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Carbon Footprints

Review

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Carbon footprint in agriculture sector: a literature review

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Abstract

As the climate problem becomes more serious, controlling greenhouse gas emissions has become an overarching issue facing all countries. The agriculture sector is one of the main sources of carbon emissions. The measurement of its carbon footprint not only can quantitatively evaluate agricultural greenhouse gas emissions but also provide technical support for low-carbon agricultural construction. However, most reviews focus on the carbon footprint of manufacturing or international trade. Thus, this study selects the agriculture sector and summarizes the literature associated with the carbon footprint. First, this paper analyzes the different definitions of carbon footprint at macroscopic and microscopic levels. Then, Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is used to summarize the advantages and disadvantages of two main accounting methods, Life Cycle Assessment (LCA) and Input-Output Analysis (IOA). Third, the research on carbon footprint in the agricultural sector is concluded and quantified using CiteSpace. Therefore, this paper gives the implications and prospects of carbon footprint in the agriculture sector. It is necessary to further agree on the definition of carbon footprint and consider other pollutants, water, and energy footprints to optimize agricultural management. Additionally, establishing a carbon footprint accounting model in line with local realities will provide scientific support for developing low-carbon agriculture.

Keywords: Agriculture sector, carbon footprint, input-output analysis, life cycle assessment, SWOT analysis, CiteSpace analysis

INTRODUCTION

According to World Population Prospects 2022, the global population exceeded 8 billion in 2022[1], and the global population is highly likely to exceed 10 billion by 2060[2]. With the rapid increase of the global population, more income and food are demanded[3], which has become the major challenge faced by governments[4]. Due to the significant improvement in agricultural productivity, global agricultural output was tripled to avoid food shortage[5]. Although agricultural productivity and modernization have increased the profitability of the agricultural sector, they have also increased energy demand, water use, and emissions of greenhouse gases such as carbon dioxide[6]. The COP26 Climate Summit reported that global greenhouse gas emissions from agriculture and food production have increased by 17 percent over the past 30 years, and the global agriculture and food system emitted 17 billion tons of carbon dioxide in 2019, encompassing 31 percent of the global total emissions[7]. The agriculture sector may become an important source of CO_2, N_2O, and CH_4 in 2050[8]. After the UN Climate Change Conference in Paris, almost all the documents submitted by the governments of various countries regarded agriculture as an important content, and all have made a strong commitment to reduce greenhouse gas emissions and save energy and water in the agriculture sector[9-11].

As one of the major agricultural countries in the world, China's grain output has constantly improved for 12 consecutive years from 2004 to 2015 due to the positive impact of agricultural policy changes at various stages of development on agricultural growth[12]. The agriculture sector in China, which produces 17% of China's greenhouse gases through traditional agriculture methods[13] and accounts for approximately 12% of the global agriculture sector[14], is currently undergoing a transition from high-carbon and inefficient traditional agriculture to low-carbon and highly efficient modern agriculture[15]. Thus, developing methods for addressing the issues of increased agricultural production and environmental problems has become a crucial and urgent need. This will not only satisfy the food requirements of the growing population but also help achieve sustainable development goals in the agriculture sector.

On the basis of the above realistic background, this paper elucidates knowledge on the measurement of carbon footprint in agriculture. Methodologically, the paper analyzes different methods of measuring carbon footprint in the agricultural sector. As an example, we use strength-weakness-opportunity-threat analysis (SWOT) to analyze the advantages and disadvantages of two mainstream carbon footprint methods and conclude the use of carbon footprints in the agricultural sector by CiteSpace. This study provides policy suggestions for low-carbon agricultural development and guidance for optimizing agricultural resources and adjusting planting structures. It also contributes to reducing carbon emissions in specific stages of agricultural production. Measuring the carbon footprint of agricultural products in the process promotes more efficient and greener ways to produce agricultural products.

This paper will make the following two central contributions. First, it compares the advantages and disadvantages of different methods of measuring carbon footprint and utilizes SWOT analysis to summarize the strengths, weaknesses, opportunities, and threats of micro-level LCA and macro-level IOA. Second, although some scholars have summarized the literature on carbon footprint, most of them either outlined the whole footprint family or concentrated on international trade[16-18] or the industry sector[19,20] and are less focused on the agriculture sector. Therefore, in this paper, CiteSpace is used for literature analysis, providing a review of measuring and applicating carbon footprint in the agriculture sector.

The rest of this paper is organized as follows. Section "BACKGROUND" explores the origin, definition, and boundary of carbon footprint. Section "THE METHODS OF MEASURING CARBON FOOTPRINT" elaborates on the main methods of carbon footprint measurement in the existing literature. Section "THE

RESEARCH OF CARBON FOOTPRINT IN THE AGRICULTURE SECTOR" describes the research on carbon footprint in the agriculture sector. Section "CONCLUSION" summarizes the whole article and gives some implications and prospects.

BACKGROUND

This section begins with the origin of the concept of carbon footprint. It analyzes the existing two mainstream viewpoints in the academic world: the macro perspective of the regional carbon footprint derived from the ecological footprint and the micro perspective of the individual carbon footprint originating from the life cycle of a single product. It then discusses the sources and different definitions and boundaries of the carbon footprint from the perspective of carbon sequestration by agricultural plants and soil.

The inconsistent definition of carbon footprint

As the most important assessment method to account for the sustainable development of a country or a region in the course of human life, footprint accounting has been prevailing for the last 30 years. Scholars proposed the concept of "ecological footprint" to measure the utilization level of the ecological environment and the functions provided by it in a region[21]. Later, they developed and refined a mathematical method for calculating the carrying capacity of natural ecosystems, expanding the concept of "ecological footprint" from a simple linear concept to a planar model[22]. After the concept of ecological footprint emerged in 1992, the idea of carbon footprint, which originated from ecological footprint, began to attract attention in 2007.

Some literature only employed the carbon footprint accounting to measure carbon emissions, and the earliest concept of the carbon footprint proposed was used to measure the level of carbon emission in the direct and indirect greenhouse gas emissions of a product or service during its life cycle[23]. But there is still no agreement with the definition of carbon footprint that only considers carbon emissions. For instance, some believed that the carbon footprint was derived from the ecological footprint theory, as they supposed that the carbon footprint referred to the total amount of CO_2 emitted by daily activities, including direct and indirect carbon emissions[24,25]. On the other hand, some argued that the carbon footprint encompassed not only "carbon" but also included other emissions (NO_X, SO_2, *etc.*) and even considered land use and surface reflectance that affected climate change[26]. Some scholars[27,28] argued that the carbon footprint was originally an impact assessment index of climate change in the Life Cycle Assessment system, viewed from the life cycle perspective, rather than being based on the ecological footprint theory.

Although scholars have different definitions and research perspectives of carbon footprint, they reach a consensus on key information such as CO_2 emission in the whole life cycle or the whole process of production activities. Accordingly, we believe that carbon footprint should cover the greenhouse gas emissions of the entire life cycle of a product or the whole process of an activity, including all sources.

The boundary of carbon footprint in the agriculture sector

The agricultural production system is an ecosystem that can both emit carbon and fix carbon; thus, two mainstream carbon footprint concepts of the agriculture sector were proposed in early times, considering only carbon emissions and the carbon footprint reflecting net emissions[29,30]. Although most scholars only looked at the carbon emissions in agricultural production, the carbon sequestration of agricultural ecosystems should not be overlooked due to the dual properties of carbon source and carbon sink in the agriculture sector. For instance, some scholars found that the carbon sequestration of agricultural soils can eliminate some of the carbon emissions or even make the carbon footprint negative[31,32] and explored the carbon uptake from two aspects, crop photosynthesis and soil[33].

Although scholars have different definitions and research perspectives on the carbon footprint, the above studies mainly highlight three main differences in its definition. First and foremost, especially in the agriculture sector, while most scholars reach a consensus on key information such as CO_2 emission throughout the entire life cycle or the entire process of production activities, there is debate regarding whether it is necessary to include the carbon sequestration of soil or carbon sequestration of plant photosynthesis for the calculation of carbon footprint. Second, there is a question of whether CH_4, N_2O, and other emissions be included in addition to CO_2. Third, there is a variation in the unit of measurement used to calculate a carbon footprint[33,34].

Based on this, the generally accepted definition of carbon footprint refers to the greenhouse gas emissions of the entire life cycle of a product or the whole process of an activity, including all sources. The main discussion of the agricultural carbon footprint in this paper temporarily ignores the carbon sequestration of soil and crops. It adopts the view that the carbon footprint of crops includes the greenhouse gases directly or indirectly emitted by each link in its production process[35].

THE METHODS OF MEASURING CARBON FOOTPRINT

The study of carbon footprint has been on the rise since its proposal, making it the top priority among footprints. At present, studies on carbon footprint are also analyzed from different perspectives. The accounting methods of carbon footprint include Life Cycle Assessment (LCA) and Input-Output Analysis (IOA). The two methods have different perspectives and focus. This section concludes the previous literature on the agriculture sector from a methodological perspective.

SWOT analysis is used in this section to examine and synthesize prior assessments of the two methods. Although it was first used in corporate management, SWOT analysis has since undergone continuous refinement for adaptation to diverse domains. The analysis comprises four dimensions: strengths, weaknesses, opportunities, and threats, analyzing these two methods' internal advantages and disadvantages, as well as the associated external opportunities and threats.

Some scholars tried to analyze the carbon footprints at a macro level. Most of them employed IOA, the main method of accounting at a macro level, especially in analyzing the carbon footprint of one or more regions or sectors. For example, some researchers analyzed the carbon footprint of international trade and found that China's implied carbon emissions increased due to trade[16,36-38]. Some researchers studied the transportation sector's carbon footprint to promote the sustainable development of this sector within the region[39-41]. In the agricultural sector, although rarely observed at the macro level, the flow characteristics and trends of the carbon footprint can be reflected[16].

Nevertheless, some scholars studied the carbon footprint of products from a micro perspective using the Life Cycle Assessment method; for example, most of the research in the agriculture sector focused on the different planting patterns and fertilization methods of certain crops[42,43]. In addition, the carbon footprint of major crops was accounted for to improve variety and farming practices and techniques[44,45].

Carbon footprint based on life cycle assessment

Life Cycle Assessment, a "bottom-up" process-based analysis method, considers the whole process from raw material extraction, production and processing, storage and transportation, use, and waste disposal[46].

LCA consists of four steps: objective and scope definition, life cycle inventory, life cycle impact assessment, and result interpretation[47]. Figure 1 below takes the agricultural sector as an example. First, in the objective

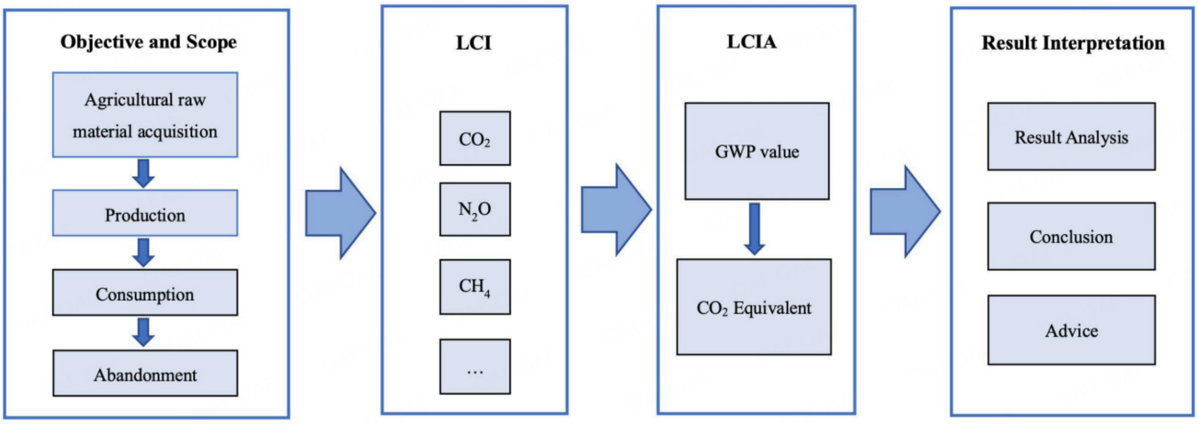

Figure 1. Procedure of carbon footprint measuring based on LCA. Notes: 1. LCI includes life cycle material input and corresponding greenhouse gas output. 2. LCIA converts gases with different greenhouse effects into emissions equivalent to the greenhouse effect of CO_2.

and scope definition phase, the material use, process and scope of the entire activity should be determined. Second, in the life cycle inventory phase, the carbon footprint calculation criteria have to be defined and direct and indirect carbon emissions, which will be taken into account, should be determined. Third, different greenhouse gases should be converted into CO_2 equivalents. Finally, after the calculation, the carbon footprint results should be checked to ensure scientific rigor and accuracy, which, in turn, helps formulate appropriate recommendations.

The carbon footprint measurement based on the LCA method can consider both direct and indirect carbon emissions, making it suitable for assessing the carbon footprint of microscopic objects[48,49]. However, some scholars proposed Input-Output Analysis to study the flow characteristics and differences in the carbon footprint of the agriculture sector in different regions. This was done because of significant obstacles in obtaining data at the macro level[50] and the high economic and human costs involved in obtaining detailed information about individual products while using LCA. Figure 2 uses SWOT to analyze the strengths, weaknesses, opportunities, and threats of LCA. According to some literature[49,51], we conducted a SWOT analysis of LCA. For the strengths, LCA based on process analysis is more accurate and suitable for the carbon footprint calculation of specific products, which can help governments and enterprises find a greener way to achieve carbon reduction. However, the boundary of different systems and the difficulty of obtaining macro data restrict the use of this method.

Carbon footprint based on input-output analysis

Most existing studies on measuring footprint use Input-Output Analysis, which is a "top-down" analysis method reflecting the relationship between initial input, intermediate input, total input, intermediate output, final output, and total output of each department. This analysis includes the Single-Regional Input-Output method (SRIO) and Multi-Regional Input-Output method (MRIO)[52-54]. Figure 3 uses SWOT to analyze the strengths, weaknesses, opportunities, and threats of IOA. Input-output method fully considers the flow of hidden carbon footprints between regions and sectors but cannot obtain the carbon emissions of products on a micro level[55-58].

Single-regional input-output

The SRIO model is the earliest method to study the carbon footprint related to the final consumption of a country or a region by using the input-output table, commonly used to assess greenhouse gas emissions and other environmental impacts resulting from final demand.

Figure 2. SWOT Analysis of carbon footprint measuring based on LCA.

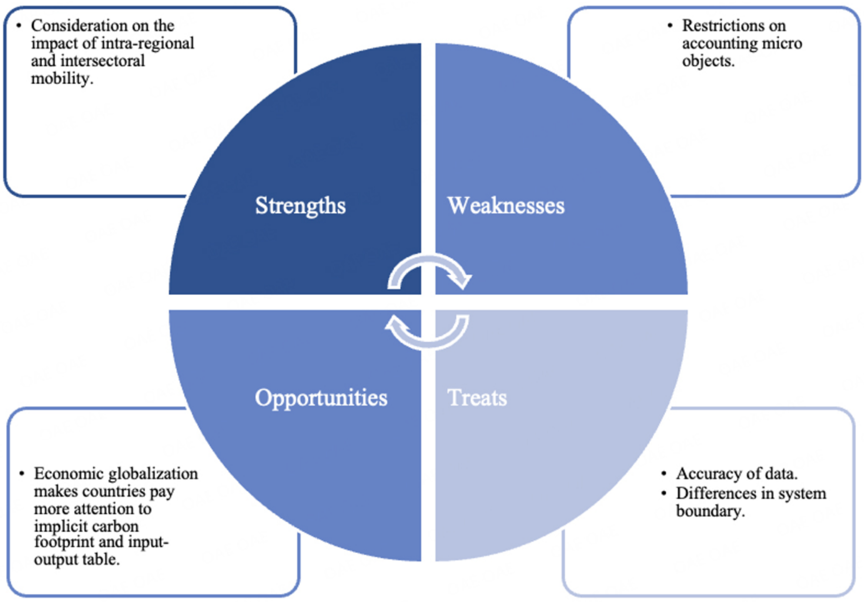

Figure 3. SWOT Analysis of carbon footprint measuring based on IOA.

The SRIO model simplifies the involved data and makes the calculation process more convenient in the traditional IO model. However, the SRIO model is employed on the premise that there is no technological difference in different regions, ignoring the impact of technological differences in other countries and regions on carbon footprint, which is obviously in conflict with globalization and trade internationalization[49]. The greenhouse gas emissions resulting from imports of intermediate products and final consumption in some countries cannot be adequately reflected in the SRIO model, which reduces the scientific rigor and accuracy of the study[55].

Multi-regional input-output method

The MRIO model is improved under the trend of economic globalization to solve the problem of no difference in production technology faced by the SRIO model. Based on the SRIO model, the MRIO model requires the input and output structure and embodied carbon and atmospheric pollutant emission of various countries according to the reality, overcoming the problems of technical heterogeneity and processing trade to improve the accuracy of calculation[59-62]. The MRIO model has become the most widely used and effective IOA model through the study of the footprint family[55]. Thus, the MRIO model has developed into the most important accounting method for agricultural carbon footprint[49]. This section introduces the fundamentals of the multi-region input-output model.

Table 1 reflects the input-output table. The columns reflect the intermediate input, value-added, and total inputs of the products produced by each sector in each region. On the other hand, the rows reflect intermediate inputs, final demand, and total outputs for each sector in each region. In Table 1, X_{ij}^{rs} represents the intermediate use of products from department *j* of region *s* to department *i* of region *r*. Y_i^{rs} represents the final use of the products of department *i* of region *r* by region *s*. V_j^s represents the added value of department *j* in region *s*. X_i^r and X_j^s represent the total outputs of department *i* in region *r* and inputs of department *j* in region *s*, respectively.

At present, a multi-regional input-output model has been widely applied to analyze the flow of carbon footprint in different regions, as shown below[63,64]:

$$X_i^r = \left(z_{i1}^{r1} + \cdots + z_{in}^{r1}\right) + \left(z_{i1}^{r2} + \cdots + z_{in}^{r2}\right) + \cdots + \left(z_{i1}^{rm} + \cdots + z_{in}^{rm}\right) + f_i^{r1} + \cdots + f_i^{rs} = \sum_{s=1}^{m}\sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m} f_i^{rs} \quad (1)$$

where X_i^r is the total output of department *i* of region *r*, z_{ij}^{rs} is the intermediate input provided by department *i* of region *r* to department *j* of region *s*, and f_i^{rs} is the final demand provided by department *i* of region *r* to region *s*.

Direct consumption coefficient a_{ij}^{rs} represents the product or service value of department *i* provided by region *r*, which is required by the unit output of department *j* in region *s*. The direct consumption coefficient in the regional input-output model is given as follows:

$$a_{ij}^{rs} = z_{ij}^{rs} / x_j^s \quad (2)$$

The direct consumption coefficient can be expressed by the matrix:

$$A^{rs} = [a_{ij}^{rs}] \quad (3)$$

$$X_i^r = \sum_{s=1}^{m}\sum_{j=1}^{n} a_{ij}^{rs} x_j^s + \sum_{s=1}^{m} f_i^{rs} \quad (4)$$

where X_j^s is the total output of industry *j* in region *s*.

Table 1. Structure of MRIO table

Outputs / Inputs		Intermediate transaction R^A	...	R^R	Final demand	Total outputs
Intermediate transaction	R^A					
	...	X_{ij}^{rs}			Y_i^{rs}	X_i^r
	R^R					
Value added		V_j^s				
Total inputs		X_j^s				

According to the above formula, it can be concluded that:

$$X = AX + F \tag{5}$$

$$X = (I - A)^{-1}F \tag{6}$$

where I is the unit matrix of the same order as A, X is the total output matrix of each region, A is the direct consumption coefficient matrix of each region, and F is the final demand matrix of each region, $(I - A)^{-1}$ represents the Leontief matrix of the multi-region input-output model.

Compared with the single-regional input-output model, the multi-regional input-output model connects multiple sectors in multiple regions, fully considers the influence of intra-regional mobility, and helps to analyze the carbon footprint within a region in a larger scope.

Besides the two main IOA approaches, some scholars have extended the methodology, utilizing environmentally extended input-output analysis (EE-IOA) to illustrate the associations between product production, utilization, and environmental cost. EE-IOA is based on the traditional static value-based input-output table, adding satellite accounts such as energy, resources, and emissions. This method reveals not only explicit costs incurred by producers but also estimates implicit costs, such as greenhouse gases contributing to heightened temperatures, air pollution, and water pollution. For instance, most scholars employed this method to measure interrelations between the natural and economic domains[65,66].

THE RESEARCH OF CARBON FOOTPRINT IN THE AGRICULTURE SECTOR

In recent studies on carbon footprint within the agricultural industry, quantitative analysis is performed by using CiteSpace. CiteSpace is a software tool designed to identify trends and patterns within the scientific literature and utilize visual analysis[67]. With this in mind, we aim to establish an analytical framework centered around the carbon footprint of the agricultural sector. The framework not only allows for the observation of changes over time concerning published research on the topic but also enables the identification of key developmental trends and areas of focus within the field.

The data utilized in CiteSpace is primarily obtained from the Web of Science (WoS). To exploit the wealth of research conducted on the carbon footprint in this field, some specialized terms, namely "Carbon Footprint" and "Agriculture or Agricultural", are directly assigned to it as the main topic. Article and Review document types were employed to refine search records from the Web of Science Core Collection database. Moreover, only records generated within the last fifteen years are considered, resulting in 1980 articles being ultimately analyzed.

The soaring trend in publications over the past 15 years is depicted in Figure 4. The data indicates the prominence and significance of the agricultural sector in the context of carbon footprint. Meanwhile, as the global population increases and concerted efforts are made to restrict global warming to below 2 C and preferably limit it to 1.5 C, as adopted by the Paris Climate Agreement, the implementation of sustainable farming practices will shape the trajectory of the carbon footprint in the agricultural domain, building on the aforementioned upward momentum.

Table 2 shows the top 10 countries in terms of total number of research and review papers in the past 15 years, 2009-2023. The table reveals that most articles are from China and the United States, accounting for nearly 40% of the total number of articles, which sufficiently demonstrates the importance of the carbon footprint in the agriculture sector in the academic field.

Figure 5 displays the top ten high-frequency keywords obtained by analyzing the keywords from the Web of Science. The majority of these prominent terms are specifically focused on achieving sustainable development in the agriculture sector and addressing climate and environmental changes by studying the carbon footprint.

Figure 6 demonstrates an analysis of keywords associated with the research conducted within the realm of carbon footprint in the agriculture sector over the last 15 years. As observed, shifts in research focus include a transition from biofuel, livestock, and beef production to land use, industrial ecology, and international trade, and, more recently, to rice productivity and temperature. It is reasonable to deduce that these topical preferences may be attributed to the impacts of climate change as well as population growth.

We devised an intuitive map that allows for direct observation of the research topics pertaining to carbon footprint within the agriculture sector by applying keyword cluster analysis. Figure 7 presents the result of a keyword cluster map based on English literature published over the past 15 years. The cluster modularity index, Q = 0.4166, and the cluster contour index, S = 0.705, indicate that the clustering effect is remarkable. We categorized the keywords into ten distinct clusters, reflecting different research focuses. Cluster 0, "sustainability", delves into sustainable development practices in the agriculture sector. Cluster 1, "water footprint", and Cluster 8, "power", jointly address the carbon, energy, and water footprint issues. Cluster 3, "biofuel", focuses on a method of reducing pollution with biofuel. Cluster 4 and Cluster 5 investigate various calculation methods for measuring the carbon footprint in the agriculture sector. Cluster 6, "climate change", Cluster 7, "carbon neutrality", and Cluster 9, "greenhouse gas emissions", all highlight the importance of reducing greenhouse gas emissions in the agriculture sector and suggest potential mitigation strategies.

According to the generated cluster map, most research has been focused on facilitating climate change mitigation and achieving sustainable development in the agriculture sector. Thus, we mainly divided the discussion into the following parts, including summarizing production links, livestock, meat or animal agriculture, regional scale, and carbon footprint, along with other footprints in the agriculture sector.

Research based on crops and their production links

With the gradual extension of the agricultural production chain, some scholars proposed considering a carbon footprint in various stages of the agriculture production process. Figure 8 shows the carbon footprint of the agricultural sector can be roughly divided into agricultural material production, planting process, product processing, transportation, consumption, and waste[68].

Table 2. Top 10 countries in researching the carbon footprint of the agriculture sector

Ranking	Country	Record	Proportion (%)
1	China	371	19.8
2	USA	327	17.4
3	Italy	125	6.7
4	India	110	5.8
5	Australia	103	5.4
6	Spain	91	4.8
7	England	89	4.7
8	Germany	89	4.7
9	Canada	66	3.5
10	Brazil	65	3.5

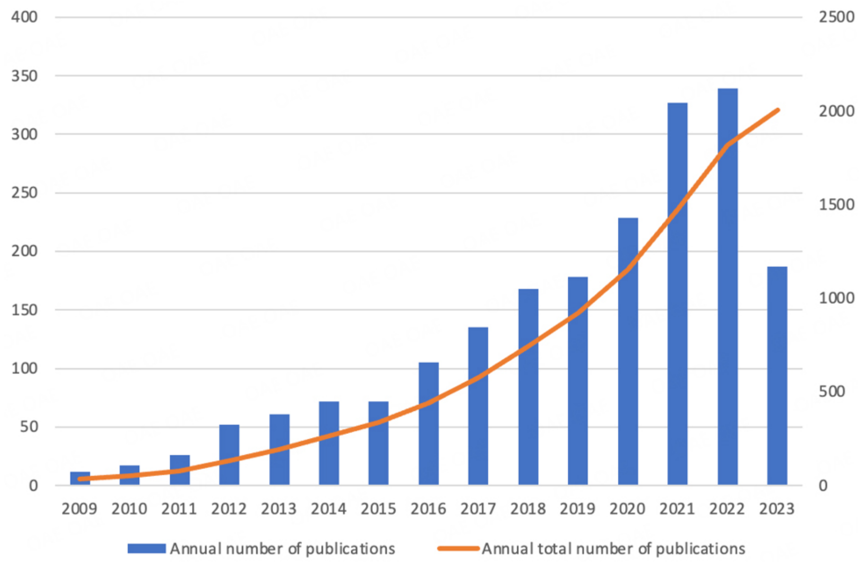

Figure 4. Changes in the number of published studies on the carbon footprint of the agricultural sector in the last 15 years.

Carbon footprint accounting has been carried out for a wide variety of crops and their farming methods. Some scholars assessed the carbon footprint and influencing factors in crop production by investigating major crops. For example, studies have shown that corn has the largest carbon footprint, followed by rice, wheat, and barley. Additionally, the use of nitrogen fertilizer has been found to result in higher carbon emissions[69,70]. On the other hand, some literature employed carbon footprint accounting to research planting strategy[71-73], a greener way to use factor endowments[74], and recycling of agricultural waste[75]. In addition, most scholars focus on assessing the carbon footprint of the upstream and production links, identifying the production stage with the largest carbon footprint to improve the product manufacturing process[76].

Alongside the deepening of agricultural mechanization and modernization, it is essential to consider the contribution of agricultural machinery to carbon emissions. This involves exploring the impact of machinery on the carbon footprint by studying the environmental indicators throughout the life cycle of different agricultural machinery and equipment[77]. The transport link is also a part that cannot be ignored. More energy-saving and emission-reduction transportation methods can be explored by studying the transportation links of agricultural products[78]. All these efforts will help China improve agricultural total

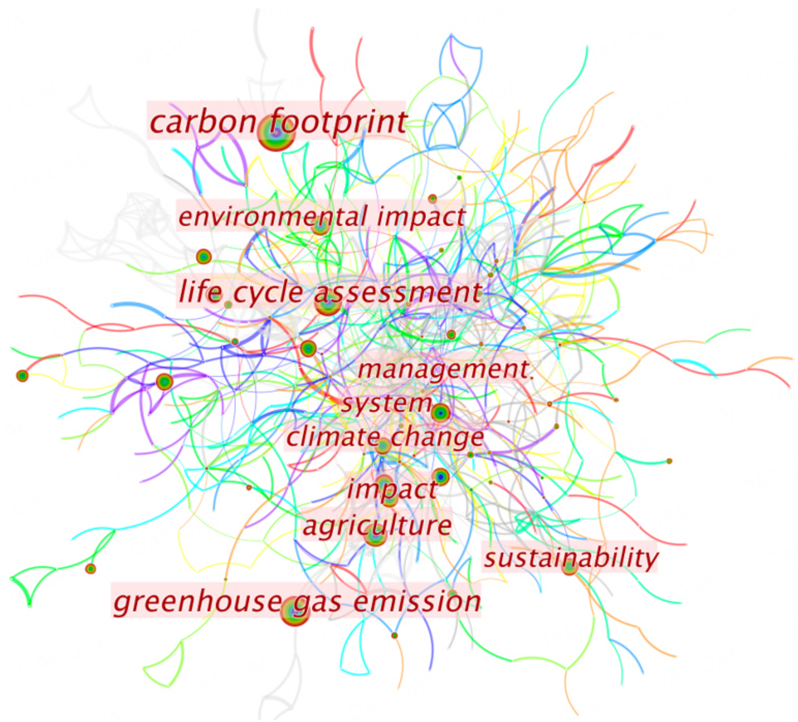

Figure 5. High-frequency keywords in the field of carbon footprint in the agricultural sector.

factor productivity and fully leverage the role of green technology as a driving force for low-carbon economic transformation.

Research on livestock, meat, or animal agriculture

Methane produced from manure and ruminant enteric fermentation cannot be overlooked when calculating the greenhouse gas emissions from the agriculture sector. Effective regulation of livestock production practices can significantly mitigate the impending threats of climate change by reducing methane emissions into the atmosphere.

Scholars in the field of livestock and animal products focused on analyzing the carbon footprint associated with milk products, exploring potential interventions to minimize this footprint, and synthesizing milk production with other agricultural commodities as a prospective measure[79-81].

Later, based on the study of milk products, countries with pasture-based production found that most of their agricultural footprint was related to methane emissions from intestinal fermentation, indicating that livestock and animals contribute significantly to the carbon footprint of the agricultural sector[82]. However, the carbon footprint of different animal herds varies considerably. For instance, beef exhibits a more substantial carbon footprint than other animal products[83]. Therefore, scholars proposed to choose low-carbon food and offered relative dietary recommendations, emphasizing that consumers' personal dietary choices will contribute to the environment. For instance, on the one hand, farmers should reduce livestock feeding and plowing. On the other hand, individuals should also reduce their meat intake, which may explain why more and more people advocate artificial meat and vegetarianism[84,85].

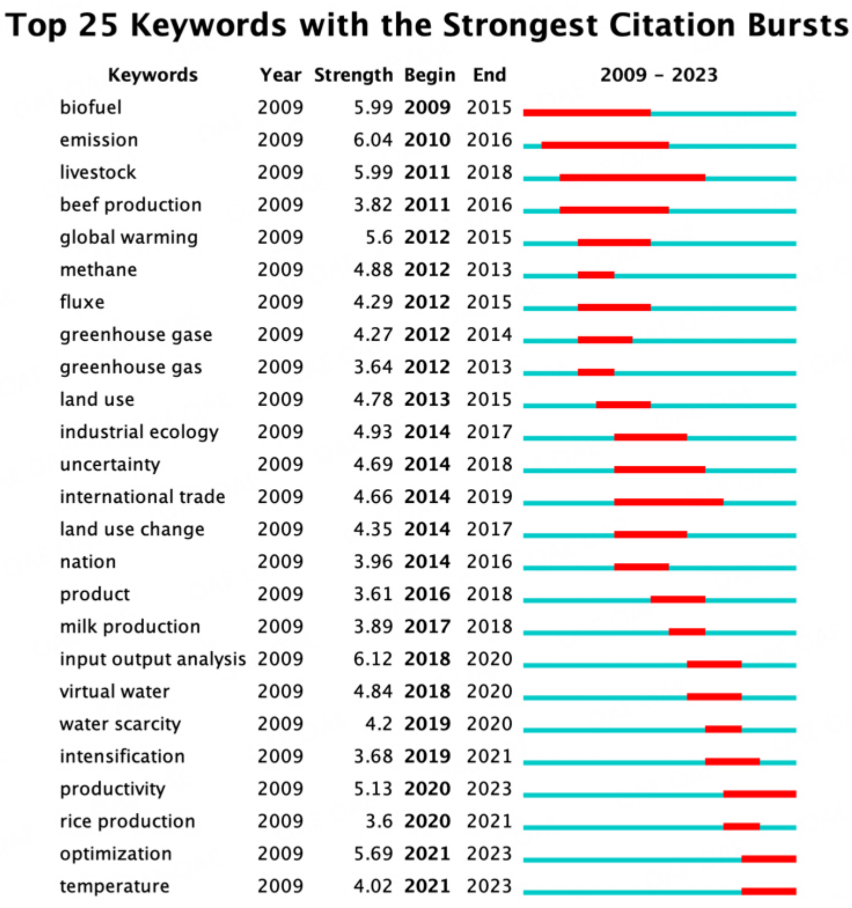

Figure 6. Keywords emergence map.

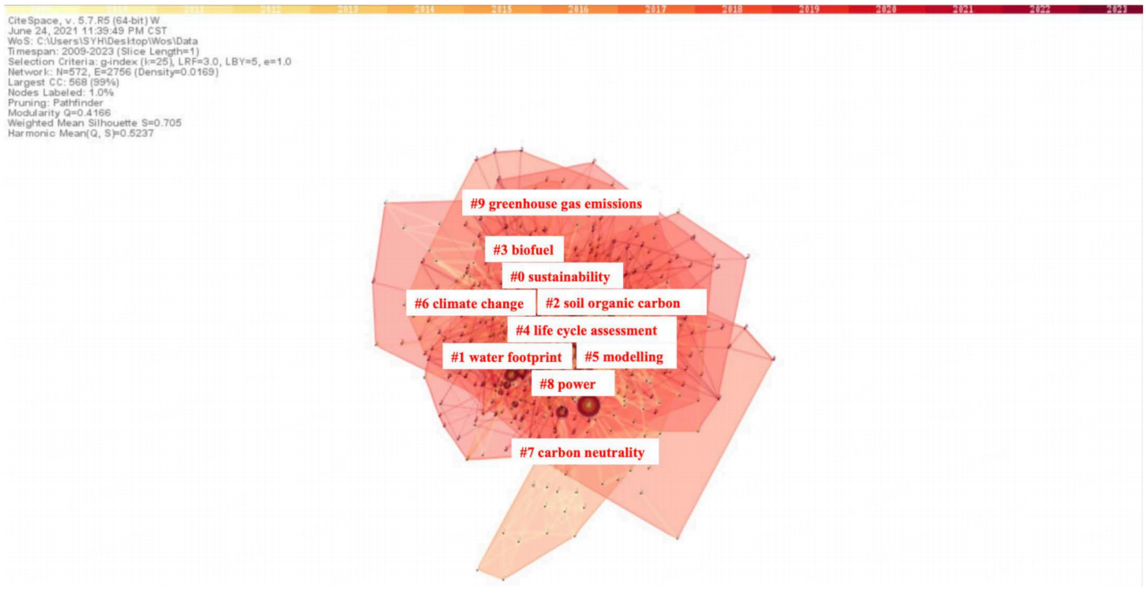

Figure 7. Keywords cluster analysis.

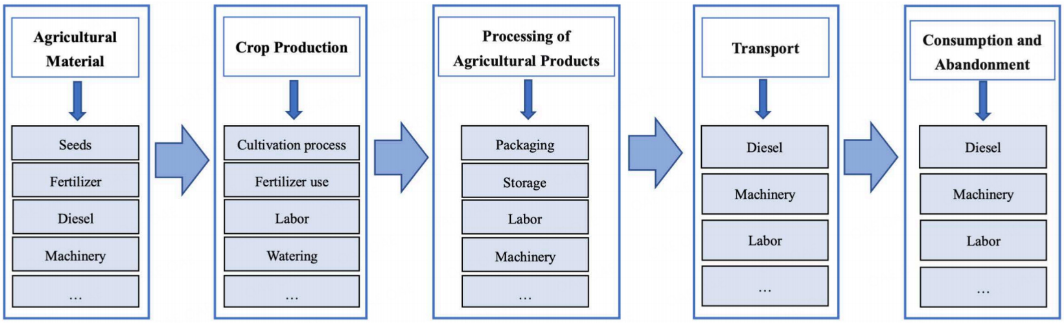

Figure 8. Possible production links of the agriculture sector.

Overall, when estimating the greenhouse gas emissions from the agriculture sector, it is essential not to overlook the large amounts of methane produced by ruminant manure and intestinal fermentation. Policymakers must prioritize addressing this critical issue to promote sustainable agriculture that recognizes the value of environmental protection.

Research based on different spatial scales

In the spatial scale of agricultural carbon footprint accounting, scholars mostly analyzed agricultural carbon footprint from three different scales, including national or provincial macro-region, landscape, and field experiments.

First, scholars mostly started from the main producing areas of crops at a regional level. For example, some literature employed footprint accounting to measure flow characteristics of carbon footprint in the agriculture sector from a macro perspective. Some noteworthy results include the finding that the agricultural sector in the Beijing-Tianjin-Hebei region of China released a considerable ecological footprint, including the carbon footprint, towards the coastal provinces in eastern China. At the same time, the region received the ecological footprint of Hebei Province, which can help the government to balance the carbon footprint of these areas and achieve more effective reductions[63,84]. Similar studies also found provincial level carbon footprint; for instance, Heilongjiang's carbon footprint from the farmland ecosystem of the reclamation area flowed to the eastern[86] and northeastern parts of the province and the carbon footprint in China mainly flowed from the western and northern regions to the eastern and southeastern regions, which was related to regional consumption characteristics of agricultural products[70]. The above literature analyzed the flow direction and trend characteristics of the carbon footprint from the provincial level, improving the ability to cope with climate change in different regions in the agriculture sector. Second, scholars mainly aimed to promote the integrated development of agriculture and tourism on the landscape level, exploring the relationship between the carbon footprint and economic effect of farmers' business models of terrace tourism and field fish farming to ensure sustainable long-term development[87]. Third, some scholars calculated the carbon emission contribution of agricultural products in different regions at the field experimental scale; for instance, they conducted field experiments on cotton production and rice beans to evaluate the balance between carbon emissions, yield, and economic benefits[88,89].

In general, the measurement of the carbon footprint from the perspective of macro space usually pays more attention to the flow of carbon between regions. Conversely, the measurement of the carbon footprint from a smaller space pays more attention to the carbon emissions generated by the production process of agricultural products. These approaches correspond to the MRIO and LCA, respectively, in the previous methods.

Research on the nexus of carbon with other footprints

Some scholars proposed to relate carbon with energy; for example, due to the continuous extension of the agricultural industry chain, a group established a multi-regional input-output table in the UK to calculate the impact of energy and carbon dioxide on the final demand in the supply chain[90]. Another study explored the relationship between energy resource endowment and carbon emissions to confirm the Kuznets curve relationship, represented by an inverted U-shaped curve demonstrating a tendency to increase first and then decrease, between energy poverty and carbon emissions. The study found that the richer the agricultural factor endowment, the more carbon emitted[91].

However, only a limited number of studies have been conducted on the carbon-water-energy nexus in the agricultural sector[92,93]. Carbon, water, and energy are all indispensable parts of the production process of the agricultural sector. Hence, there exists a close and significant relationship between these three[94]. For instance, in the agricultural sector, large amounts of water are consumed during the irrigation process, while energy is utilized throughout various stages, such as using machinery for sowing and harvesting, automated fertilization, *etc*., leading to continuous carbon emissions[95,96]. Therefore, it is impossible to independently reduce carbon emissions, water consumption, and energy utilization. Studying the relationship between carbon reduction, water conservation, and energy saving as a whole becomes increasingly necessary in future studies.

CONCLUSION

The above literature has investigated the agricultural sector's carbon footprint in various countries or regions from different perspectives and methodology frameworks. As a tool to measure sustainability, carbon emissions, and human impact on the natural environment, the carbon footprint possesses rich concepts and implications, and research methods are constantly improving and perfecting. It can realize the calculation, analysis, and comparison of specific goals, aiding in monitoring the impact of human production activities and lifestyle on global warming. From a consumption perspective, the carbon footprint guides the agricultural industry towards adopting more low-carbon and environmentally friendly behavior. Compared with the direct emissions of resource utilization, carbon emissions, or pollutant emissions, the implied carbon footprint of resource and environmental factors can more accurately and scientifically measure the externalities of their impacts on the social economy. Therefore, studying the carbon footprint in the agricultural sector can unveil the spatial pattern, flow direction, and improvement links of the carbon footprint in the agricultural sector, thereby facilitating the realization of low-carbon development in the agriculture industry. However, the research on agriculture's carbon footprint still requires further improvement.

Implications

As the issue of carbon emission has received widespread attention, the study of the carbon footprint of the agricultural sector will provide a solid foundation for sustainable development.

First, carbon footprint, as a measure of greenhouse gases produced in agricultural production, interacts with agricultural production. On the one hand, agricultural production contributes to climate change; on the other hand, the impacts of climate change will affect crop yield, moisture levels, and soil fertility in agricultural production. By reducing its carbon footprint, the agriculture sector can contribute to sustainable development by mitigating the effects of climate change. Second, the carbon footprint of the agricultural sector is still poorly studied compared to the industrial and transport sectors. As agriculture has gradually become a key industry, more scholars are needed to pay attention to this research. Studies of the carbon footprint of the agricultural sector can identify ways in which farmers can reduce their carbon footprint by adopting sustainable agricultural practices such as conservation tillage, crop rotation, and mulching. Policymakers can use this information to develop policies incentivizing farmers to adopt these practices. Third, consumers are increasingly concerned about the environmental impact of food production, including its carbon footprint. Carbon footprint studies in the agricultural sector can also inform labeling initiatives, providing information on the carbon footprint of agricultural products. Policymakers could set labeling standards that would require farmers and food producers to disclose the carbon footprint of their products, enabling consumers to make more informed purchasing decisions and contribute to sustainable agriculture. Fourth, carbon footprint and agricultural sustainability have important policy implications. Governments can support sustainable agricultural development by developing policies that encourage sustainable practices, investing in research and technology development, promoting renewable energy and encouraging carbon credits. In addition, policies that promote transparency, labeling and certification can build consumer trust and support sustainable agricultural development. Lastly, the utilization of machine learning and artificial intelligence techniques and the role of digital solutions cannot be ignored, not only using AI and digital models to develop solutions to the problem of agriculture's carbon footprint but also providing a new method to reduce carbon emissions[97-99].

Prospects

Combined with the deficiencies of existing research, future research on the carbon footprint in the agriculture sector can be considered from the following aspects:

First, there is no clear definition of the carbon footprint at present. Given the limitations of current research, it is essential to further promote the related research on agricultural greenhouse gas emissions. The academic community needs to establish a unified definition of the implication of carbon footprint, addressing aspects such as whether it includes all greenhouse gases and whether it considers soil and crop carbon sequestration. These factors will have a significant impact on the analysis and calculation of carbon footprint.

Second, research on carbon sinks in the process of agricultural production should be strengthened, especially the research on the carbon sequestration capacity of soil and crops in the process of carbon footprint accounting.

Third, more studies on the agricultural carbon footprint of farmers and enterprises are needed, especially in China's agricultural sector. As a representative of the small-scale peasant economy, China's agricultural carbon emission reduction and sequestration policies should be implemented on farmers, enterprises, and other micro-entities in the final analysis.

Fourth, more research on carbon, water, energy, and land footprint should be carried out as a whole nexus research. Because water, energy, and land are all necessary in the agricultural production process in the agricultural sector, taking them as a whole can improve agricultural productivity more effectively, reduce emissions of carbon and other pollutants, and reduce energy consumption.

Therefore, future research on the carbon footprint in the agriculture sector should focus on improving from the above four perspectives. Scholars can work towards perfecting a common definition of carbon footprint, establishing a carbon footprint accounting model suitable for the agricultural sector in the region. Building upon this foundation, the carbon, water, and energy footprints can be jointly analyzed to create a more comprehensive and accurate accounting that aligns with the actual situation.

DECLARATIONS

Authors' contributions

Writing original draft: Long T, Chen X
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Availability of data and materials

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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