19	-1.38	-4.46
Final demand per capita	-2.43	0.44	-1.91	-2.99	-1.63
Emission efficiency of production	2.10	2.09	2.83	1.94	8.97
Trade structure of final demand	0.31	0.35	0.98	0.60	2.24
Advances in production technology	-3.93	-6.50	-6.62	-4.66	-21.69
Increase in population	3.82	5.69	6.15	4.98	20.64
Trading of inputs of intermediate products	0.29	0.28	0.29	0.34	1.19

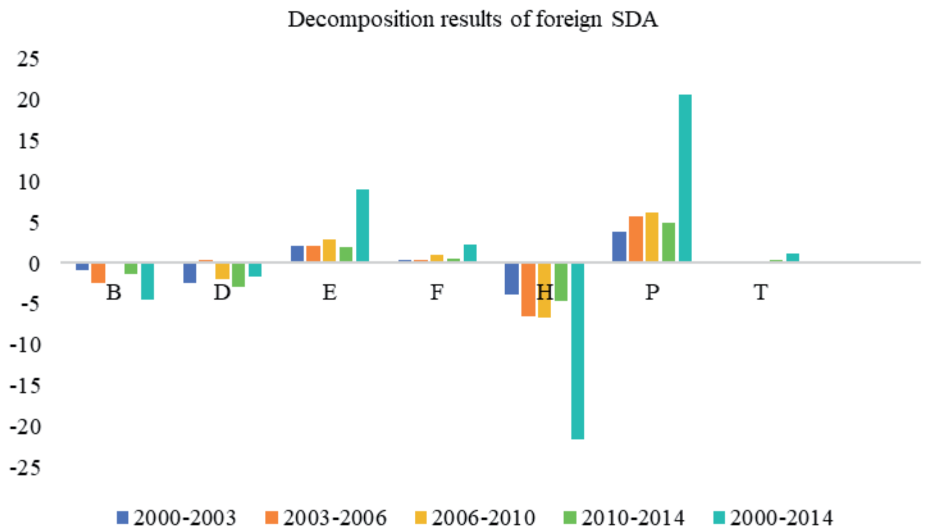

Fig. 2. Decomposition results of foreign SDA
Note: B represents the effect of change in ultimate foreign demand; D represents the effect of change in per capita final foreign demand; E reflects the impact of changing foreign production's emission efficiency; F represents the effect of change in trade structure of the final foreign market; H reflects the impact of change in foreign production technology; P reflects the impact of change in foreign population, and T reflects the impact of trade in foreign intermediate goods inputs.

trade (T) on carbon emissions was relatively stable in the first decade, fluctuating around 0.29. Since 2010, it has gradually driven an increase in consumption-based carbon emissions, but to a lesser extent. From a global perspective, the sum of domestic and foreign intermediate input trade effects is positive, indicating that domestic production technology is less efficient than its counterparts compared to foreign countries. This increases carbon emissions and puts pressure on environmental carrying capacity.

For ultimate demand trade structure (F), local ultimate demand trade structure change F_{dom} decreases carbon emissions. While carbon emissions caused by foreign final demand trade structure change F_{for} show an overall increasing trend except for 2010-2014. However, the change is small compared to other factors, indicating that domestic carbon emissions decreased due to final demand in China's agricultural industry, while foreign implied carbon emissions increased. Regarding economic implications, F represents the proportion of imports of agricultural products in China. The makeup of ultimate demand trade has changed relatively little over time, which shows that the proportion of local production and imports of agricultural products in China has remained broadly stable. This reinforces the existence of a domestic production substitution effect. From a global perspective, the sum of the structural impacts of domestic and foreign final demand trade is negative. This suggests that China is more carbon efficient in its last-demand trade than foreign countries. Furthermore, the two main factors contributing to the rise in carbon emissions in the global supply chain are the population growth effect (P) and the emission efficiency of production (E). Moreover, the critical factor in reducing implied carbon emissions from import trading is the development of industrial technology (E).

Analysis of Drivers of Carbon Emission Changes at the Industry Level

While the previous section focused on analyzing the drivers affecting carbon emission changes in Chinese agriculture, this section will further explore how these drivers affect carbon emission changes at the industry level. Table 6 displays the complete findings of the decomposition. Remarkably, the red portion denotes a rise in carbon dioxide emissions, while the green portion denotes a fall in emissions. The depth of the color represents the degree of impact on carbon emissions change. The detailed industry breakdown is shown in the Appendix. The results show that the emission efficiency change effect of domestic production, E_{dom},

Table 6. SDA decomposition results for major domestic and foreign industries.

SDA decomposition results for major domestic industries from 2000 to 2003

	B	D	E	F	H	P	T
AG	6.76	-0.32	-1.01	-0.19	-15.14	14.91	1.12
MI	-0.24	-0.37	0.54	-0.02	-1.29	1.30	0.10
FO	-1.42	-0.10	0.93	-0.02	-1.18	1.22	0.09
N-EI	-0.77	-0.07	0.39	-0.01	-0.67	0.68	0.05
EI	0.63	-3.16	-1.70	-0.14	-11.65	11.75	0.89
EN	-7.46	-2.88	17.01	-0.27	-21.54	21.45	1.62
SE	-0.01	-0.06	-0.15	-0.01	-0.59	0.59	0.04
TR	-0.37	-0.16	-0.07	-0.02	-1.55	1.56	0.12

SDA decomposition results for major foreign industries from 2000 to 2003

	B	D	E	F	H	P	T
AG	-0.06	0.31	-0.01	0.14	-0.22	0.21	0.02
MI	0.16	0.27	0.15	0.00	-0.35	0.33	0.02
FO	0.00	0.02	0.01	0.00	-0.02	0.02	0.00
N-EI	-0.02	0.04	0.01	0.00	-0.09	0.09	0.01
EI	-0.47	1.05	0.87	0.02	-1.55	1.52	0.11
EN	-0.39	0.83	0.95	0.11	-1.28	1.24	0.09
SE	-0.02	0.06	0.04	0.01	-0.10	0.10	0.01
TR	-0.03	0.25	0.09	0.03	-0.32	0.31	0.02

SDA decomposition results for major domestic industries from 2003 to 2006

	B	D	E	F	H	P	T
AG	11.25	-0.26	-0.26	-0.25	-27.77	23.78	1.16
MI	-0.86	-0.32	-0.42	-0.01	-1.34	1.22	0.06
FO	0.72	0.02	2.04	-0.02	-2.60	2.27	0.11
N-EI	0.07	0.12	0.24	-0.01	-0.99	0.84	0.04
EI	0.48	0.37	0.01	-0.14	-17.18	14.86	0.73
EN	-28.98	-0.37	17.37	-0.26	-30.18	27.10	1.32
SE	-0.14	0.05	0.10	-0.01	-0.94	0.81	0.04
TR	-0.86	-0.09	-0.56	-0.01	-1.88	1.67	0.08

SDA decomposition results for major foreign industries from 2003 to 2006

	B	D	E	F	H	P	T
AG	-0.09	0.20	0.01	0.16	-0.48	0.41	0.02
MI	0.02	0.18	-0.01	0.01	-0.67	0.58	0.03
FO	-0.01	0.00	0.02	0.00	-0.04	0.03	0.00
N-EI	-0.09	0.00	0.04	0.00	-0.11	0.10	0.00
EI	-1.14	-0.19	0.19	0.03	-2.17	1.94	0.10
EN	-0.84	0.11	1.77	0.12	-2.35	2.02	0.10
SE	-0.10	-0.02	0.04	0.01	-0.14	0.13	0.01
TR	-0.18	0.16	0.04	0.03	-0.53	0.47	0.02

SDA decomposition results for major domestic industries from 2006 to 2010

	B	D	E	F	H	P	T
AG	-4.13	-0.12	-0.14	-0.62	-27.76	25.51	1.18
MI	0.49	0.16	0.76	-0.03	-1.43	1.39	0.07
FO	-2.81	0.05	3.14	-0.06	-3.14	3.14	0.15
N-EI	-0.67	0.05	0.27	-0.02	-0.98	0.95	0.04
EI	-7.15	2.92	9.44	-0.38	-17.00	16.03	0.75
EN	6.01	2.20	-4.00	-0.63	-29.02	27.63	1.29
SE	-0.34	0.00	-0.20	-0.02	-0.83	0.78	0.04
TR	-0.11	-0.01	-0.63	-0.03	-1.43	1.36	0.06

SDA decomposition results for major foreign industries from 2006 to 2010

	B	D	E	F	H	P	T
AG	0.09	0.15	0.02	0.42	-0.62	0.54	0.03
MI	0.05	-0.41	0.43	0.01	-0.65	0.62	0.03
FO	0.00	-0.01	0.03	0.01	-0.04	0.04	0.00
N-EI	0.05	0.09	-0.06	0.00	-0.13	0.12	0.01
EI	-0.08	-0.94	1.14	0.09	-1.91	1.77	0.08
EN	0.07	-0.80	1.12	0.35	-2.55	2.39	0.11
SE	-0.02	-0.01	0.04	0.02	-0.14	0.13	0.01
TR	0.02	0.03	0.10	0.07	-0.57	0.53	0.02

SDA decomposition results for major domestic industries from 2010 to 2014

	B	D	E	F	H	P	T
AG	-10.29	0.05	-1.50	-0.26	-14.01	15.10	1.02
MI	-2.12	0.40	0.54	-0.02	-1.08	1.17	0.08
FO	-4.69	0.09	1.79	-0.03	-1.71	1.94	0.13
N-EI	-1.07	0.09	0.10	-0.01	-0.44	0.49	0.03
EI	-13.48	3.16	5.36	-0.18	-11.22	12.05	0.82
EN	-16.26	2.94	7.64	-0.33	-19.51	21.12	1.44
SE	-0.11	0.04	-0.01	-0.01	-0.40	0.45	0.03
TR	-0.20	0.08	0.43	-0.01	-0.80	0.90	0.06

SDA decomposition results for major foreign industries from 2010 to 2014

	B	D	E	F	H	P	T
AG	-0.07	-0.01	-0.11	0.26	-0.51	0.53	0.04
MI	0.10	-0.62	0.23	0.02	-0.43	0.46	0.03
FO	-0.02	-0.03	0.03	0.00	-0.03	0.04	0.00
N-EI	-0.05	0.03	0.06	0.00	-0.09	0.10	0.01
EI	-0.61	-1.13	0.61	0.07	-1.23	1.31	0.09
EN	-0.60	-1.06	1.05	0.20	-1.87	2.00	0.14
SE	-0.02	-0.04	0.02	0.01	-0.10	0.10	0.01
TR	-0.11	-0.13	0.05	0.03	-0.40	0.44	0.03

the domestic population growth effect, P_{dom}, and the input trade effect of domestic intermediate products, T_{dom}, are most responsible for China's agricultural carbon emissions growth. The major portion of them comes from domestic population growth's carbon emissions. Meanwhile, agriculture, energy-intensive industries, and energy supply industries are mostly attributable to increased carbon emissions, while the food and transport industries are secondarily responsible.

The domestic intermediate product input change effect T_{dom} is always positive. In contrast, the local ultimate demand trade structure change effect F_{dom} is always negative. However, compared with other factors, the vertical and horizontal comparisons of the two factors have hardly changed. In addition, the domestic final demand change effect B_{dom} is generally negative on the change of China's agricultural carbon emissions, but different subperiods show different evolutionary paths. Before 2006, it significantly increases carbon emissions from China's agricultural sector, and after 2006, it substantially decreases carbon emissions. One possible explanation is that with the development of the economic level, the change of final domestic demand triggers the upgrading change of the food consumption structure. With the modification of the structure of food consumption, the carbon emission in agriculture, a byproduct of farming activities, would also be altered. For changes in domestic production emission efficiency, E_{dom} increases the actual carbon emissions from agriculture, mainly originating from the food industry, energy-intensive industries, and energy supply industries. Besides, the domestic per capita final demand effect D_{dom} accelerated the increase in carbon emissions after 2006, also originating mainly from energy-intensive and energy supply industries. This is due to the degree of mechanization of agriculture, limited domestic carbon abatement technologies, and the need to improve the energy system.

From an import perspective, in addition to the industries mentioned above, the mining and transport sectors also contributed to the increase in international carbon emissions. Through the results of the SDA decomposition of the main foreign industries, the overall production technology progress H_{for} for agriculture, mining, energy-intensive industries, and energy supply industries reduces the implied carbon emissions. The emission efficiency of production E_{for} and the population growth effect P_{for} of foreign nations contribute to a rise in the amount of carbon emissions, similar to the outcomes of domestic decomposition. This mainly stems from agriculture, mining, energy-intensive, energy supply, and transportation industries. In contrast, the ultimate demand trade structure effect F_{for} and the foreign intermediate product input effect T_{for} are less variable or even unchanged across all industries. This stems from the fact that Chinese agriculture uses more domestic intermediate input products to satisfy demand, which, to a certain extent, replaces inputs of foreign intermediate products. Compared with domestic countries, foreign-developed countries have more advanced carbon emission reduction technology and more perfect energy systems. The reduction of imported products leads to the reduction of emission efficiency of China's agricultural import production and the increase of embodied carbon emissions. Over the years, per capita demand for foreign ultimate products D_{for} has led to a small decline in carbon emissions, mainly originating from mining, energy-intensive industries, and energy supply industries.

Discussion of Research Results

From the results of the SDA decomposition of the global supply chain, China's major partners in the agricultural sector can be broadly categorized into four groups. The first category is advanced countries such as the United States, Australia, and Canada, which are geographically distant from China. The second category is the "BRIC" countries proposed in 2001, namely Brazil, India, and Russia. "South-south Cooperation" is part of the Special Program on Food Security proposed by the Food and Agriculture Organization of the United Nations. Since 2006, Brazil, India, Russia, and China have become important Allies in developing South-South cooperation, and agricultural trade cooperation has become closer. The third group consists of Japan, South Korea, and Indonesia. These countries share the common characteristic of being China's closest Asian neighbors and are geographically close to China. The fourth category is the Taiwan Province of China, which has a "One country, two systems" policy with the Chinese mainland and is one of China's important agricultural trade partners. There are distinctive characteristics of the degree of productivity and development of the four categories of trading partners.

By looking at the sources of carbon emissions from China's agricultural imports from regional and industry perspectives, the results show that although Russia's carbon emissions are on a decreasing trend, it has a large carbon emission base and ranks first in terms of carbon sources, which are mainly concentrated in the energy supply industry. India's carbon emissions increased significantly between 2000 and 2010, mainly concentrated in the mining sector. Brazil's carbon emissions grew faster, concentrated in the plantation and farming sectors. This suggests that while the BRIC countries are deepening their trade cooperation in agriculture, they should also be concerned about the ensuing environmental consequences. In addition, the agricultural trade between the Chinese mainland and the Taiwan Province of China should be further considered. Because Taiwan is the largest source of carbon emissions in China's agriculture, it could be more challenging to achieve the goal of carbon neutrality. Agriculture-related carbon emissions in Japan and South Korea are greater than those in industrialized nations like Canada and Australia, but lower than in the US and Russia. China should consider geographic distance to cut back on long-distance transportation's carbon emissions.

The results of the SDA decomposition indicate that population growth is the main driver of increased agricultural carbon emissions in China, although final demand per capita has a smaller impact on carbon emissions. China's long-standing concept of agricultural self-sufficiency has driven the expansion of agricultural production and production efficiency while meeting domestic demand. While technological advances have slowed the growth of carbon emissions to some extent, the expansion of demand continues to drive an increase in agricultural production activities, exacerbating the pressure on carbon emissions. In addition, despite the relatively low share of agricultural imports, the expansion of demand due to population growth has pushed up the scale of agricultural production, further exacerbating carbon emissions. Overall, population growth indirectly contributes to the rise in agricultural carbon emissions by boosting domestic market demand, expanding agricultural production capacity, and increasing supply chain complexity.

Although technological progress (H) is a key driver of carbon emission reduction in Chinese agriculture [39], improving the emission efficiency of production (E) may sometimes lead to a rise in carbon emissions. This is a reflection of the gaps in the application of carbon reduction technologies and the limitations of the energy mix in the country. China has made significant progress in areas such as precision agriculture and water-saving irrigation, but the low-carbon transition is limited by its continued reliance on traditional, high-carbon energy sources. Meanwhile, improvements in production efficiency are often accompanied by an increase in the scale of production, which increases the intensity of resource use and, thus, the intensity of carbon emissions. This is closely linked to the linkages between domestic and international agricultural production and consumption. Especially in the global supply chain, carbon emissions from Chinese agriculture are often constrained by external factors. In addition, the impact of international trade on China's agricultural carbon emissions has become increasingly significant in the context of globalization. In particular, when imported intermediate inputs come from high-carbon emitting countries, it may lead to carbon emissions transfer, shifting part of the carbon emissions responsibility to China. In summary, in addition to domestic technological progress and production conditions, the impact of international trade structure on China's agricultural carbon emissions also needs attention.

Conclusion and Policy Implications

Understanding the standing of Chinese agriculture in the worldwide supply chain is conducive to promoting green agricultural development and accelerating the process of low-carbon agriculture in China. Therefore, this research explores the origins of Chinese agricultural consumption-based carbon emissions and examines its position at the regional and industry levels. Then, based on the two perspectives of the domestic and international supply chain, it utilizes the SDA model to factorize the changes in implied carbon emissions of Chinese agriculture. Finally, particular proposals for policy are made in light of the research presented above.

First, the energy supply has always been the biggest constraint to the development of low-carbon agriculture in China. The energy supply consistently ranks first in terms of carbon emissions among the top ten industries that contribute to carbon emissions from Chinese agriculture. It is the primary cause of China's agricultural sector's carbon emissions. To date, energy over fertilizers remains the number one source of emissions from agriculture. With the development of agricultural modernization, the level of land intensification and mechanization will continue to increase, and the carbon emissions from energy consumption generated by agricultural production, processing, storage, and consumption are likely to increase dramatically. Beginning in 2016, China explicitly put forward relevant policies to support the development of electric farm machinery and advocated the development of new energy technologies. However, new energy-powered agricultural machinery products have yet to be put into the market on a large scale fast enough, resulting in China's agricultural mechanized production still being dominated by energy consumption. However, with the background of carbon neutrality, it is urgent to accelerate the development of low-carbon agriculture in China. In agriculture, the Chinese government mainly encourages farmers to adapt to and develop green agriculture through subsidies and incentives.

However, it does not specify how to achieve the development of low-carbon agriculture. In addition to focusing on increasing production and reducing consumption in the agricultural sector, the Chinese government should monitor the carbon emissions of important sectors, such as the domestic agricultural supply chain. Then, the highly polluting and energy-consuming industries located upstream and downstream of the supply chain need to be given more attention. China should improve its effective management of sectors like the production of food, chemical products, machinery and equipment maintenance, and energy supply in the future. To lessen the carbon footprint of agricultural energy use, the government ought to promote increased use of clean, renewable energy sources or bioenergy. In addition, reducing the use of chemical fertilizers and pesticides should also be encouraged to increase the capacity of the soil to absorb and sequester carbon.

Second, this is the main factor behind the change in China's agricultural carbon footprint, as population growth drives the increase in total social consumption demand. Therefore, low-carbon agricultural policies should focus on the demand at the consumption end to achieve carbon reduction targets. At the enterprise level, Governments should encourage agricultural enterprises to adopt low-carbon technologies and sustainable production methods, such as precision agriculture and water-saving irrigation, through policies such as financial subsidies and tax incentives. Meanwhile, it should strengthen the supervision of the whole life cycle of agricultural products and optimize the production, transportation, and packaging processes to enhance green efficiency. A low-carbon product standard and certification system should be established to encourage enterprises to obtain green certification, clarify their responsibility for emission reduction, and set emission reduction targets.

At the individual level, the government advocates low-carbon consumption and promotes green food through education, publicity, and incentives. Through subsidy policies, it will support farmers in adopting energy-saving and emission-reduction technologies, promote the transition of agricultural facilities to low-carbon energy, and reduce the use of high-carbon energy. At the same time, it should strengthen the building of green production capacity in rural areas and promote the development of the rural consumption market in a low-carbon direction. While population growth is driving increased demand for agriculture, policies should avoid over-reliance on agricultural expansion to meet demand and instead optimize the allocation of agricultural resources. Examples include rationalizing land-use planning and supporting circular agricultural models to further reduce agricultural carbon emissions.

Third, the key factor in diminishing carbon emissions is the general advancement of production technology. As a result, promoting low-carbon agriculture should encourage accelerated advancements in technology. Self-sufficiency remains one of the concepts of agricultural development in China. It is essential to fundamentally realize energy saving and emission reduction in agriculture rather than relying on imported agricultural products to indirectly reduce carbon emissions. The Chinese government should advocate carbon reduction through green breeding technology innovation. It focuses on researching and developing green breeding techniques for plants and animals, promoting the application of green varieties, conserving water and fertilizer resources, reducing the use of chemical fertilizers and pesticides, and promoting energy conservation and emission reduction in the plantation industry. In addition, the government can also improve technological progress in energy factors, increasing energy use efficiency and developing low-emission energy technologies. Finally, optimizing the energy structure of agriculture will also effectively reduce carbon emissions from agriculture. Increasing the amount of clean energy used, such as solar, geothermal, and wind energy, is one instance.

Fourth, the majority of China's agricultural carbon emissions are attributable to farming and animal husbandry. According to research data released by the FAO in recent years, the livestock industry accounts for 14.5% of human greenhouse gas emissions. As more than 1/6 of the total human greenhouse gas emissions of the livestock industry, its low-carbon green development has become a problem that cannot be ignored. It can be foreseen that, with economic and social development, the public's demand for meat, eggs, milk, and other livestock products will continue to grow. Carbon emissions from the livestock industry and the fishery industry will maintain a sustained growth trend. Therefore, on the one hand, the Chinese government should promote energy conservation and emission reduction in the planting industry. Based on strengthening the ability to ensure food security, it is encouraged to optimize the water irrigation management of rice fields and reduce methane emissions from rice fields. At the same time, the government should also promote good varieties and green and efficient cultivation techniques. On the other hand, to lower the release of pollutants from livestock and poultry manure administration, the Chinese government should encourage precision feeding technology, breed development, and improved resource usage of livestock and poultry dung.

Finally, the implied carbon emissions from agriculture declined from 53.27 Mt to 49.64 Mt, a decrease of 6.8% from 2000 to 2014 in China. The results show that the overall trend declined slightly. As mentioned earlier, the main partners of Chinese agriculture are categorized into four groups. China's agricultural sector should factor in the carbon intensity of each country when selecting trade partners and encourage the selection of partners with high productivity and low carbon emissions. In addition, China can also take geographical distance into account when cooperating with developed countries to reduce carbon emissions from long-distance transportation. Of course, China will give better play to its role in leading and promoting South-South cooperation among the three agencies of the FAO and the Global Initiative for Agricultural Development and will implement the concept of green development in depth.

Limitation

The World Input-Output Database is based on officially published and available data from statistical agencies. Due to data availability constraints, the latest release, the 2016 edition, includes only 14 years of data. This also limits the research year span of this paper to use the most recent data for analysis. Therefore, in the future, the field will be deepened to track updates to this database and deepen the existing research.

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Author Contributions

All authors contributed to the study's conception and design. Nan Feng: Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft; Pei Xu: Conceptualization, Supervision, Project administration, Methodology, Writing - Review & Editing, Visualization. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets analyzed during the current study are available from the first author upon reasonable request.

Conflict of interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript, and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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