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Spatial Analysis of Agricultural Eco-Efficiency and High-Quality Development in China

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High-quality development has become a new requirement for China's social and economic development. As an important industry related to the national economy and people's livelihood, achieving high-quality development in agriculture has become the most urgent task currently facing agriculture. This study focuses on agricultural eco-efficiency to indicate spatial distribution of high-quality development based on agricultural input–output data from 2001 to 2019 and the SBM-Undesired model; this study focuses on Agricultural Eco-efficiency, a key indicator related to the high-quality development of agriculture, to measure the temporal and spatial evolution of Agricultural Eco-efficiency. The results show that the Agricultural Eco-efficiency has increased from 0.363 in 2001 to 0.818 in 2019, with a growth rate of 125.34%, and the provinces with higher agricultural eco-efficiency are mainly located in the eastern regions. In addition, there is a U-shaped change trend between Agricultural Eco-efficiency and the total output value of agriculture, forestry, animal husbandry, and fishery. In other words, the provinces with the total output value of agriculture, forestry, animal husbandry, and fishery in the low range and high range enjoy higher Agricultural Eco-efficiency. Compared with the eastern region, the middle reaches of Yellow River and middle reaches of Yangtze River have great potential to reduce carbon emissions. In order to achieve high-quality agricultural development, it is necessary to pay attention to key indicators for improving Agricultural Eco-efficiency, and the technology development of the central and western regions will be very useful to decrease the gap.

Keywords: agricultural eco-efficiency, high-quality development, spatial analysis, carbon emission, carbon neutrality

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INTRODUCTION

In 2021, the COP 26 UN Climate Change Conference in Glasgow highlighted a crucial time mode for mankind's positive actions and explained that the next 10 years will be a crucial last window. If we do not take positive actions in time, humans and the Earth will face unimaginable natural disasters, such as sea level rise and biological extinction. Global warming of 2°C will have a wide-ranging and serious impact on humans and nature (Liu, 2019). One-third of the world's population will be regularly exposed to severe high temperatures, thus causing health problems and increasing death rates related to high temperatures. In addition, almost all warm water coral reefs will be destroyed, and Arctic sea ice will completely melt at least one summer every 10 years, generating devastating effects on the wildlife and communities they support. The latest "Emissions Gap Report" released by the United Nations Environment Program (UNEP) shows that despite the global climate ambitions and "net zero" commitments, the total amount of fossil fuels that countries plan to produce in 2030 is still more than double the amount of fossil fuels that are required to achieve the 1.5°C temperature control target of the Paris Agreement. The fossil fuels that governments around the world plan to produce in 2030 are about 110% higher than the production level required to achieve the global 1.5°C temperature control target and 45% higher than the production level required to achieve the 2°C temperature control target. Compared with the previous assessment, this production gap remains basically unchanged (Ji and Hoti, 2021).

Agriculture is one of the most sensitive fields affected by climate change (Elahi et al., 2021a), and climate change may cause China's agriculture to be more vulnerable. In addition to carbon dioxide, agricultural production also causes a large amount of methane and nitrous oxide emissions (Chen et al., 2020). In comparison with carbon dioxide, the two greenhouse gases methane and nitrous oxide are 20 and 310 times more capable of causing global warming than carbon dioxide, respectively. Agriculture is facing pressures and major challenges to alleviate and adapt to climate change and feed the huge population around the globe (Zhao et al., 2017; Abid et al., 2019; Van et al., 2019). The promotion of sustainable agriculture is an important means to adapt to climate change, reduce greenhouse gas emissions in agriculture, and alleviate the problem of deforestation caused by food demand (Han et al., 2018).

The ecological development of the agricultural industry is an important feature of achieving green and sustainable development of agriculture. The ecologicalization of the agricultural industry requires integrating the development of primary, secondary, and tertiary industries of agriculture, making full use of resources, and coordinating the relationship between economy, society, and ecology (Chen et al., 2021). Among them, the realization of ecological development of the agricultural primary industry is the key to achievement of ecological development of the entire agricultural industry. Agricultural eco-efficiency is not only the core indicator of green development of agriculture but also one of the important measures to fulfill agricultural modernization (Pang et al., 2016; Elahi et al., 2019a; Elahi et al., 2020). Sustainable Development Goals (SDGs) consider no poverty, zero hunger, and good health and wellbeing as the first three goals for achieving sustainable development, which shows the significance of realizing the three goals for human development; the sustainable development of agriculture is the key to achieve the three goals (Balezentis et al., 2016). From the perspective of global agricultural development, all countries have entered into comprehensive agricultural modernization with mechanization, improved varieties, chemistry, electrification, and informationization as the main content. Circular agriculture and low-carbon agriculture have become crucial methods to achieve sustainable agricultural development (Czyzewski et al., 2021). On the one hand, various countries have developed a variety of circular agriculture models, including material reuse models, resource reduction models, and waste utilization models (Elahi et al., 2019b). On the other hand, low-carbon agriculture mainly achieves low-carbon development goals through rational use of chemical fertilizers, water-saving irrigation, and energy-saving farming (Ke et al., 2012). With the tightening of resource environment constraints, agriculture in various countries around the world is moving toward green transformation, and China is no exception. In 2015, China formulated the "Zero Growth Action Plan of Chemical Fertilizer and Pesticide by 2020," implementing the policy of "one control, two reduction" on chemical fertilizer use (Qu et al., 2021). According to the data from the Ministry of Agriculture and Rural Affairs of People's Republic of China, the action of zero increase in the use of chemical fertilizers and pesticides since 2015 has achieved initial results. By the end of 2020, the reduction and efficiency enhancement of chemical fertilizers and pesticides have successfully helped achieve the expected goals. The chemical fertilizer utilization rate of the three staple crops of rice, wheat, and corn was 40.1%, which increased by 5 percentage points from 2015 (Bai and Tao, 2017). However, the further realization of green development is a challenge facing China's agriculture (Deng and Gibson, 2019).

Through analyzing the relationship between agricultural eco-efficiency and industrial green development, this study will propose a spatial heterogenous scheme of agricultural industrial green development.

This study is organized as follows: *Literature Review* consists of the literature review, *Methodology and Data* consists of methodology and data, *Results and Discussion* explains the results and discussion, and the final *Policy Implications* explains the policy implication.

Literature Review

The efficiency theory focuses on analyzing the conflict between the effectiveness of resources and infinity of human desires. "Pareto efficiency" is the earliest and widely recognized theory of resource utilization efficiency in economics (Charnes et al., 1978) "The New Palgrave Dictionary of Economics" states that the efficiency refers to the efficiency of resource utilization; subsequently, Samuelson and Nordhaus pointed out that efficiency means that there is no waste. When there is a state in which society has to increase the output of a certain product at the cost of damaging or reducing the output of another product, then such production is effective, and the indicated efficiency is the "optimal" state of the described resource usage. However, with the development of economic research theory and development practice, the concept of "efficiency" has not been an exactly unified definition. Although "Pareto efficiency" can show the possibility boundary of realizing effective allocation of resources, it cannot identify different distributions between actual and effective allocation of resources and cannot provide a feasible expansion path. Therefore, most scholars use the concept of reflecting resource utilization and allocation to study efficiency when using the concept of efficiency, and this connotation has gradually been recognized (Coelli and Rao, 2012). At this time, efficiency research not only reflects the actual use and allocation of resources but also maps the "optimal" state of resource utilization. Based on the different emphasis of investigating resource utilization, efficiency is divided into two parts: utilization efficiency and production efficiency (Zeng et al., 2020). Therefore, the general meaning of efficiency refers to the ratio of the relationship between limited production resources and what can be provided for human consumption under certain production conditions and technical levels (Zhong et al., 2020).

The concept of eco-efficiency originated from abroad and was first proposed by German scholars, and it integrates the concept of economic and ecological two-way efficiency (Baum and Bienkowski, 2020). It is used to measure the relationship between economic value change and environmental impact caused by a certain change. With the deepening of research in China and abroad, the concept of ecological efficiency is getting perfect. The concept recognized by academics is that based on necessary materials and products and services that could improve the quality of life, human beings achieve the goal of coordinated coupling between the environment and economy. Agricultural eco-efficiency is the specific application of eco-efficiency in the agricultural field. Taking the sustainable use of agricultural resources as the core and considering the realization of resource conservation and pollutant emission reduction as the goal, it is an indicator that evaluates the comprehensive performance of agricultural production and economy on the basis of meeting human needs for agricultural products (Magarey et al., 2019). The goal of Agricultural Eco-efficiency is to realize the efficient utilization of resources in the process of agricultural production, focusing on measuring the relationship between resources in the natural ecology and agricultural economic production. In other words, it refers to the simultaneous realization of multiple goals of high efficiency of agricultural production, reduction of resource input, and decrease of waste loss in the process of agricultural production (Reith and Guidry, 2003). Its main features contain the following five aspects: to achieve efficient use of resources and maximize the use of renewable resources, to avoid environmental losses caused by the production process to the local and surrounding environment, to produce expected agricultural products, to maintain biodiversity, and to make rapid adjustments to social, economic, and environmental impacts. (Golas et al., 2020). Based on the abovementioned research interpretation, the connotation of Agricultural Eco-efficiency can be summarized into three levels. The first level is that Agricultural Eco-efficiency demonstrates a research method for the regulation and control of the entire production process of agriculture. To increase the overall output level of agriculture, we must find ways to improve the utilization efficiency of various input elements in the agricultural system. Therefore, in this state, it not only reduces the use of chemical fertilizers and pesticides and other productive materials in the agricultural production process but also relies more on technologies (mixed planting, crop rotation, and the complementarity of agriculture and animal husbandry, etc.) to effectively increase the level of agricultural output (Todorovic et al., 2018). The second level is that Agricultural Eco-efficiency should be a key goal pursued by agricultural production. The level of Agricultural Eco-efficiency means the level of utilization efficiency of agricultural resources, and the improvement of utilization efficiency characterizes the reduction of pollutants discharged into the environment. The improvement of ecological efficiency is based on reducing the adverse effects in the system as a "reward". Its improvement can effectively reduce the input of fossil fuels, chemical fertilizers, and other agricultural materials in the agricultural production process, decrease the entire agricultural production cost, and indirectly increase the agricultural income (Czyzewski et al., 2021). Therefore, the level of Agricultural Eco-efficiency is not only consistent with the entire ideological connotation and extension of sustainable agricultural development but also an indispensable development goal for the ecologicalization of the agricultural industry. At the third level, Agricultural Eco-efficiency is a vital means of assessing the sustainable development capability in the process of agricultural production (Gava et al., 2020). It can effectively evaluate ecological and economic performance, thus providing an important method for evaluation.

Agricultural Eco-efficiency is an important measurement indicator for sustainable agricultural development. It focuses on the coupling of the ecological and economic objectives in the agricultural production process, and based on the maximization of expected output and the minimization of undesired output, the increase in output and reduction of pollutants are realized. Existing studies have discussed the connotation of Agricultural Eco-efficiency, which will provide an important basis for this research. However, the adoption of any technology is dependent on the sociopsychological behavior of people (Elahi et al., 2021b).

There are certain differences in the measurement methods of Agricultural Eco-efficiency due to different disciplines. In terms of methods, they mainly include ratio method, life cycle assessment (Soteriades et al., 2016), ecological footprint analysis (Wackernagel and Galli, 2007), energy analysis (Wang and Zhao, 2021), data envelopment analysis (Tone and Tsutsui, 2009), and stochastic frontier analysis (Guo et al., 2020), etc.

The ratio method is the earliest measurement method, which has gradually faded out of the field of vision of scholars. Early methods of eco-efficiency evaluation mainly used the ratio of economic value of products to the environmental impact of products (Ke et al., 2012), and the more common calculation formula was proposed by the World Business Council for Sustainable Development (WBCSD).

$$\text{Eco}-\text{efficiency} = \frac{\text{Economic Value of Products}}{\text{Environmental Impact of Products}} \quad (1)$$

The particularity of using the ratio method to calculate Agricultural Eco-efficiency is mainly manifested in the fact that in the entire agricultural production process, not only will the use of chemical fertilizers and pesticides cause negative effects, such as pesticide residues and soil compaction, but also due to the carbon sequestration effect of the crop itself; the absorption of toxic gases will generate a positive effect (Lwin et al., 2017). Therefore, in the calculation process, the formula is deformed as follows:

$$\text{Agricultural Eco} - \text{efficiency} = \frac{\text{Economic Value of Agricultural Products}}{\text{Negative Evironmental Effects} - \text{Positive Evironmental Effects}} \quad (2)$$

The ratio method characterizes the possible negative impacts of economic development on the environment to a certain extent. However, the defect of this indicator is that it only considers the impacts on the output side and completely ignores the description of the input side, but for agriculture, the resource and environmental impacts are generated precisely on the input side. Therefore, this method has gradually faded out of scholars' research horizons.

Life cycle assessment is a method that originated in the 1960s. Due to resource consumption and oil crisis, it has had serious impacts on social and economic development. However, Chinese and foreign academic research evaluation methods were limited to a few concentrated environmental load methods (Soteriades, A.D. et al., 2016). In the 1990s, with the gradual deepening of sustainable development research, the method of life cycle assessment appeared. The detailed definition is given by the International Society for Environmental Toxicology and Chemistry and the International Organization for Standardization (Fridrihsone et al., 2020). Specifically, it refers to evaluating the potential impacts of energy and resource consumption and waste pollutants generated during the entire production process (from raw material extraction, material preparation, to the product becoming waste) of products (Holka, 2020). The quantification of life cycle assessment appeared in 1990. It is an ecological scarcity method developed by Swiss researchers. Its calculation formula is as follows:

$$\frac{\text{Ecopoints}}{kg} = \frac{Emissions_A}{Emissions_T} \times \frac{1}{Emissions_T}. \quad (3)$$

Among them, the subscript A represents the actual environmental load, and the subscript T represents the environmental load in an ideal state.

In the process of calculation based on the life cycle assessment, the whole process needs to be measured, especially in the calculation of Agricultural Eco-efficiency as it is difficult to define the boundary, and the data of the whole analysis process are more complicated. At the same time, the comparative analysis mechanism between regions needs to be further deepened.

Ecological footprint analysis was first proposed by Rees, a Canadian ecologist, in the early 1990s and then developed and improved by Wackernagel. It mainly compares the overall loss caused by human production activities to nature and converts it into the corresponding land area through the conversion coefficient. Moreover, this value is compared with the overall amount of supply that nature can provide to human beings, and it is determined whether the regional economic development is within the carrying range of the ecosystem (Costa et al., 2018) based on the comparison result. If the area of productivity required by human activities is greater than the amount that nature can provide for humans, at this time, it is in a situation of over-utilization of ecological resources. The use of ecological footprint analysis is simple and globally comparable. However, this method has some shortcomings, which are manifested in the lack of data on the actual consumption of products of various biological resources in the calculation. Therefore, it is easy to cause errors when using different product usage data for substitution (Wackernagel and Galli, 2007). In addition, there is lack of groundwater resource measurement in the account coverage, and no attention is paid to the quality of the land in the production process.

Energy analysis was put forward by Odum, a famous American ecologist, in the 1980s, focusing on the quantitative evaluation of the "nature–economy–society" complex system. This method mainly takes energy as the core of the research, uses the energy conversion rate to convert the different types and the same types of energy in the ecosystem into the same standard solar energy value to evaluate the energy value of various energies within the system (Wang and Zhao, 2021), comprehensively analyzes the energy value (material flow, currency flow, information flow, etc.), and assesses the structure, benefit, and function of the ecosystem. Based on energy analysis, the changes in the natural environment and carrying capacity over a period of time (Llinas et al., 2021), sustainable development capabilities, and energy usage could be evaluated.

The energy analysis takes into consideration the value of economy, resources, and the environment as a whole and makes up for the difficulties of traditional economics in resource pricing and measurement. However, the energy analysis also has the problems such that the energy conversion rate will change greatly with the change of regions, and the evaluation indexes are relatively single.

Stochastic frontier analysis is a type of parametric analysis. It has been widely used to measure the efficiency in different research topics. This method was proposed by Farrell in 1957, and by 1977, Aigner, Meeusen, and Van DenBroeck conducted independent research on this method (Li et al., 2021). In the process of measuring Agricultural Eco-efficiency, the first step is to determine the form of the production function. Then, the difference value between the actual production output level and the maximum expected output level is calculated based on the specific form of the production function. Finally, the inefficiency term and the random error term are separated. This method is considered to be a commonly used evaluation method of Agricultural Eco-efficiency.

Data envelopment analysis is currently the most widely used method for evaluating Agricultural Eco-efficiency. This method was proposed by Charnes, Cooper, and Rhodes in 1978 and can evaluate the effectiveness of decision-making units (Liu et al., 2020) with multiple inputs and multiple outputs. This method does not need to emphasize the specific form of the model, is more convenient to use, and does not require dimensional processing of the data.

Owing to the difference in various disciplines, there are certain differences in the measurement methods of Agricultural Eco-efficiency. However, every calculation method has its own pros and cons. Therefore, it is necessary to conduct an in-depth analysis of the measurement framework system of Agricultural Eco-efficiency and seek a measurement method that is more suitable for resource-environmental constraints.

METHODOLOGY AND DATA

SBM Model With Undesired Output

The DEA–Slack-Based Model (DEA-SBM) can break the shortcomings of input–output angle selection and radial improvement of traditional BCC and CCR models so that the efficiency values can be better measured based on non-angular, non-radial, and actual slack variables to the target. The specific model is as follows:

$$min_{\lambda,s^-,s^+}\rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s}\sum_{r=1}^{s}\frac{s_r^+}{y_{r0}}}. \tag{4}$$

$$\text{s.t. } x_0 = X\lambda + s^- \tag{5}$$

$$y_0 = Y\lambda - s^+ \tag{6}$$

$$\lambda \geq 0, s^- \geq 0, s^+ \geq 0 \tag{7}$$

Among them, λ represents the weight vector; s^- s^+ represents excess input and insufficient output, respectively; x_0 y_0 represents the input and output of each decision-making unit, respectively; and X, Y is the input and output matrix, respectively; $X = [x_1, ..., x_n] \in R^{m\times n}$, $Y = [y_1, ..., y_n] \in R^{s\times n}$. It is assumed that X > 0, Y > 0 and ρ is the efficiency value that needs to be calculated.

It is assumed that there are n production decision making units (DMUs) in the agricultural evaluation system, and each DMU comprises the following three sets of vectors: input vector $x \in R^m$, expected output vector $y^e \in R^a$, and undesired output vector $y^n \in R^b$ Among them, m, a, b represents the types of input–output elements. The matrices $X = [x_1, \cdots, x_n]\epsilon R^{m\times n}$, $Y^e = [Y_1^e, \cdots, Y_n^e]\epsilon R^{a\times n}$, $Y^n = [Y_1^n, \cdots, Y_n^n]\epsilon R^{b\times n}$, and $X > 0, Y^e > 0, Y^n > 0$are defined, and the possible set of system production based on constant returns to scale (CRS) is defined as follows:

$$\begin{cases} \rho^* = min\dfrac{1-\dfrac{1}{m}\sum_{i=J}^{m}\dfrac{d_i^-}{x_{i0}}}{1+\dfrac{1}{a+b}\left(\sum_{r=1}^{a}\dfrac{d_r^e}{y_{r0}^e}+\sum_{h=1}^{b}\dfrac{d_h^n}{y_{h_0}^n}\right)} \\ s.t.\, x_0 = X\lambda + D^-, y_0^e = Y^e\lambda - D^e, y_0^n = Y^n\lambda + D^n \\ D^- \geq 0, D^e \geq 0, D^n \geq 0, \lambda \geq 0 \end{cases}. \tag{8}$$

In **Eq. 8**, D^-, D^e, D^n represents the slack variable of the input, expected output, and undesired output, respectively. ρ^* indicates the target value of the Agricultural Eco-efficiency of the production decision-making units, $\rho^*\epsilon$ (0,1).

Data

The research object of this study focuses on the agricultural planting industry in a narrow sense. In order to measure the Agricultural Eco-efficiency, land, labor, machinery, irrigation water, pesticide, chemical fertilizer, agricultural film, and agricultural diesel are selected as input elements. In addition, agriculture itself has the value of ecosystem services so that agricultural carbon emissions and agricultural non-point sources are selected as undesired outputs. The specific indicator system is shown in **Table 1**.

This study conducted research on 31 provinces, municipalities, and autonomous regions in China (excluding Hong Kong, Macao, and Taiwan). The data of indicators are obtained from "China Rural Statistical Yearbook," "China Statistical Yearbook," and China's social and economic big data research platform.

RESULTS AND DISCUSSION

Overall Trends in Agricultural Eco-Efficiency

The growth trend of Agricultural Eco-efficiency is obvious; the provincial Agricultural Eco-efficiency in 2001 and 2012 is shown in **Figure 1**. From 2001 to 2019, the Agricultural Eco-efficiency showed an increased trend. The average value of Agricultural Eco-efficiency increased from 0.363 to 0.818, with a growth of 125.34%. All 31 provinces in the mainland are classified into three groups, namely, the eastern, central, and western. Overall, the provinces with higher Agricultural Eco-efficiency are mainly located in the eastern region, such as Zhejiang, Shanghai, Shandong, and Jiangsu. In 2019, the provinces mentioned above all equaled to 1. These provinces feature small agricultural output or a well-developing economy. For example, Zhejiang and Shanghai are two typical provinces with small agricultural output, and the gross domestic product (GDP) ranks at the upper level in China. In contrast, most provinces in the western region feature with low Agricultural Eco-efficiency, and these regions are characterized by a relatively high agricultural output and less developed economics. For instance, in 2001, Qinghai, Shanxi, Ningxia, and Gansu were the four provinces with lowest Agricultural Eco-efficiency. Nevertheless, the growth rate of Agricultural Eco-efficiency in the western region is faster than that in the eastern region, and there are significant differences in Agricultural Eco-efficiency among different provinces. For instance, as a typical representative of the western region, the Agricultural Eco-efficiency of Qinghai was 0.081 in 2001, while it increased to 1 in 2019.

However, it is interesting that although most regions in the western provinces had relatively low Agricultural Eco-efficiency, they were very likely to enjoy higher growth rates. Such rapid growth can be attributed to technology increase and urbanization. Due to rapid technology increase, the increase of Agricultural Eco-efficiency was generally faster than that of other regions. For example, the Agricultural Eco-efficiency of Shaanxi increased from 0.196 to 1, with an average growth rate of 21.59%. In addition, with the increased pace of urbanization, a large number of people tend to live in cities, and more machinery and equipment are put into production, which effectively improves the Agricultural Eco-efficiency.

TABLE 1 | Agricultural Eco-efficiency indicator system.

Indicator type	Indicator name	Indicator description	Unit
Input	Land input	Total sown crop area	Thousand hectares
	Machinery input	Total agricultural machinery power	10 thousand kilowatts
	Labor input	Primary industry practitioners *(total agricultural output value/total agriculture, forestry, animal husbandry, and fishery output value)	10 thousand people
	Chemical fertilizer input	Chemical fertilizer consumption	10 thousand tons
	Agricultural water input	Irrigation water consumption	Ton
	Pesticide input	Pesticide consumption	10 thousand tons
	Agricultural film input	Agricultural film consumption	10 thousand tons
Expected output	Total agricultural output value	Total agricultural output value	100 million yuan
	Ecosystem services	Ecosystem service value	10 thousand yuan
Undesired output	Agricultural carbon emissions	Total carbon emissions of chemical fertilizers, pesticides, agricultural films, agricultural diesel oil, agricultural irrigation, and agricultural sowing	The following carbon emission sources and their emission coefficients are selected: chemical fertilizer 0.8956 (kg/kg), pesticide 4.9341 (kg/kg), agricultural films 5.18 (kg/kg), diesel oil 0.5927 (kg/kg), agricultural sowing 312.6 (kg/km2), and agricultural irrigation 20.476 (kg/hm2)
	Comprehensive index of agricultural non-point source pollution	Calculated by the entropy method	—

There is a U-shaped change trend between the Agricultural Eco-efficiency and the total output value of agriculture, forestry, animal husbandry, and fishery. In other words, the provinces with the total output value of agriculture, forestry, animal husbandry, and fishery in the low range and high range enjoy higher Agricultural Eco-efficiency. For example, the total output value of agriculture, forestry, animal husbandry, and fishery in Zhejiang, Xinjiang, and Tibet is in the low range, and their Agricultural Eco-efficiency values in 2019 were all 1. Similarly, Shandong, Jiangsu, and other provinces are the regions with a high range of the total output value of agriculture, forestry, animal husbandry, and fishery, and their Agricultural Eco-efficiency all equaled to 1.

Provincial Agricultural Eco-efficiency Inequality

We also measure the provincial Agricultural Eco-efficiency inequality in **Figure 2**, and it can be found that Agricultural Eco-efficiency inequality declines with the growth of economics in China. At the provincial level, Agricultural Eco-efficiency inequality could be divided into three tiers. The first tier is the provinces with the Agricultural Eco-efficiency of 1, including Beijing, Shanghai, Hainan, and Tibet; these provinces featured with low agricultural output or high gross domestic production from 2001–2019, and the Agricultural Eco-efficiency of these four provinces was equal to 1. The second tier is the regions that did

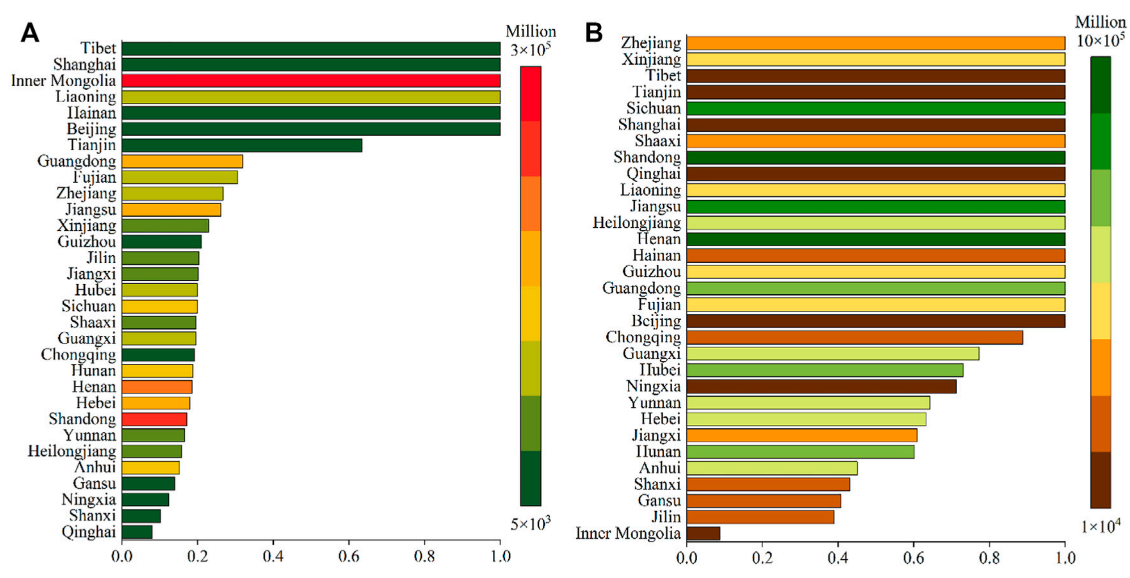

FIGURE 1 | Agricultural Eco-efficiency in China from 2001–2019 [**(A)**: 2001, **(B)**: 2019].

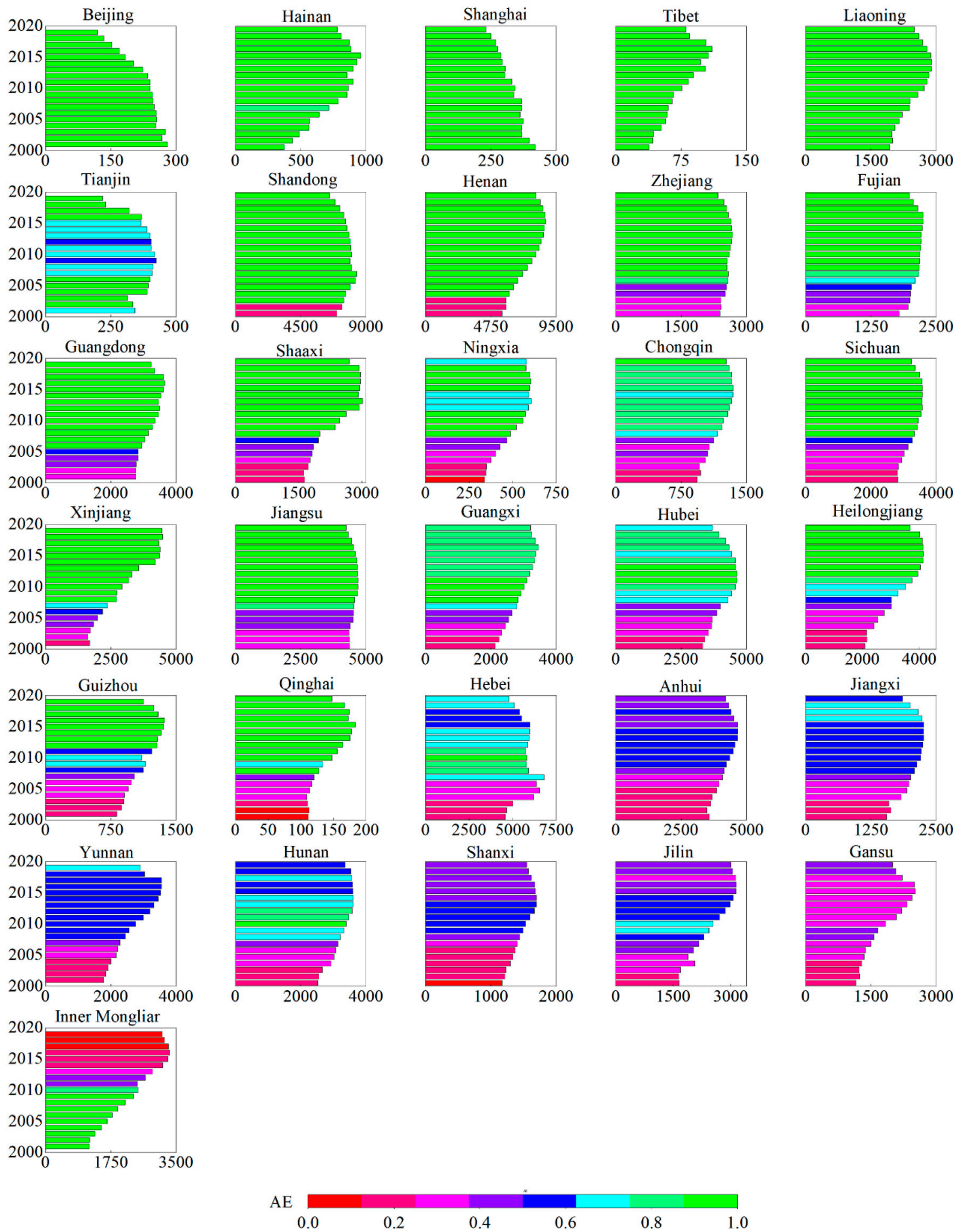

FIGURE 2 | Agricultural Eco-efficiency in different provinces from 2001–2019.

not start with an Agricultural Eco-efficiency of 1, but reached 1 in 2019, including 14 provinces. Many of these provinces are China's main grain producing areas, such as Shandong and Henan. This shows that with the implementation of China's ecological civilization construction, agricultural green development has become the mainstream of development, and Agricultural Eco-efficiency inequality between provinces is gradually decreasing. The third tier is provinces that have consistently failed to achieve an Agricultural Eco-efficiency of 1, such as Shanxi, Jilin, Gansu, and Inner Mongolia. These

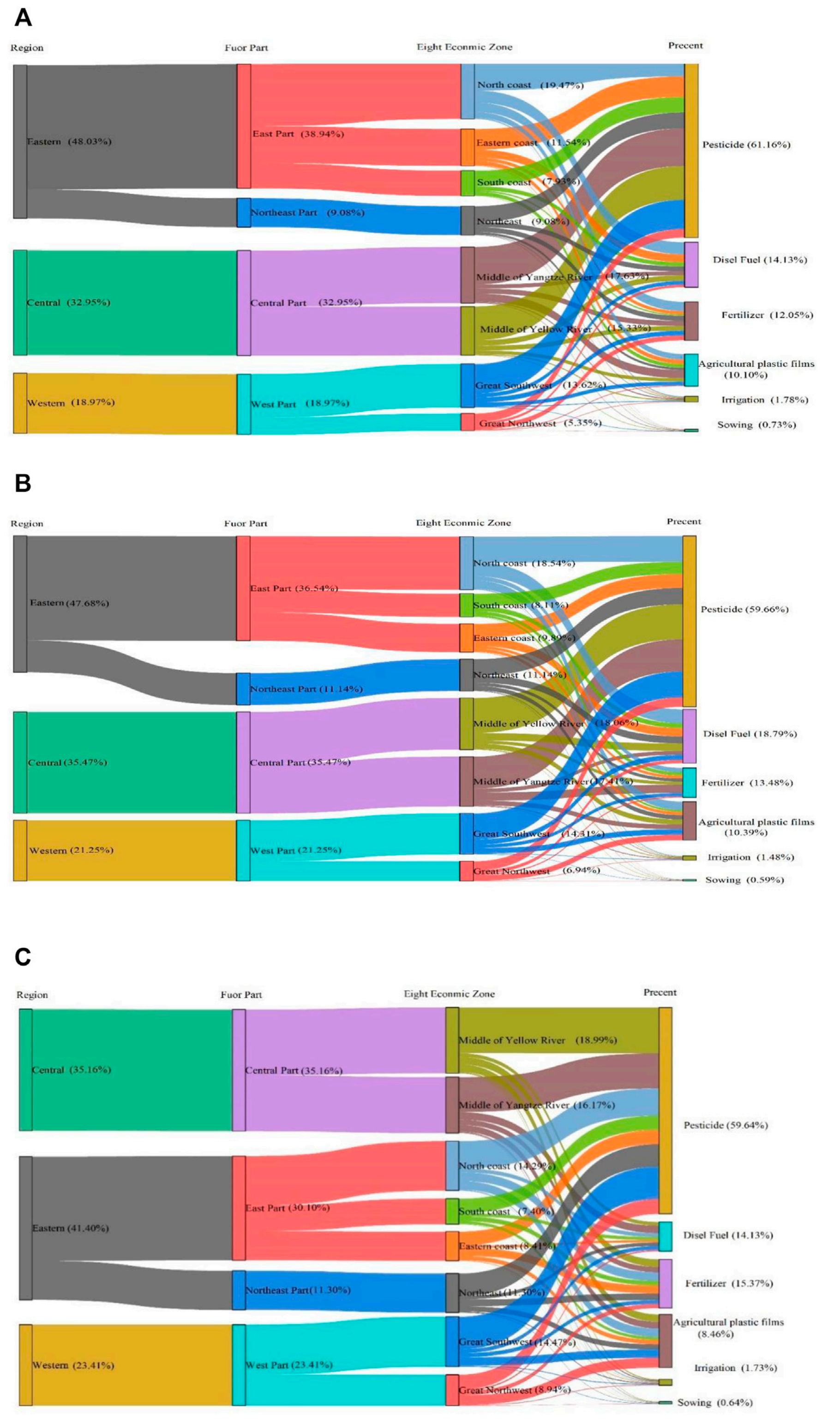

FIGURE 3 | Agricultural Carbon Emission Flow from 2001–2019 [**(A)**: 2001, **(B)**: 2010, **(C)**: 2019].

provinces are characterized with less developed economics. From 2001–2019, Agricultural Eco-efficiency inequality declined; to increase Agricultural Eco-efficiency, appropriate reduction measures should be taken by encouraging low-carbon and low–non-point source pollution production style. For instance, reduced fertilizer and pesticide use could influence Agricultural eco-efficiency inequality.

Drivers of Agricultural Eco-efficiency Inequality

The influencing factors of Agricultural Eco-efficiency inequality could date back to the source of undesired outputs. In **Figure 3**, pesticide, diesel fuel, fertilizer, agricultural plastic films, irrigation, and sowing are the main undesired output sources. The main source of carbon dioxide emitted during agricultural production was pesticides. In 2019, carbon dioxide from the pesticides accounted for 59.64% of total emissions, followed by fertilizer (15.37%), diesel fuel (14.13%), agricultural plastic films (8.46%), irrigation (1.73%), and sowing (0.64%). From the perspective of major carbon dioxide emission regions, provinces in the eastern region emitted the highest level of carbon dioxide, accounting for 41.40% in 2019, followed by the central (35.16%) and the western (23.41%) regions. In view of the distribution of the four major parts and the eight major economic zones, the eastern is divided into the east part and northeast part. The east part accounted for 30.10% of carbon dioxide emissions and the northeast part occupied 11.30%. Among the eight major economic zones, the middle reaches of Yellow River took up the highest carbon dioxide emissions, reaching 18.99%. This is closely linked to the important agricultural production bases in this economic zone such as Henan, Shandong, and other provinces. The economic zone that ranked second in terms of emissions was the middle reaches of Yangtze River (16.17%), which fully confirms that the Yellow River Basin and the Yangtze River Basin are the main agricultural planting areas in China. Such performance of agricultural carbon emission was primarily due to increase of planting area. With the implementation of the green development strategy, the agricultural carbon emissions are expected to decrease.

In terms of time and space, the proportion of carbon dioxide emitted by agricultural production has decreased in the eastern region and the share in the Central and Western regions has increased. From the perspective of spatial change, from 2001 to 2019, carbon emissions in the eastern region showed a downward trend, from 48.03% in 2001 to 47.68% in 2010 and 41.4% in 2019, with a decrease of 6.63%. Specifically, the main reason for the change was the decline in the east part, especially due to the rapid urbanization of the eastern provinces, such as Beijing and Shanghai, which has caused part of the agricultural land to be replaced by urban land. What is more special is that the percentage of carbon emissions in the northeast part has shown an increasing trend, increasing by 2.22% from 2001 to 2019, mainly caused by the use of pesticides and machinery in northeast China. In addition, the shares of agricultural carbon emissions in the central and west part have shown an increasing trend, with 32.95%–35.16% in the central and 18.97%–23.41% in the western region.

To achieve carbon neutrality, the Chinese government should pay more attention to agriculture, especially for Agricultural Eco-efficiency. National Agricultural Eco-efficiency increased by 125.34% from 2001 to 2019, and all provinces experienced rapid growth. Due to the implementation of green development policy and urbanization, Agricultural Eco-efficiency inequality is expected to decrease in China, and great efforts should be paid to deal with this problem in the future.

Our results highlight the influencing factors affecting Agricultural Eco-efficiency. The eastern region always enjoys high Agricultural Eco-efficiency; in 2001, Agricultural Eco-efficiency in Shanghai was 12.35 times higher than that of Qinghai, also characterized with low agricultural output. The Agricultural Eco-efficiency will exist for a very long time in China, the green development strategy will give an opportunity for sustainable agricultural development, and the technology development of the central and western regions will be very useful to bridge the gap. Furthermore, compared with the eastern region, the middle reaches of Yellow River and middle reaches of Yangtze River have great potential in reducing carbon emissions. The output of grain and meat in the Yellow River Basin accounts for one-third of the country's output, and the Yangtze River Basin is a land of fish and rice in China. The grain produced in the Yellow River Basin and the Yangtze River Basin accounts for more than 60% of the country's production. Therefore, taking these two regions as key emission reduction regions will be significant to agricultural eco-efficiency improvement.

POLICY IMPLICATIONS

Given the outputs of agriculture, the government should focus on guiding the planting type. The changing planting type should join the government and farmer together. For the government, a more greener planting guide should be given. A model of agricultural development in harmony with nature, such as combining planting and raising, intensive farming, and using land for cultivation, should be formed. Focusing on the adaptation of the development of the planting and breeding industry to the carrying capacity of the resources and environment, efforts should be taken to solve the outstanding problems of the dirty, chaotic, and poor rural environment, such as reducing livestock manure, crop stalks, and other planting and breeding wastes. According to the cyclical development concept of "planting industry drives breeding industry; breeding industry promotes planting industry," taking local consumption, energy recycling, and comprehensive utilization as the main line and considering equal emphasis on economic, ecological, and social benefits as the guide, the operation mode of government support, enterprise operation, social participation, and promotion of the whole county should be adopted to build a coordinated development model of planting and breeding that combines intensive, standardization, organization, and socialization. In addition, it is necessary to explore comprehensive and overall solutions for waste recycling of the planting and breeding industry in typical counties, and form a long-term mechanism of county-rural enterprise linkage and construction management operation, so as to effectively prevent and control agricultural non-point source pollution, improve the efficiency of agricultural resource utilization, promote the transformation of agricultural development mode, and boost sustainable agricultural development.

It is necessary to continue to reduce the use of chemical fertilizers and pesticides and increase their efficiency. On the one hand, the government should further promote the development of soil testing, formula fertilization, unified control of crop diseases and insect pests, and whole-process green prevention and control and improve farmers' awareness and skills of scientific fertilization and pesticide use, thus reducing the use of fertilizers and pesticides. On the other hand, it is also important to integrate and promote green and efficient technologies, such as deep application of chemical fertilizers by machinery, simultaneous sowing of fertilizer and integration of water and fertilizer, and applying green prevention and control technologies such as ecological regulation, biological control, and physical and chemical control. In addition, quality standards for agricultural inputs, such as chemical fertilizers and pesticides, should be revised and strictly implemented so as to strictly control the use of high-toxicity and high-risk pesticides and develop and promote new products and advanced fertilization and application machinery, such as high-efficiency and slow-controlled release fertilizers; high-efficiency, low-toxicity, and low-residue pesticides; and biological fertilizers and pesticides.

CONCLUDING REMARKS

Carbon neutrality is not a constraint on economic growth but an important source of China's total factor productivity growth. It will promote rapid changes in China's economic growth momentum and growth model in the new development stage. These carbon node industries include both production-oriented industries and consumer-oriented industries, which are not completely overlapped with traditional high-energy consuming industries. The core of agricultural emission peaking and carbon neutrality is to promote the transformation of the agricultural development mode to a comprehensive green and low-carbon mode. The results show that the provinces in the central and western region had a low value of Agricultural Eco-efficiency in China, and the middle reaches of Yellow River is the key zone of carbon emissions and non-point source pollution control, so it is necessary to effectively improve agriculture based on the improvement of Agricultural Eco-efficiency. Agriculture, as a basic industry, plays an important role in the whole socioeconomic development. In the process of supporting agricultural development, agriculture will produce "desirable" products, such as grain, fruit, and other products, and "undesirable" outputs, such as greenhouse gases, such as carbon dioxide, methane, and nitrogen dioxide. Taking these undesired factors into account in agricultural production is of great significance to accurately quantify agricultural inputs and outputs and provide important parameters for the next step of promoting greener Chinese agriculture.

Although our study produced some informative findings, there still exist some limitations of this study. This study focuses on agricultural planting, innovatively taking agricultural ecosystem services as expected outputs, and considering carbon emissions and non-point source pollution as undesired outputs. However, agriculture will also produce undesired outputs, such as methane and nitrous oxide, which will be introduced into our research as new variables in the future.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

LM and JH conceived the study and wrote the manuscript. GW and ZQ analyzed data for figures and table. All authors contributed to manuscript development and edited the final version.

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