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Dynamic Analysis of the Carbon Footprint in Winter Wheat Production Based on Lifecycle Assessment and the LMDI Model: A Case Study of Jiangsu Province in China

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Abstract: This study applies the lifecycle assessment (LCA) to quantify the carbon footprint within the winter wheat production system in Jiangsu Province during 2011–2020. Additionally, the study employs the Logarithmic Mean Division Index (LMDI) to analyze the driving factors behind its changes. The results show that (1) the greenhouse gas emissions from wheat production in the region increased from 4837.8 kgCO_2-eq/hm^2 to 5701.1 kgCO_2-eq/hm^2 with an annual average increase of 95.9 kgCO_2-eq/hm^2; (2) the primary carbon sequestration method for wheat production in Jiangsu Province is straw returning; (3) the carbon footprint of wheat at yield scale and value scale generally increased during the period, whereas the carbon footprint at cost scale decreased over the years; (4) the driving factors effects' cumulative contribution rates are as follows: economic level > population size > employment structure > production structure > production efficiency. This research explores the dynamic changes and driving factors influencing the carbon footprint associated with winter wheat production in Jiangsu Province, which could provide theoretical references for the future clean production of winter wheat.

Keywords: lifecycle assessment (LCA); carbon footprint; carbon sequestration; carbon emission; Logarithmic Mean Division Index (LMDI)

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1. Introduction

It is an undeniable fact that global climate change caused by human-induced greenhouse gas emissions poses a threat to the sustainable development of the world economy and human society. Addressing the adverse impacts of climate change has become a focal point of attention across all sectors of society [1]. Based on the concept of the ecological footprint, the carbon footprint can be used to quantitatively evaluate the impact of human activities on global climate change [2]. To standardize accounting standards, in 2013, the International Organization for Standardization (ISO) published the technical specification draft ISO/TS 14067 to calculate the product carbon footprint. The lifecycle assessment (LCA) method is used to calculate the sum of greenhouse gas emissions (sources) and net uptake (sinks) within the product production system, and the carbon footprint is expressed in CO_2 equivalent to evaluate its impact on climate change [3].

The agricultural ecosystem is the system most significantly impacted by human activities, with key steps in the agricultural production process involving the carbon footprint. According to the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the agricultural and forestry sectors account for 17% of global greenhouse gas emissions [4]. Agricultural development faces the dual challenges of natural resource constraints and climate change [5], and low-carbon agricultural development is the inevitable trend for the future. As a responsible agricultural and populous nation globally, China is focusing on developing its economy while protecting the ecological environment [6]. Based on the lifecycle assessment (LCA) method and in accordance with the national conditions of China, establishing a carbon footprint accounting method for agricultural production is of great significance towards guiding the development of green agriculture [7].

Jiangsu Province is located in the middle and lower reaches of the Yangtze River Plain in China and has typical temperate continental monsoon climate characteristics. The climate conditions with abundant rainfall and warmth in the same season are very suitable for the growth of winter wheat and other crops [8], and it is an important grain production base in China and an economic powerhouse. With the continuous improvement of agricultural mechanization and the large input and consumption of agricultural products such as fertilizers and pesticides [9], the stable increase in grain yield has been accompanied by a series of problems such as ecological environmental deterioration [10].

This paper analyzes the evolution of the carbon footprint associated with winter wheat production in Jiangsu Province, China, from 2011 to 2020. The study employs three different functional units of the carbon footprint: the carbon footprint at yield scale, the carbon footprint at value scale, and the carbon footprint at cost scale. This enables tracking changes in the carbon footprint associated with winter wheat production in Jiangsu Province. In addition, by using the LMDI method, the paper decomposes the driving factors that influence the carbon footprint and analyzes the contribution rates and interannual variations of each driving factor for the carbon footprint in the winter wheat production system.

Quantitatively analyzing the carbon footprint in agricultural production can provide a theoretical basis for developing measures and methods to reduce carbon sources and increase carbon sinks. The ultimate goal of this research is to provide theoretical support for the development of low-carbon and clean winter wheat production in Jiangsu Province.

2. Materials and Methods

2.1. The Source of Research Data

The data for the inputs and outputs of winter wheat production in Jiangsu Province used in this study were obtained from the "The National Cost-Benefit Survey for Agricultural Product" released from 2012 to 2021 [11]. These data include information on the yield, output value, and cost per unit area of winter wheat. In these statistical data, various fertilizers, including nitrogen, phosphorus, potassium, and compound fertilizer, are recorded as net content. The amount of straw produced is estimated based on the ratio of economic yield utilization of grass meadow, with 67.9% of winter wheat straw returned to the field [12]. The pesticides use and electricity consumption for irrigation per unit area were indirectly calculated based on the "The National Cost-Benefit Survey for Agricultural Product" [11] and the "China Price Yearbook" [9]. To determine the cost of machine operations, we divided the statistical data into diesel consumption for tillage, sowing, and harvesting operations, which was estimated based on the diesel consumption costs of each process in winter wheat machinery production, as calculated by Cui et al. [13]. Tillage, sowing, and harvesting account for 26.9%, 29.3%, and 30.7% of the machine operation cost, respectively. The diesel unit price data were sourced from East Money (http://www.eastmoney.com, accessed on 6 June 2023). The soil carbon sequestration rate used in this study was based on the carbon sequestration model estimated by Lu et al. [14] under the conditions of straw returning and nitrogen fertilizer application. The carbon emission and sequestration coefficients of the study were developed by Chinese scholars and were based on agricultural production statistics data.

2.2. Overview of Study Area

Jiangsu Province, situated in China's eastern coastal region, stretches from south to north and from west to east, spanning the longitude range of 116°22′ to 121°55′ and the latitude range of 30°46′ to 35°07′. Located near the Tropic of Cancer, it receives ample sunlight, with an average annual temperature ranging from 11.8 to 17.8 °C, creating favorable conditions for winter wheat production [8]. Moreover, it has a generally flat terrain with numerous lakes, mainly consisting of plains, water areas, and low hills, making it highly conducive to agricultural development and earning it the nickname "Land of Fish and Rice". As of 2020, the sown area of wheat in Jiangsu Province reached 2338.89 kilo hm^2, with a total wheat production of 13,338,690 tons [9]. Taking Jiangsu Province as an example, based on the LCA and LMDI method, the carbon footprints of winter wheat agroecosystems are studied to evaluate the status of agricultural production in Jiangsu Province and to analyze the variations in the driving factors that change the carbon footprint.

2.3. The System Boundary of the Research

The system boundary of this study encompasses the entire winter wheat production process, from raw material extraction to crop harvesting and all inputs and uses of agricultural materials during the full lifecycle process as shown in Figure 1. The calculation system boundary for the crop production system's carbon footprint includes the following: (1) carbon emissions from the input of agricultural inputs such as seeds, fertilizers, and pesticides; (2) energy consumption during the various stages of crop production; (3) carbon emissions directly from the nitrous oxide (N_2O) emissions caused by nitrogen fertilization and indirect emissions from ammonia volatilization and N_2O conversion caused by nitrogen leaching; and (4) carbon sequestration caused by nitrogen fertilization and straw return. Since relevant information on no-till cropping in actual production in Jiangsu Province is difficult to obtain, the greenhouse gas emissions caused by no-till are not considered in this study.

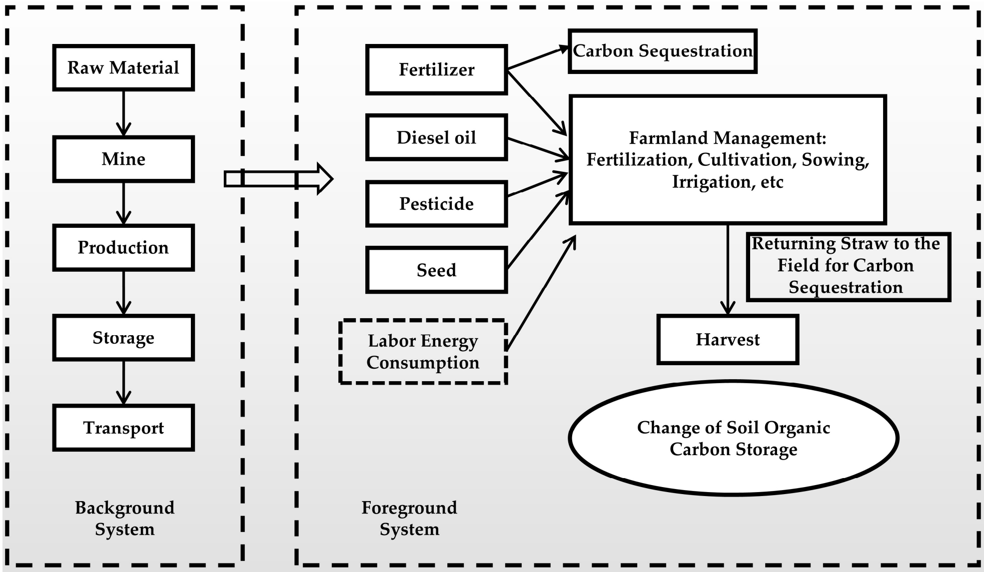

Figure 1. The system boundary of winter wheat production in this study.

The carbon emission model used in this study mainly covers two greenhouse gases, CO_2 and N_2O, and the carbon sequestration model mainly considers carbon sequestration caused by straw return and nitrogen fertilization. According to the lifecycle assessment (LCA) method, the carbon footprint calculation of the crop planting system consists of two parts: carbon emissions and carbon sequestration. The calculation of carbon emissions and carbon sequestration is based on the method proposed by Zhang [15]. Carbon emissions include carbon emissions caused by agricultural inputs such as seeds, fertilizers, pesticides, irrigation electricity consumption, and diesel consumption, as well as direct and indirect N_2O emissions caused by fertilization. Carbon sequestration includes organic carbon sequestration caused by nitrogen fertilization and straw return.

2.4. Computation of C Sequestration

In Equations (1)–(3), *SOCSR* represents the total carbon sequestration amount ($kgCO_2$-eq/hm^2) of the winter wheat production system calculated in CO_2 equivalents. The conversion factor of 44/12 represents the conversion relation between the carbon content in soil and the molecular weight of CO_2. $C_{S\text{-}Fern}$ is the amount of carbon sequestration (kgC/hm^2) caused by nitrogen fertilization, and F_{SN} represents the amount of nitrogen applied in the winter wheat production system (kg/hm^2), including nitrogen fertilizer and compound fertilizer. The nitrogen content of the compound fertilizer is estimated based on the recommended formula of the Jiangsu Provincial Agriculture and Forestry Bureau for major crops, with a mass ratio of N:P_2O_5:K_2O of 20:10:15. S_{Fern} is the carbon sequestration coefficient of nitrogen fertilizer application. $C_{S\text{-}Straw}$ is the amount of carbon sequestration (kgC/hm^2) due to the straw return; $C_{R\text{-}Straw}$ is the amount of straw returned (kg/hm^2), and S_r is the straw return coefficient.

$$SOCSR = (C_{S\text{-}Fern} + C_{S\text{-}Straw}) \times 44/12 \tag{1}$$

$$C_{S\text{-}Fern} = F_{SN} \times S_{Fern} \tag{2}$$

$$C_{S\text{-}Straw} = C_{R\text{-}Straw} \times S_r \tag{3}$$

2.5. Computation of C Emission

In Equations (4) and (5), CE_{CO2} represents the total carbon emissions ($kgCO_2$-eq/hm^2) of the winter wheat production system calculated in CO_2 equivalents, and CE_{input} represents the greenhouse gas emissions (kg/hm^2) caused by agricultural inputs. CE_{N2O} represents the amount of N_2O emitted directly and indirectly from cropland ($kgCO_2$-eq/kg). Q_{usedi} is the number of agricultural inputs used during crop production, and ε_i is the carbon emission factor ($kgCO_2$/kg) for each agricultural input.

$$CE_{CO2} = CE_{input} + CE_{N2O} \tag{4}$$

$$CE_{input} = \sum_i Q_{usedi} \times \varepsilon_i \tag{5}$$

N_2O emissions from soil are estimated according to the "IPCC guidelines for national greenhouse gas inventories" [16]. The total N_2O emissions are calculated by separately estimating the direct N_2O emissions from soil, the indirect N_2O emissions caused by atmospheric nitrogen deposition, and the N_2O emissions indirectly caused by nitrogen leaching and runoff in cropland.

$$CE_{N2O} = D_{N2O} + V_{N2O} + L_{N2O} \tag{6}$$

$$D_{N2O} = F_{SN} \times E_{f1} \times 44/28 \times 298 \tag{7}$$

$$V_{N2O} = F_{SN} \times F_{Vratio} \times E_{f2} \times 44/28 \times 298 \tag{8}$$

$$L_{N2O} = F_{SN} \times F_{Lratio} \times E_{f3} \times 44/28 \times 298 \tag{9}$$

Equations (7)–(9) describe the components involved in estimating the N_2O emissions from soil. D_{N2O} represents the direct N_2O emissions from soil ($kgCO_2$-eq/hm^2), E_{f1} is the emission factor (0.01 kgN_2O/kgN) for N_2O emissions directly caused by nitrogen fertilizer input, and 298 is the global warming potential factor for converting N_2O to CO_2 over a 100-year time horizon [16]. V_{N2O} represents the indirect N_2O emissions caused by the NH_3 and NO_x forms of nitrogen volatilizing from the soil and depositing back to the soil ($kgCO_2$-eq/hm^2), F_{Vratio} is the proportion (0.1 kgN/kgN) of nitrogen that volatilizes from soil in the form of NH_3 and NO_x, E_{f2} is the emission factor (0.01 kgN_2O/kgN) for N_2O

emissions indirectly caused by atmospheric nitrogen deposition to soil. L_{N2O} represents the indirect N_2O emissions caused by nitrogen leaching and runoff (kgCO_2-eq/hm^2), and F_{Lratio} is the proportion (0.3 kgN/kgN) of nitrogen lost through leaching and runoff. E_{f3} is the emission factor (0.0075 kgN_2O/kgN) for N_2O emissions indirectly caused by nitrogen loss due to leaching and runoff. All these emission factors are from the "IPCC Guidelines for National Greenhouse Gas Inventories" [16]. Table 1 shows the greenhouse gas emission factors for various agricultural inputs, most of which are sourced from China's lifecycle inventory database. The labor emission factor is from Liu's research [17].

Table 1. Greenhouse gas emission factors for various input materials.

Item	Unit	Emission Factor
Urea	kgCO_2-eq/kg	2.39
Ammonium bicarbonate	kgCO_2-eq/kg	0.65
Other N fertilizers	kgCO_2-eq/kg	1.53
Calcium superphosphate	kgCO_2-eq/kg	2.68
Other P_2O_5 fertilizers	kgCO_2-eq/kg	1.63
Potassium chloride	kgCO_2-eq/kg	0.71
Other K_2O fertilizers	kgCO_2-eq/kg	0.65
Diesel oil for machine	kgCO_2-eq/kg	4.99
Pesticides	kgCO_2-eq/kg	12.44
Wheat seed	kgCO_2-eq/kg	0.58
Electricity	kgCO_2-eq/kwh	1.23
Labor	kgCO_2-eq/m·d	0.86

2.6. Computation of the C Footprint

In Equations (10) and (11), F_N represents the calculated net carbon emissions (kgCO_2-eq/hm^2), Y_d represents the winter wheat yield per unit area (kg/hm^2), F_Y represents the carbon footprint per unit at yield scale (kgCO_2-eq/kg), V_t represents the winter wheat output value per unit area (CNY/hm^2), F_A represents the carbon footprint per unit at value scale (kgCO_2-eq/CNY), C_t represents the winter wheat input costs per unit area (CNY/hm^2), and F_V represents the carbon footprint per unit at cost scale (kgCO_2-eq/CNY).

$$F_N = CE_{CO2} - SOCSR \tag{10}$$

$$F_Y = F_N/Y_d \tag{11}$$

$$F_A = F_N/V_t \tag{12}$$

$$F_V = F_N/C_t \tag{13}$$

2.7. C Footprint Driving Factors Decomposition Method

Based on the LMDI method and the relevant equations proposed by Pang [18] and Chen [19], we decomposed the driving factors of the carbon footprint in the winter wheat production system in Jiangsu Province as follows:

$$Ei = Ce/RGDP \tag{14}$$

$$Si = RGDP/AGDP \tag{15}$$

$$Mi = AGDP/AP \tag{16}$$

$$Ui = AP/TP \tag{17}$$

$$Ce = Ei \times Si \times Mi \times Ui \times TP. \tag{18}$$

In Equations (14)–(18), *Ce* represents the total carbon emissions from the winter wheat production system in a specific region. *RGDP* represents the winter wheat output value. *AGDP* represents the total agricultural output value. *AP* represents the agricultural employment population in the region, and *TP* represents the population size of the region. *Ei* represents the ratio of the winter wheat output value to the total agricultural output value, indicating the production efficiency. *Si* represents the ratio of the winter wheat output value to the total agricultural output value, indicating the production structure. *Mi* represents the ratio of the total agricultural value to the agricultural employment population, indicating the economic level. *Ui* represents the ratio of the agricultural employment population to the total population of the region, indicating the employment structure.

The driving effect values of the five major factors are denoted as ΔEi, ΔSi, ΔMi, ΔUi, and ΔTP, respectively. The calculation methods are as follows:

$$\Delta Ei = \frac{Ce^t - Ce^0}{\ln Ce^t - \ln Ce^0} \times \ln\frac{Ei^t}{Ei^0} \tag{19}$$

$$\Delta Si = \frac{Ce^t - Ce^0}{\ln Ce^t - \ln Ce^0} \times \ln\frac{Si^t}{Si^0} \tag{20}$$

$$\Delta Mi = \frac{Ce^t - Ce^0}{\ln Ce^t - \ln Ce^0} \times \ln\frac{Mi^t}{Mi^0} \tag{21}$$

$$\Delta Ui = \frac{Ce^t - Ce^0}{\ln Ce^t - \ln Ce^0} \times \ln\frac{Ui^t}{Ui^0} \tag{22}$$

$$\Delta TP = \frac{Ce^t - Ce^0}{\ln Ce^t - \ln Ce^0} \times \ln\frac{TP^t}{TP^0} \tag{23}$$

The variable "*t*" in Equations (19)–(23) represents the target year, while "0" represents the base year. In the context of this article, the base year is 2011. Therefore, the total effect of the contribution values for each factor is:

$$\Delta Ce = \Delta Ei + \Delta Si + \Delta Mi + \Delta Ui + \Delta TP \tag{24}$$

3. Results

3.1. The Dynamic Changes in the C Emission in the Winter Wheat Production System

From 2011 to 2020, the total greenhouse gas emissions from winter wheat production showed an increasing trend, with only a few exceptions, peaking in 2016. The emissions increased from 4837.8 kgCO_2-eq/hm^2 in 2011 to 5701.1 kgCO_2-eq/hm^2 in 2020, with an overall increase of 17.8% over the decade and an average annual increase of 95.9 kgCO_2-eq/hm^2. The amount of greenhouse gas emissions caused by different input materials varied greatly. Soil N_2O emissions, mechanical operations, compound fertilizers, and nitrogen fertilizers were the main sources of greenhouse gas emissions in winter wheat production system, accounting for 31.8–35.5%, 18.6–27.5%, 15.2–18.7%, and 16.1–20.4% of the total emissions, respectively. The proportion of the other greenhouse gas emission sources to the total emissions ranged between 6.5% and 10.6%. The emission changes of various sources are shown in Figure 2.

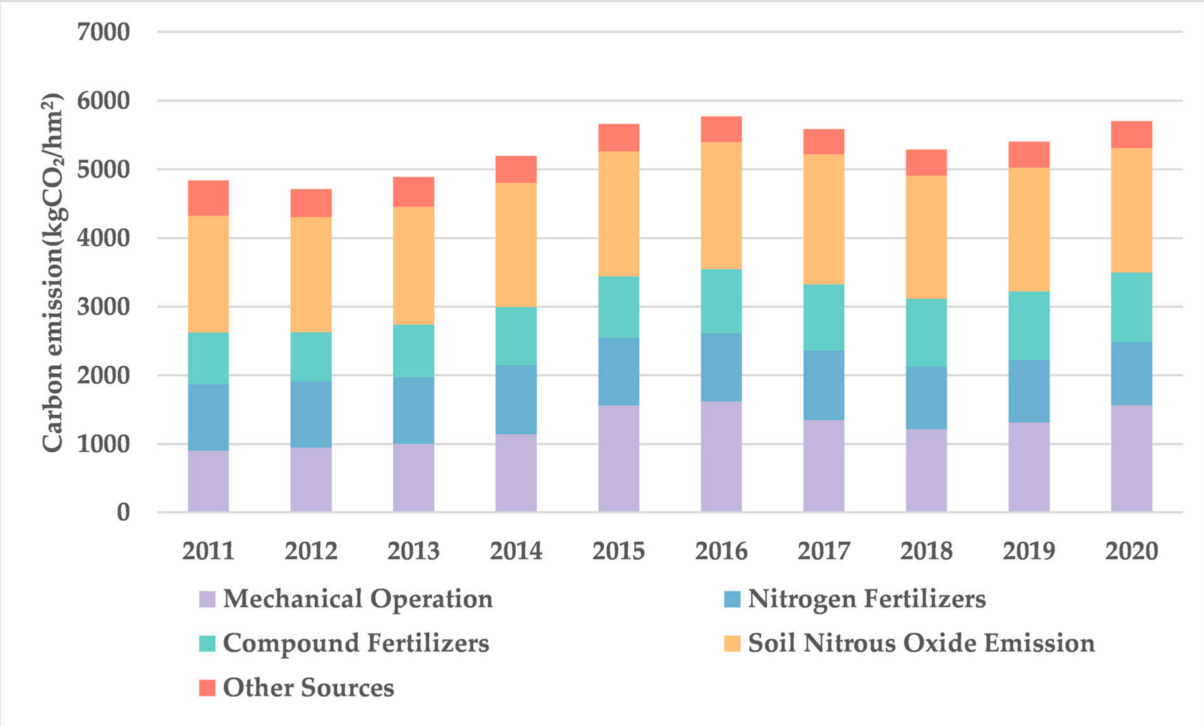

Figure 2. Emission changes in various greenhouse gas emission sources from the winter wheat production system.

3.2. The Dynamic Changes in C Sequestration in the Winter Wheat Production System

Referring to Lu et al.'s [14] carbon sequestration model under the conditions of straw returning and nitrogen fertilizer application, the carbon sequestration caused by the winter wheat production per unit area in Jiangsu Province from 2011 to 2020 can be calculated, as shown in Figure 3. Overall, the soil carbon sequestration caused by winter wheat production in Jiangsu Province showed a slightly increasing trend with fluctuations during this period. The variation range of soil carbon sequestration caused by straw returning was between 2201.9 and 2368.8 $kgCO_2$-eq/hm^2. The soil carbon sequestration caused by nitrogen fertilizer application exhibited an upward trend from 2011 to 2017 and after 2017 demonstrated a slightly declining trend.

3.3. The Dynamic Changes in the C Footprint of the Winter Wheat Production System

We evaluated the carbon footprint variation in the Jiangsu Province winter wheat production system from 2011 to 2020 from multiple perspectives. The results show that the choice of functional unit affects the carbon footprint performance. The carbon footprint per unit at yield scale in Jiangsu Province ranged between 0.32 and 0.48 $kgCO_2$-eq/kg from 2011 to 2020. The fluctuation was observed between two distinct periods, with a slow increase from 2011 to 2013, reaching its peak in 2016. Between 2017 and 2020, the carbon footprint showed a slight decrease and then fluctuated with an upward trend. The carbon footprint per unit at value scale in Jiangsu Province from 2011 to 2020 ranged between 0.13 and 0.25 $kgCO_2$-eq/CNY. The carbon footprint per unit at cost scale ranged between 0.16 and 0.2 $kgCO_2$-eq/CNY. The changes in these three functional carbon footprints are shown in Figure 4. The carbon footprint of the winter wheat production value in Jiangsu Province from 2011 to 2020 showed an overall upward trend consistent with the changes seen in the production carbon footprint. The percentage of increase or decrease during this period ranged between −41.8 and 33.4%. However, the carbon footprint per unit of cost in Jiangsu Province during this period showed a trend of gradual annual decline, with an average annual decrease rate of 4.7% and a percentage of increase or decrease ranging from −22.5 to 17.4%.

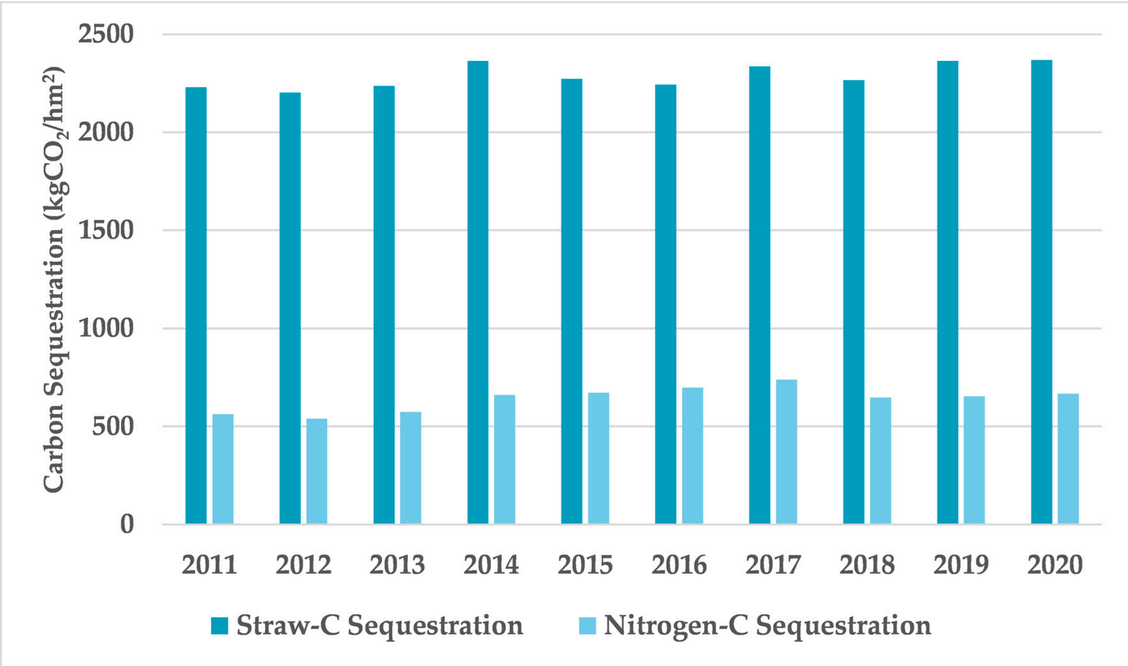

Figure 3. Soil carbon sequestration changes in the winter wheat production system.

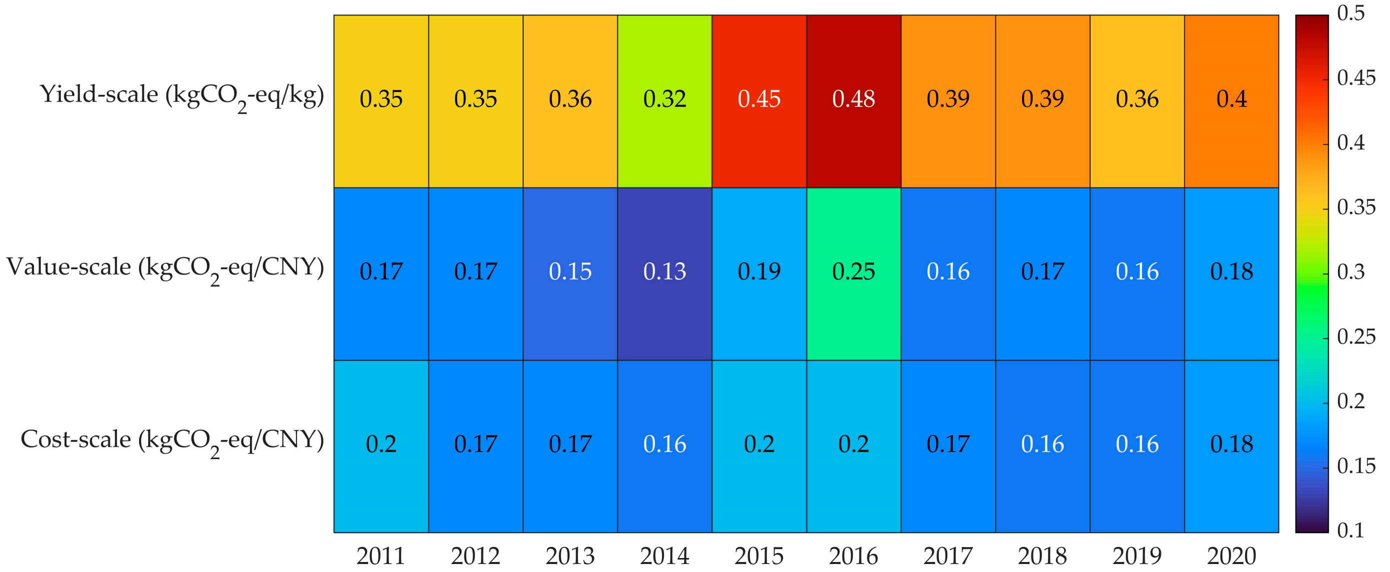

Figure 4. Trends of three different functional carbon footprints per unit in the winter wheat production system in Jiangsu Province.

3.4. Driving Factors for the C Footprint in the Winter Wheat Production System

The cumulative contribution rates of various factors driving the carbon footprint of wheat production in Jiangsu Province, with 2011 as the base year, are shown in Figure 5. The factors are ranked in descending order of the contribution rates as follows: economic level (*Mi*) > population size (*TP*) > employment structure (*Ui*) > production structure (*Si*) > production efficiency (*Ei*). The cumulative contribution rate of the *Mi* factor was 464.1%, making it the primary driving force behind the carbon footprint. The *TP* factor contributed to a cumulative rate of 44.01%, making it a secondary driver of carbon footprint growth. The *Ei* factor had a cumulative contribution rate of −120.2%, indicating that it played a key role in mitigating the carbon footprint growth. Both the *Si* and *Ui* factors had cumulative contribution rates of approximately −80% and served to alleviate carbon footprint growth.

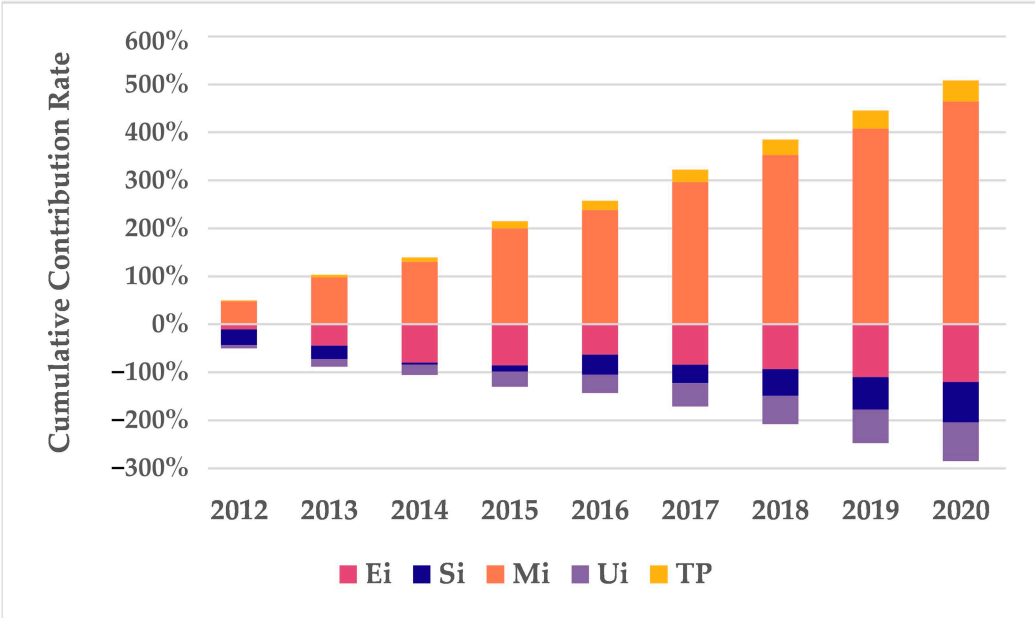

Figure 5. Changes in the cumulative contribution rates of driving factors to the C footprint.

The changing trends of the driving factors of carbon footprint are presented in Figure 6 and a summary of the trends follows:

(1) From the perspective of changes in the productivity efficiency (*Ei*), it can be observed that overall, the *Ei* suppressed the growth of carbon footprint during the observation period. This result indicates that *Ei* had a positive driving effect on the carbon footprint growth in 2016, while it had negative driving effects in all other years. The negative driving effects of *Ei* during the years 2012–2014 gradually intensified, reaching a peak negative impact in 2014 at −2.77 million tons. The negative driving effects weakened during the years 2015–2016, with a peak positive driving effect of 2.44 million tons observed in 2016. From 2017 onwards, *Ei* reverted to having a negative driving effect, with a reduced year-to-year fluctuation.

(2) From the perspective of changes in the production structure (*Si*), the overall carbon footprint growth was suppressed during the observation period, although there were fluctuations between years. There were two positive driving peaks during the observation period, namely 1.87 million tons in 2014 and 0.252 million tons in 2017. In 2016, there was a negative driving peak of −3.201 million tons. After 2017, the driving effects showed a slowdown and all became negative.

(3) From the perspective of changes in the economic level (*Mi*), the *Mi* has consistently exerted a positive driving effect on the growth of the carbon footprint. The positive driving effect continuously strengthened in two periods: 2012–2016 and 2017–2020, with annual growth rates ranging from 11.5% to 56.5%. However, between 2016 and 2018, the positive driving effect slowed down, with annual decreases ranging from 1.1% to 2.3%.

(4) From the perspective of changes in the employment structure (*Ui*), the *Ui* consistently suppressed the growth of the carbon footprint during the observation period. Furthermore, the negative driving effect of the *Ui* on the carbon footprint has been increasing. The emission reduction amount from the negative driving effect increased from 0.18 million tons in 2012 to 1.05 million tons in 2020, with an average annual growth rate of 10.8%, exhibiting a linear increasing trend.

(5) From the perspective of changes in the population size (*TP*), the *TP* had a positive driving effect on the growth of carbon footprint, but the overall driving force was small, with a range of change between 0.05 million tons and 0.56 million tons. From its development trend, the driving effect of *TP* on promoting the growth of the carbon footprint increased year by year, with an annual average increase of 0.06 million tons.

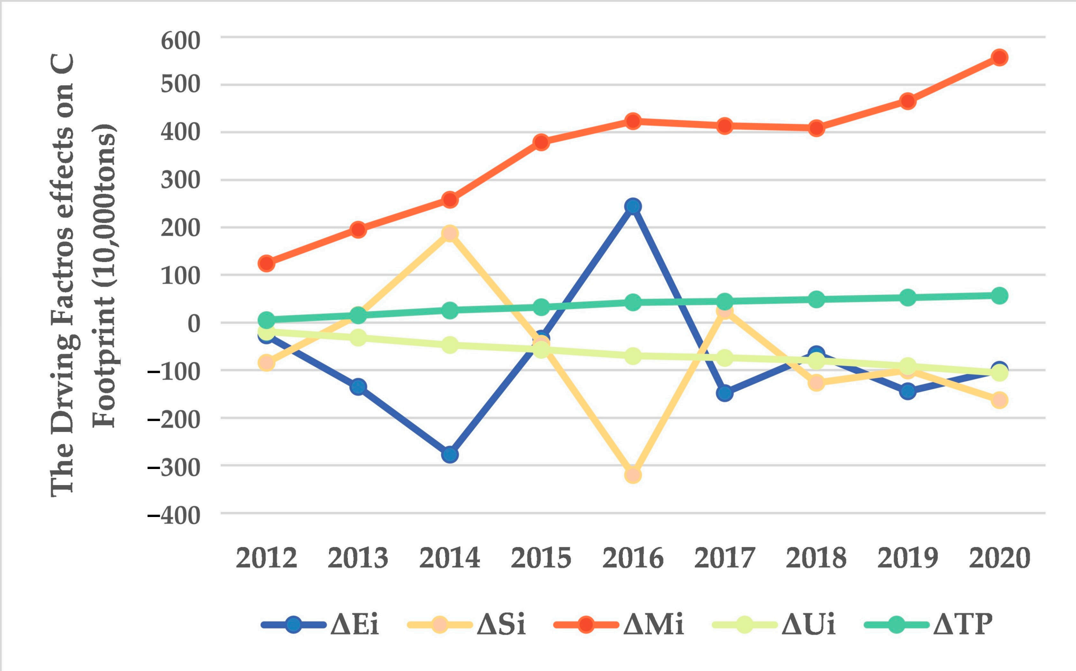

Figure 6. Trends of the C footprint driving factors in the winter wheat production system.

4. Discussion

4.1. Analysis of the Influencing Factors of Greenhouse Gas Emissions in Winter Wheat Production

This study found that the greenhouse gas emissions per unit area caused by winter wheat production in Jiangsu Province showed an increasing trend from 2011 to 2020. This was mainly due to the increased use of nitrogen fertilizers, compound fertilizers, soil nitrous oxide emissions, and higher fuel consumption for mechanical operations. Analysis showed that the use of nitrogen and compound fertilizers increased in winter wheat production in Jiangsu Province, while potassium fertilizers were rarely used, and the application of phosphate fertilizers decreased annually. In the winter wheat production process, the direct and indirect greenhouse gas emissions caused by the use of compound and nitrogen fertilizers accounted for the largest contribution, with a contribution ratio of over 60%. The results of the current research are well aligned with the previous study, where fertilizers were the main source of emissions during the production process of many agricultural crops including wheat [20]. Chuan et al.'s research showed that the nitrogen fertilizer input for winter wheat in the middle and lower reaches of the Yangtze River had exceeded 183 kg/hm^2, far exceeding the nutritional balance needs of winter wheat [21]. Therefore, the application of appropriate amounts of fertilizer according to local conditions can maintain the winter wheat yield [22], improve the fertilizer utilization efficiency, and reduce greenhouse gas emissions. Returning straw to the field is the main way to sequester carbon in soil, and from 2011 to 2020, carbon sequestration caused by winter wheat straw returning accounted for more than 75% of the total carbon sequestration contribution.

Since the official implementation of mechanized straw returning in Jiangsu Province in 2015, the government has promoted the technology through measures such as funding subsidies and launching eco-plowing and straw returning pilot programs. The straw returning technology, as a carbon sink measure, not only increases the soil carbon storage but also improves crop yield. Research by Zhang has shown a significant increase in grain crop yields under straw returning, and the potential carbon sequestration capacity in China from straw returning is currently 7×10^{10} kg per year, which can still be increased by 7% compared to the current carbon sequestration capacity [23]. In the future, further improving the technical level and scope of straw returning is an important way to achieve agricultural greenhouse gas reduction and effectively improve the quality of cultivated land.

4.2. Analysis of the Driving Factors on the C Footprint Changes in Winter Wheat Production

From the analysis of the carbon footprint at yield scale, it can be observed that there was a general upward trend from 2011 to 2020, which aligns with the findings of Xu et al. [24]. The LMDI decomposition results suggested that the economic level played a crucial role in driving the growth of the carbon footprint during the observation period. Specifically, there was a consistent increase in the use of agricultural inputs and production capital investment in wheat production [25]. A noteworthy peak in the carbon footprint at yield scale occurred in 2015–2016. The LMDI decomposition analysis revealed a significant decrease in the negative impact of the production efficiency on the carbon footprint during these two years, and in 2016, a positive driving effect was observed. This unusual occurrence may be attributed to an increased frequency of extreme weather events, particularly a significant rise in precipitation during the wheat growing season [26]. Prolonged periods of rainy weather led to substantial reductions in wheat production [27], and the additional inputs of agricultural resources to mitigate the meteorological disasters contributed to an increase in carbon emissions per unit of wheat production [25], consequently leading to an elevation in the carbon footprint. The interannual variability of agro-meteorological conditions has emerged as a significant factor influencing wheat crop yield. Developing a robust meteorological service system can effectively safeguard wheat production and mitigate the adverse impacts of meteorological disasters on crop yields [28]. In this study, the calculated carbon footprint at yield scale accounted for net carbon emissions after deducting carbon sequestration. It is worth noting that different calculation methodologies can yield divergent results for carbon footprints. For instance, Zhang et al. [29] estimated the carbon footprint per unit of output for wheat in Jiangsu Province as 0.99 $kgCO_2$-eq/kg without considering soil carbon sequestration. The research findings highlighted that soil carbon sequestration accounted for approximately 50.9% to 58.1% of the annual carbon emissions in the wheat production system. Consequently, accounting for carbon sequestration yields a more accurate reflection of the carbon footprint. Regarding the carbon footprint at value-added scale, it exhibited a similar trend to that of the carbon footprint at yield scale. Furthermore, there was a pronounced positive correlation between wheat value added and the production volume, indicating a consistency in the factors driving their variations with those influencing the carbon footprint at yield scale.

From the perspective of the carbon footprint at cost scale, the overall trend of the carbon footprint during the observation period showed a downward trend. According to the decomposition results of the LMDI, the production efficiency and production structure are the main reasons driving the decrease in carbon footprint. Zheng et al.'s research indicates that agricultural production efficiency has a negative driving effect on carbon emissions [30]. From 2011 to 2020, the total power of agricultural machinery in Jiangsu Province showed a year-on-year increase, with a higher proportion of high-performance, large-scale, and multifunctional operation machines [25]. The improvement in agricultural machinery modernization effectively reduces the agricultural production costs [31]. National policies are important factors in achieving a reduction in agricultural production costs. The Chinese Ministry of Agriculture has introduced a series of comprehensive subsidies for agricultural inputs, timely arrangements, and increased subsidy funds, effectively reducing the cost of agricultural production materials [32]. Currently, the Chinese Ministry of Agriculture and the National Development and Reform Commission have jointly issued the "Implementation Plan for Agricultural and Rural Greenhouse Gas Emission Reduction and Carbon Sequestration" which helps to form an agricultural and rural industrial structure that saves resources, protects the environment, and provides guidance for achieving peak carbon emissions and carbon neutrality in agricultural production in the future [33]. From the driving effect of the production structure, the production structure during the observation period showed an overall negative driving effect on the carbon footprint, which indicates that the wheat agricultural production structure has been adjusted. However, there is still a lot of room for reducing carbon emissions in the production process through the improvement in the agricultural technology level. Wheat production needs to balance economic and ecological benefits by innovating production methods and reducing resource consumption, while striving to improve economic efficiency. Measures such as adjusting the fertilizer application rates and selecting appropriate fertilizer varieties can reduce greenhouse gas emissions in the production process while increasing crop productivity [34].

4.3. Analysis of Uncertainty Factors

This paper applied the lifecycle assessment method to analyze the changes in the carbon footprint of winter wheat production in Jiangsu Province. Most of the data were sourced from the "The National Cost-Benefit Survey for Agricultural Product" [11], but this database still has some missing or incomplete data that required corresponding conversions. Additionally, the carbon emission coefficient used in this study was not specifically obtained for the actual situation in Jiangsu Province and was influenced by the local social development level, resulting in uncertainty in the carbon emission calculation for different regions. Furthermore, due to a lack of actual field measurements for carbon sequestration data, this paper used Lu's [14] carbon sequestration model to calculate soil carbon sequestration. However, directly using regional models to calculate carbon sequestration carries some degree of uncertainty. Further research is needed to obtain carbon emission coefficients that meet regional objectives, conduct field carbon sequestration monitoring, and provide more accurate data for the development of green agriculture in the research area.

5. Conclusions

This paper presented an analysis of the carbon footprint of winter wheat production in Jiangsu Province, China, from 2011 to 2020. The study applied LCA to calculate the carbon footprint in winter wheat production. Additionally, LMDI was employed to decompose and analyze the driving factors changes behind the carbon footprint. The goal of the study was to provide theoretical support for clean winter wheat production in Jiangsu Province.

The results indicate that (1) greenhouse gas emissions caused by winter wheat production in Jiangsu Province have increased at an average rate of 95.9 kg/hm^2 per year from 2011 to 2020; (2) the major sources of emissions include mechanical operations, nitrogen fertilizers, compound fertilizers, and soil N_2O emissions. The overall carbon sequestration of winter wheat production in Jiangsu Province has slightly increased over the same period, and the most significant contributor is straw returning; (3) the carbon footprints of winter wheat at yield scale and value scale in Jiangsu Province have increased over time, while the cost carbon footprint at cost scale has declined; (4) the economic level has the highest positive cumulative contribution rate to carbon footprint, reaching 464.1%. The efficiency has the lowest negative contribution rate, reaching -120.2%.

By analyzing the driving factors that influence carbon footprints, the study proposes that implementing a robust meteorological service system, along with the enhancement of agricultural mechanization and adjusting fertilizer application usage, can mitigate carbon emissions and reduce carbon footprints in the production process.

While there are limitations to the methodology used in this study, further improvements in statistical data and field observation technology can help create more accurate carbon emission coefficients and carbon sequestration models, providing robust theoretical support for calculating agricultural carbon footprints in the future. Overall, this study provides evidence for the development of low-carbon agriculture in Jiangsu Province and achieving energy savings and emission reduction in the production process of winter wheat.

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