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Research article

Research on agri-environmental technology efficiency——take Jilin Province in China as an example

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A R T I C L E I N F O

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A B S T R A C T

From the perspective of the world agricultural development law, agricultural economic development and ecological environmental protection usually fall into a dichotomy paradox, according to the history of agricultural development in developed countries, they also experienced the rapid development of agriculture led to the destruction of the agro-ecological environment, which has become a key element hindering the sustainability of agriculture. Subsequently, developed countries rely on modern technology to achieve the transition from traditional agriculture to modern agriculture, crossing the paradoxical trap of economic development and ecological construction. At the present stage, China also shows the sharp contradiction between agricultural development and ecological construction, the traditional agricultural production methods of agricultural output has basically reached the limit, however, the established production methods of the ecological environment caused by the negative effects of the more and more serious, so that the agricultural environmental technology efficiency is not optimistic, so there is an urgent need to have a clear understanding of the main grain-producing areas of China's agricultural environmental technology efficiency and the factors affecting it. As an important grain producing area in China, Jilin Province's agricultural development level is in the forefront of the country, and it is also facing the contradiction between agricultural development and ecological environmental protection at the present stage. In order to realize the green transformation of agriculture and improve the technical efficiency of agricultural environment, it is necessary to rely on the optimisation of multi-dimensional factors such as technology and system. The study of agricultural environmental technical efficiency in Jilin Province has important theoretical significance and practical value for guiding other agricultural areas to realize the green transformation of production mode.

1. Introduction

Economic development and environmental breakthroughs are unavoidable contradictions in the process of social development, often falling into the dichotomy of economic development and environmental protection, and the effective elimination of obstacles between the two has become the key to the transformation of development. The dichotomy between development and environmental protection in the field of agriculture is particularly obvious. Throughout the history of agricultural development in developed countries, we have experienced the stage of agricultural development at the cost of resource consumption and environmental damage,

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and achieved rapid agricultural development, but the negative effects derived from this mode of production for a long time have made the developed countries re-examine the relationship between agricultural development and ecological environment, and focus on the synergy between the two, and put the solution idea on the green transformation of the mode of agricultural production, and reduce the ecological damage caused by the link in the agricultural production. With the rapid development of the economy and society, the connotation of agricultural green production tends to be subtle and specific, agricultural carbon emissions have become the focus of attention in the current stage of agricultural green development and deepen the important consideration of agricultural green sustainable development factors [1].

Agriculture is the basic industry of China's national economy, and the agricultural development path with Chinese characteristics has been formed in the process of historical development [2]. In China's gradual development from a poor and weak country to the second largest economy in the world, agriculture has made an important contribution to economic growth. In addition to this, the role of agriculture has become even more pronounced in terms of its social attributes, such as guaranteeing a stable supply of agricultural products and ensuring food security. As the world's largest developing country, China uses only about 7% of the world's arable land to feed about 21% of the world's population, which is a world miracle created by China's agricultural development [3], and stems from the result of the timely reform and innovation of China's agricultural economic system and the continuous improvement of agricultural technology to bring about an increase in productivity, which lays a solid foundation for China's entry into the world's agricultural products market, and its participation in international competition and cooperation. China's great achievements in agricultural development are obvious to all.

However, the objective fact that needs to be recognised is that for a long time China's rapid agricultural development has been at the expense of resource consumption and environmental damage, which is reasonable and necessary in the early stage of development to promote economic growth, and provides a necessary source of funds for the construction of a perfect economic system. However, with the gradual improvement of the economic system, agriculture is no longer the main engine for achieving economic growth. The negative effects of the longstanding crude production methods have come to the fore. Modern agricultural means of production and production technology innovation breaks through the traditional agriculture due to resource constraints and long-term unchanged lower agricultural productivity. The use of fertilisers, pesticides and other external means of production breaks through the original crop yield boundaries, resulting in the marginal contribution to promote the application of fertilisers, pesticides and other agricultural production, popularity. On the other hand, the high-yielding crop varieties developed are dependent on chemical fertilisers and pesticides, and higher inputs of chemical fertilisers and pesticides must be used to obtain higher yields, so that agriculture has entered a stage of development characterised by "fossil agriculture". This kind of crude production method does not fully consider the carrying capacity of agro-ecology, and the lack of rational application causes the decline of arable land strength and the pollution of water sources, and the atmospheric pollution caused by straw burning constitutes the three-dimensional pollution of the agro-ecological environment. Although the application of exogenous agricultural production materials and agricultural technology has greatly improved the efficiency of agricultural production, the negative effects derived from them are becoming more and more acute with the contradiction of the agro-ecological environment, contrary to the principle of sustainable development of agriculture, and restricting the transformation of China's agricultural modernisation. At the same time, it is contrary to the principle of agro-ecological construction and green agricultural development advocated by China, and the negative benefits to the ecological environment generated by the agricultural production chain are offsetting the positive externalities generated by the improvement in the efficiency of agricultural technology brought about by agricultural technological change.

The main grain-producing areas are the foundation of China's agricultural development, and play an important role in ensuring the stable operation of the agricultural economy and the supply of grain. In the meantime, China's main grain producing areas are generally facing relatively serious problems of agricultural surface pollution. Due to the lack of property rights incentives in China's arable land system, producers do not take active ecological care of their arable land and lack protective farming measures; the monoculture planting structure has led to an imbalance in soil organic matter, and the stable production and supply of food can only be ensured by additional inputs of fertilisers, resulting in an obvious decline in the quality of arable land, which has been plunged into a vicious circle. Food production is based on the increased application of chemical fertilisers, which increases agricultural carbon emissions and releases negative effects on the agro-ecological environment. On the other hand, the large amount of straw produced annually in the main grain-producing areas is also a major cause of agricultural surface pollution in China at this stage, and this kind of undesired output in the agricultural production chain limits the improvement of the technical efficiency of the agri-environment to a certain extent. The main grain-producing areas have resource endowment advantages in promoting agricultural modernisation, and as key areas for agro-ecological construction, they need to accelerate the optimisation of the existing "crude" agricultural production methods. More attention to the control of agricultural carbon emissions in agricultural development is the main focus of green development of modern agriculture, and is an effective measure to improve the efficiency of agricultural environmental technology. Therefore, understanding the current situation of agricultural environmental technology efficiency in China's main grain-producing areas and clarifying the main factors and mechanisms affecting agricultural environmental technology efficiency are of theoretical significance and practical value for promoting the green and sustainable development of agriculture. Jilin Province has proposed the goal of taking the lead in realising the modernisation of agriculture, so the study of the technical efficiency of the agricultural environment in Jilin Province is of reference value in guiding other food-producing regions. This paper takes Jilin Province of China as a research sample, objectively and scientifically measures the agro-environmental technical efficiency of Jilin Province from 2000 to 2021, and analyses the status quo and objective facts of the agro-environmental technical efficiency of Jilin Province from 2000 to 2021 based on the results of the measurements, and assesses the factors and mechanisms affecting the agro-environmental technical efficiency of Jilin Province.

2. Literature review

Agricultural environmental technical efficiency is a comprehensive concept, research in this area has a long history, at different times, the connotation of agricultural environmental technical efficiency and the focus of research is different, from the initial focus on the impact of agricultural resources on the technical efficiency of agriculture gradually extended to the current agricultural production chain of carbon emissions on the technical efficiency of agriculture, green sustainable development of agriculture has become a cutting-edge issue in the field of agriculture.

2.1. Study on agricultural technology and technical efficiency

In the traditional agricultural stage, the means of production required for agricultural production basically come from within agriculture and animal husbandry, and the waste produced is almost embedded in the agricultural production cycle, which realises the use of resources and produces positive externalities on the agro-ecology. Agricultural production and the ecological environment formed a virtuous cycle between the relationship, but because of agricultural technology for a long time without fundamental breakthroughs, agricultural technology efficiency has been maintained at a low level. To break this special economic equilibrium of traditional agriculture, the most effective solution is to introduce modern agricultural production factors and train farmers [4]. The industrial revolution brought about worldwide technological innovation, and the rapid establishment of the industrial system and its extension to the agricultural field brought about changes in agricultural production methods. Developed countries that took the lead in completing industrialisation applied the results of industrialisation to the field of agricultural production, so that the efficiency of agricultural technology was radically improved compared with the traditional agricultural stage, and agriculture entered a stage of rapid development.

China's technological change is seriously lagging behind the pace of the world, the establishment of the industrial system began in the field of heavy industry, it is difficult to be applied to the field of agriculture, to bring about a breakthrough in production efficiency. It was not until after the reform and opening up that mature industrialised agricultural means of production were gradually applied to family agricultural production and management, and the popularisation of technology was a key factor in improving agricultural productivity and yield [5], and Chinese agriculture entered a stage of rapid development. Exogenous agricultural means of production, compared with the traditional agricultural stage originating from the limited means of production within agriculture, is the result of technological innovation and effectively realises the transformation of the results, and maintains a marginal contribution to agricultural productivity over a longer period of time. However, the negative ecological effects caused by this production mode of relying on exogenous agricultural means of production to maintain agricultural growth have gradually emerged [6], and when agricultural technological innovation has basically reached the upper limit, the agricultural production efficiency has reached the theoretical threshold, and the contradiction between the bottleneck of the growth of production efficiency and ecological environmental protection has become a key factor that needs to be solved for the sustainable development of agriculture.

With the development of the times, carbon emission has been taken as an important indicator of green development, and agricultural carbon emission has also been included in the green production evaluation system. To reduce carbon emissions from agricultural production, it is necessary to change the current crude production and management methods and optimise the use of agricultural technology and production materials. Nowadays, many countries have realised the role of technological innovation in reducing carbon emissions [7], and China has also clearly pointed out that technological progress can be used to solve ecological and environmental problems [8]. The essence of technological innovation is the improvement of technological efficiency, which is regarded as the trigger and catalyst for sustainable development [9], and the focus point for improving technological efficiency in agri-environment.

2.2. Study on the agri-environmental technology efficiency

Resources and the environment are the prerequisites and basis for economic development and are one of the driving forces of agricultural economic development. Environmental technical efficiency is not a new concept; the National Organisation for Standardisation (ISO) innovatively proposed in 1996 a measurement indicator that takes into account the carrying capacity of the environment and the quality of environmental development, which objectively defines the technical efficiency of the agricultural environment in the context of the destruction of the agro-ecological environment, which to a certain extent restricts the development of agriculture. Earlier research on the technical efficiency of the agricultural environment started with water resources, and regarded the technical efficiency of the agricultural environment as a response to the efficiency of irrigation, through the efficient use of water resources to achieve the highest yield [10], and the environmental elements of agricultural production play a positive role in promoting the improvement of the efficiency of agricultural production. If we only consider the element of water resources in the agricultural environment, from the theoretical level has its one-sidedness, for this reason. Mutry in the study of technical efficiency of the agricultural environment will be the resources and ecological environment as a double constraint, and the cost of pollution control as a non-desired outputs into the study of an important element of the consideration [11], the pollution of the environment brought about by the agricultural production chain gradually in the measurement of the technical efficiency of the agricultural environmental as an factor that cannot be ignored [12]. With the rapid advancement of industrialisation, the positive effects of its formation extend to the agricultural field, promoting agricultural production efficiency significantly increased at the same time, but seriously ignored the negative effects on the agro-ecological environment, especially fertilizers, pesticides and other agricultural chemicals into the use of both the original ecological already very fragile region to increase the pressure, but also a significant increase in greenhouse gas emissions [13]. However, agricultural development and environmental pollution are not irreconcilable conflicts, and improving the technical efficiency of the production chain will significantly reduce carbon emissions from inputs [14–16], leading to improved economic and environmental benefits [17]. The impact of agricultural production on the environment has become an important element in evaluating the performance of economic activities [18], which is conducive to a full understanding of the efficiency value of agricultural non-desired outputs incorporated into production efficiency measurements, and establishes a basis for analysing the technical efficiency of agricultural environment. China attaches importance to the restoration and protection of agro-ecological environment in the construction of macro-mechanisms, and has established a relatively perfect agro-ecological protection system, which has led many scholars to pay attention to agro-environmental technical efficiency. Relevant research shows that although China has set up a relatively strict agro-ecological environmental protection system at the macro level, there is a deviation between the agricultural production practice and the system set up, and the operators in the agricultural production cycle, the growth rate of agricultural output lagged behind the growth rate of agricultural production factor inputs, which exceeded the carrying capacity of the environment, this excessive means of production inputs have caused more and more pressure on the environment [19]. This agricultural pollution has gradually presented a cross-cutting, three-dimensional and complex trends, how to deal with the efficiency of agricultural production and ecological construction has become an important proposition, the relationship between the efficiency of agricultural production across the new growth stage, the optimisation of the growth model as well as the improvement of rural habitat [20].

2.3. Study on the methodology for measuring the efficiency of agri-environmental technologies

With the gradual deepening of the study of agro-environmental technology efficiency, the method of its measurement has been gradually improved. Envelopment analysis method is used in the analysis of agro-environmental technology efficiency, and its advantage is shown in the analysis process can not preset the production frontier function, removing the parameter problem [21]. The stochastic frontier analysis method can achieve the explanation of the reasons for the changes in the results due to technological changes [22], and it has the advantage of separating the effects of random error terms from inefficiency [23,24]. Since the lack of detailed records of production by farmers in agricultural production and management can easily lead to errors in the data obtained from the research, stochastic frontier analysis is widely used [25], and it is also a fundamental method for measuring the technical efficiency of agri-environmental technologies. Gradually, the impact of climate change on the technical efficiency of agricultural production has attracted attention, and scholars have focused on the two-stage Tobit model analysis to study how climate change affects the technical efficiency through the spillover effect in the agricultural field [26,27]. While focusing on climate change, scholars are also aware of the impact of air pollution from industrial activities on the technical efficiency of agriculture, and the technical efficiency estimated using the traditional stochastic frontier analysis method seems to be overestimated compared with the technical efficiency estimated using the modified method without considering the changes in the production function, for this reason in order to address the technical efficiency of agricultural production of air pollution, scholars proposed a method that combines the Gaussian plume dispersion model with an agricultural production function to estimate the impact of point source air pollution on agricultural production [28]. In analysing China's specific agri-environmental technical efficiency problems, scholars have expanded and innovated on the traditional measurement methods. Some scholars have constructed an environmental technology efficiency measurement model based on the SBM model and the SBM-NS model to measure the decline in agricultural environmental technology efficiency in Shandong Province as a result of environmental regulation, in combination with the phenomenon of the decline in agricultural environmental technology efficiency in Shandong Province caused by environmental regulation in the context of environmental regulation [29]. In addition to measuring agricultural environmental technical efficiency for a certain region, there are also many scholars who measure China's agricultural environmental technical efficiency from a holistic and global perspective. Based on multi-layer statistical model analysis, Q. Liu divided China into three major regions, measured the multi-period agri-environmental technical efficiency of each province using the super-efficient DEA non-parametric method, and analysed the efficiency trend [30]. Also generally dividing China into three major regions, some scholars have measured the efficiency of China's agricultural production with the help of macro data and made convergence analyses using beyond logarithmic stochastic frontier analysis [31]. In recent studies, agricultural non-desired outputs have been included in the consideration of agri-environmental technical efficiency and attention has been paid to the circulation of non-desired outputs within the agricultural system, for example, the return of straw and manure to the field is effective in transforming the non-desired outputs into productive inputs in agriculture. Therefore, the authors used the nitrogen surplus intensity of agricultural land as an indicator of undesired output, and used the Super-SBM model and the Malmquist-Luenberger productivity indicator to specifically measure agri-environmental technological efficiency and green total factor productivity growth over a multi-year period in 29 provinces in China [32].

2.4. Study on the factors influencing the efficiency of agri-environmental technologies

Many scholars have analysed and explained the influencing factors when measuring the technical efficiency of agricultural environment, and the influencing factors of the technical efficiency of agricultural environment vary significantly from different research perspectives and different regions. At the national level, some scholars have constructed a general input-output framework for agricultural production activities, in which the non-desired outputs include chemical oxygen demand and total phosphorus and nitrogen production of major pollutants produced in agricultural production activities, as well as their emissions through multiple pathways into the water as the main influencing factors to evaluate the technical efficiency of agricultural environmental technology [33]. Some scholars have also started with macro factors to analyse the influence mechanisms of the level of economic development, agricultural structure, agricultural resource endowment, agricultural infrastructure, environmental regulations and related policies on agri-environmental technical efficiency [34]. On the geographical level, existing studies have also carried out more detailed research [35–37], measured the spatial variability of interregional agri-environmental technology efficiency and clarified the main influencing factors and role of the mechanism, which leads to interregional agri-environmental technology efficiency variability of the most important influencing factors are technology and management [38]. At the same time, in the consideration of the influencing factors, the analysis is diversified from both internal and external perspectives of the region [39–41], and gradually focuses on the impact of carbon emissions on agri-environmental technical efficiency [42]. In other aspects, with the promotion of urbanisation, the phenomenon of part-time farmers is very common, and the outsourcing of agricultural production services has become more and more mature, which to a certain extent circumvents the shortcomings of smallholder production, and the introduction of outsourcing services effectively meets the challenges faced by green agricultural production, and becomes a key factor affecting agri-environmental technology efficiency [43]. Currently, in the context of the frequent occurrence of extreme weather, the impact of climate on the efficiency of agri-environmental technology should not be ignored [44].

Through the combing of the literature, agricultural environmental technology efficiency is gradually attracted the attention of scholars during the modern agricultural development process, accumulated and summarised a more mature research methodology, on the agricultural environmental technology efficiency sub-region, in different periods has done a more comprehensive measurement, the role of its influencing factors have been from a variety of perspectives to carry out an in-depth analysis of the role of the mechanism. However, the existing literature is rarely concerned about the technical efficiency of the agricultural environment of the main food-producing areas, in the situation of agricultural surface pollution is more serious in the agricultural production chain produced by the non-desired output category consideration is relatively single, and the evaluation index system update lagging behind. Therefore, this study is based on Jilin Province, which is the main grain producing areas, selects indicators for measuring agricultural non-desired outputs, and updates the evaluation system with the policy objectives of agro-ecological construction to ensure the objectivity and scientificity of the results. It analyses the mechanism of influencing factors and provides a theoretical reference basis for enhancing the capacity of sustainable agricultural development.

3. Theory, materials and methods

3.1. Theory

The theory of technical efficiency was first proposed by the British economist Farrell in 1957, who defined the concept of technical efficiency from the input perspective by applying production efficiency measures in his study of agricultural production in the UK, replacing the pre-determined function with a non-pre-determined production function to speculate on the value of the efficiency, and by using linear programming to derive the efficiency frontier [45]. Unlike Farrell, Leibenstein defined technical efficiency from the output perspective in 1966, and his concept of technical efficiency was the maximisation of the level of output that can be achieved given the stability of input sizes, resource factors and market values [46]. Taken together, the definition of technical efficiency, both from the input perspective and from the output perspective, refers to the ratio of the actual production value to the optimal production capacity, both reflecting the degree of technological development of the current optimal production. If the value of technical efficiency is 1, it indicates that the technology has been fully utilised in the production process; if the value of technical efficiency is less than 1, it indicates that there is a loss of technological performance.

Technical efficiency defined from an input perspective (Fig. 1). Assuming that in the production process X_1 , X_2 are the input factors, Y is the output factor, LL' is the output curve, then $Y = f(X_1, X_2)$ is the frontier production function on its output curve; AA' is the isocost curve. Since the market price is fixed, its slope is also fixed. Q is a technically efficient unit, the intersection point of the equal cost curve and the equal output curve is Q', which is the technologically efficient and efficiently-configured economically efficient unit; P is a non-economically efficient unit, which can be expressed as QP/OP. The value of technical efficiency is expressed as:

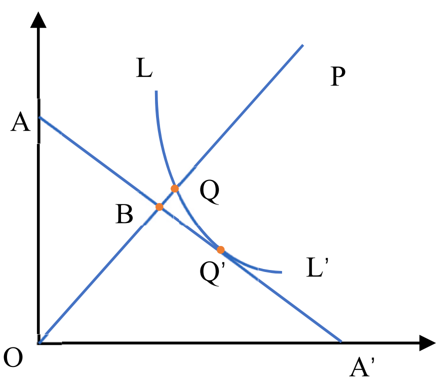

Fig. 1. Technical efficiency from an input perspective.

$$TE = OQ/OP = 1 - QP/OP$$

when Q moves to Q' while reducing the cost of production, the configurational effectiveness achieved by P is denoted as $OB/\ OQ$ and BP is represented as the distance to reach economic efficiency. The value of economic efficiency can be expressed as:

$$EE = OB/OP = OQ/OP * OB/OQ$$

Technical efficiency defined from an output perspective (Fig. 2). Assuming that in the production process X is the input factor and Y_1 , Y_2 are the output factors, RR' is the production possibilities curve, and P is the non-economically efficient unit in terms of output, which can be expressed as O P/OE, its technical efficiency is:

$$TE = OP/OE = 1 - PE/OE$$

When E moves to E', the amount of output becomes less, then P achieves an allocative efficiency of O P/OD and an economic efficiency value:

$$EE = OP/OD = OP/OE * OE/OD$$

At this stage of theoretical development, academics have mostly adopted and applied technical efficiency theories from an output perspective.

As technology advances, it drives the rapid improvement of technical and economic efficiency and is constantly being optimised. However, its negative effects on the environment are becoming more and more obvious and have become an important factor hindering development. On the basis of technical efficiency research to pay attention to ecological issues has become the focus of academic research at this stage, aimed at balancing the relationship between economic development and the ecological environment, research on technical efficiency and ecological environment has gradually developed into a cross-cutting field, especially in the agricultural production chain, inputs and outputs and ecological links there is a correlation between the scholars use the input-output ratio to measure the impact on the environment. With the development of technology and economy, the factors affecting the agro-ecological environment have become more specific, and the use of carbon emissions in agriculture as one of the factors measuring the impact of the environment and resources on technological efficiency in an all-round way is a further expansion of the previous research.

3.2. Data

In order to clearly understand the status of agricultural environmental technology efficiency and influencing factors in China's main grain-producing areas at this stage, Jilin Province is taken as a research sample to be analysed. The reason for selecting this sample is that Jilin Province is one of the 13 main grain-producing regions in China, and its agricultural development level is at the forefront of the main grain-producing regions, which has certain representative and typical. Jilin Province has proposed to take the lead in achieving the goal of agricultural modernisation, but the current stage of agricultural production and agro-ecology facing surface pollution is contrary to the goal of agricultural modernisation and sustainable development, and there is a realistic need to improve the technical efficiency of the agri-environment. The results of the study are of great significance for other major grain-producing areas to improve the technical efficiency of the agricultural environment.

Data on the total sown area of crops, the number of labourers, the total power of agricultural machinery, capital inputs, the gross agricultural product, and the amount of inputs of the main means of production in the agricultural production chain (fertilizers, pesticides, diesel fuel, and agricultural films) used to measure the technical efficiency of the agricultural environment in Jilin Province were obtained by consulting the Jilin Statistical Yearbook (2009–2022) and the portal website of the National Bureau of Statistics of

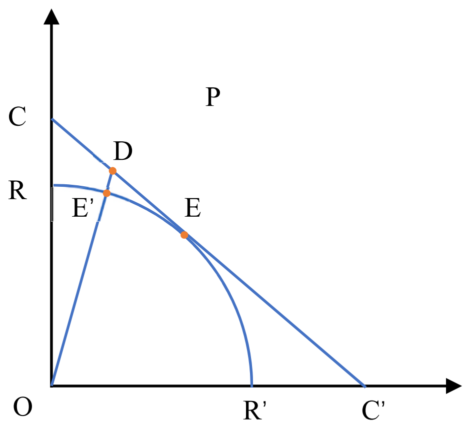

Fig. 2. Technical efficiency from an output perspective.

China. The quantification of carbon emissions from the agricultural production chain is based on the inputs of the main means of production, and is obtained through calculations based on the emission coefficients of carbon emission sources and the quantities of agricultural inputs in the Handbook of Emission Coefficients for Agricultural Pollution Sources.

The data used to analyse the crop-affected area, the income level of rural residents, the gross plantation product, the gross agriculture, forestry, animal husbandry and fishery product, the agricultural finance and total financial expenditure, the urban and total population, the total power of agricultural machinery, and the area of commonly used arable land involved in analysing the factors influencing the technological efficiency of the agricultural environment in Jilin Province were obtained by consulting the Jilin Statistical Yearbook (2009–2022) and the portal website of the National Bureau of Statistics of China.

In terms of the period of data selection, this research intercepts the data between 2008 and 2021, The data were selected on the basis of since 2008, Jilin Province, as one of the agricultural support policy pilots for corn and soybeans, has had more frequent policy changes. Behavioural decisions of agricultural producers and operators are strongly influenced by policy fluctuations, which in turn affects the deployment of household resources by farmers and, by extension, the technical efficiency of the agri-environment.

3.3. Model and variables

3.3.1. SBM model and variables

(1) Non-parametric envelopment analysis (DEA) is the basic method commonly used to measure technical efficiency, but it has more stringent requirements for data, and the model only considers input and output indicators directly related to production, i.e. the evaluation of pure technical efficiency. The evaluation of comprehensive technical efficiency is a response to the resource allocation capacity of decision-making units, which also involves the impact of scale efficiency on decision-making units, responding to the gap between the actual scale and the optimal scale. The quantitative relationship between the three of them can be expressed as follows: comprehensive technical efficiency = pure technical efficiency * scale efficiency. Different from the measurement of technical efficiency in the traditional DEA model, the SBM model can incorporate the non-desired output generated in the production chain into the measurement of technical efficiency.

Suppose there are n decision units, each with m input indicators, $X \in R^m$, h desired outputs, $X \in R^k$, and n non-desired outputs, $X \in R^n$, then it satisfies the following condition

$$X = (x_1, x_2, x_3, \ldots, x_m) \in R^m$$
$$Y = (y_1, y_2, y_3, \ldots, y_m) \in R^h \tag{1}$$
$$Z = (z_1, z_2, z_3, \ldots, z_m) \in R^n$$

The production possibility set T is thus defined as:

$$T = \{(X, Y, Z) | x \geq \lambda X, y \geq \lambda Y, z \geq \lambda Z, \lambda \geq 0\} \tag{2}$$

In the formula, λ denotes the weight vector, the SBM model based on non-expected output is:

$$\rho = min \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{S^-}{x_i}}{1 + \frac{1}{h+n}\left(\sum_{i=1}^{h}\frac{S^g}{y_i} + \sum_{i=1}^{n}\frac{S^-}{z_t}\right)}$$
$$\lambda X + S^- = x_i$$
$$\lambda Y - S^g = y_i \tag{3}$$
$$\lambda Z + S^b = z_n$$

In the formula, S denotes redundant variables for input and output indicators, S^- and S^b denote slack in inputs and undesired outputs, respectively, S^g indicates a shortfall in agreed outputs. When $\rho = 1$, S^-, S^b, S^g are all 0, indicating that the decision unit is effective; When $0 < \rho < 1$, the decision unit is relatively ineffective, and the inputs and outputs have room for improvement.

(2) For the measurement of the technical efficiency of the agricultural environment in Jilin Province, input and output indicators closely related to the production chain and the agro-ecological environment are selected, of which the input indicators are as follows:

a) Land factor inputs. Land is one of the most basic elements of agricultural production and constitutes the prerequisite and foundation of agricultural production. The land element is the key to the production behaviour of farmers to make decisions, and the size of the land directly determines the amount of agricultural production materials and productivity inputs and the final yield of crops, and the appropriate scale of operation will produce economies of scale, bringing the optimisation of agricultural production inputs and desired outputs. Meanwhile, in the agricultural production chain, ploughing, sowing, irrigation and harvesting are the main sources of carbon emissions, forming the agricultural non-desired outputs, and the level of such non-desired outputs is directly related to the inputs of land elements, so the area of arable land is regarded as the basic element of agricultural inputs.

b) Labour factor inputs. The labour force is necessary to ensure the normal operation of agricultural production and business activities, and in this research, the labour force is considered in a broad sense, including operators directly involved in agricultural production, as well as labourers involved in a certain production process, so that rural workers, who are excluded from the labour force of rural industries and services, are considered as a factor of labour force inputs.
c) Capital factor inputs. At the macro level, the agricultural expenditure component of government finances is mainly used for the construction and maintenance of agricultural infrastructure and the granting of agricultural subsidies. Agricultural infrastructure includes farm tracks, farm machinery services, canals, etc., which are related to the use of machinery in agricultural production and the irrigation of farmland. Agricultural subsidies support producers' incomes and enhance their potential to invest in productivity to realize productivity gains, hence the use of agricultural expenditures as an indicator of capital factor inputs.

The output indicators are as follows.

d) Expected output indicators. The main crop product is the most important desired output of agricultural production, so in order to achieve the unification of indicators and the measurement of benefits, the main agricultural product is economically quantified and the broad agricultural gross product is selected.
e) Indicators of non-expected outputs. Producers in the agricultural production chain usually focus on the desired product output and ignore the non-desired output, which is a subjective factor leading to agricultural surface pollution. Carbon emission is one of the means to quantify agricultural surface pollution. The use of production materials such as pesticides, fertilisers, agricultural diesel and agricultural films in the agricultural production chain is an essential element for the growth and development of crops in modern agriculture, but it is also a major source of agricultural carbon emission. Turning over the land and irrigation in the agricultural production process are also important links in generating agricultural carbon emissions. The existing statistics do not contain direct statistical indicators of carbon emissions, so it is necessary to transform the data to achieve the carbon emissions of agricultural production (Table 1 and Formulas 4) [47].

Where carbon emissions are calculated using the formula:

$$CI = \sum E_i * T_i \tag{4}$$

In the formula, CI denotes carbon emissions, E_i denotes the carbon emission coefficients of the main carbon emission sources in the agricultural production chain in Jilin Province, and T_i denotes the amount of each carbon source used in the agricultural production chain in Jilin Province.

3.3.2. Tobit model and variables

(1) Tobit regression model is usually applied to regression analysis of truncated data, and the measured agri-environmental technical efficiency value lies in the interval of [0,1], which meets the requirements of Tobit model for truncated data. On the basis of measuring the agri-environmental technical efficiency in Jilin Province, the Tobit model is constructed to explore the influencing factors of agri-environmental technical efficiency in depth.

$$y_i^* = \sum_{j=1}^{k} \beta_j x_{ij} + \beta_0 + \ell_i$$

$$y_i = y_i^*, if \;\; 0 < y_i^* \leq 1 \tag{5}$$

Table 1
Carbon emission factors for carbon from major sources of carbon emissions in the agricultural production chain.

source of carbon emissions	Carbon emission factor
Fertilisers	0.8956 kg/kg
Pesticides	4.9341 kg/kg
Diesel	0.5927 kg/kg
Agricultural film	5.18 kg/kg
Turn the soil	312.60 kg/km^2
Irrigated	266.48 kg/hm^2

Note: combing of existing literature [48–52].

$$y_i = 0, if \ \ y_i^* \leq 0$$

In the formula y_i is the explanatory variable, i.e., the technical efficiency of agricultural production that incorporates the non-desired outputs, which is the measured efficiency value. x_{ij} denotes the explanatory variable, which is the factor that affects the value of the technical efficiency of the agri-environment. β_0 denotes the constant term. $\mathscr{E}_i$ is a random variable, which obeys a normal distribution.

(2) In the selection of influencing factors, combined with the characteristics of Jilin Province and the characteristics of agricultural development, to consider the influence mechanism and role of factors related to the technical efficiency of the agricultural environment, the specific influencing factor indicators are selected as follows (Table 2):

a) Agricultural cropping structure. Agricultural planting structure can reflect the coordination and competitiveness of a region's agricultural development, and a reasonable agricultural planting structure is conducive to the construction of an internal green development mechanism in agriculture, and mitigates the negative effects on agro-ecology derived from the continuous cultivation of a single crop variety. Generally speaking, the degree of mechanisation of bulk grain production has reached a high level, basically can achieve the whole production process of mechanised operation of full coverage, greatly improving the technical efficiency of agricultural production, but at the same time, this mechanised operation also increased agricultural carbon emissions, in a sense, weakening the technical efficiency of the agricultural environment. Therefore, in this study, the proportion of the sown area of grain to the sown area of crops was chosen as an indicator of the agricultural planting structure.

b) Agricultural payment capacity. In this study, the capacity to pay for agriculture refers to the contribution of agriculture to household income. Generally speaking, if agriculture is the main source of household income, then producers will strictly control agricultural inputs and maximise agricultural outputs to optimise the technical efficiency of agricultural production. In order to achieve sustainability in agricultural development, producers will also take care of the ecological aspects of agriculture, alleviate the ecological pressure on agriculture, and reinvest in agriculture to improve the existing productivity, resulting in a marginal contribution to the technical efficiency of the agricultural environment. Therefore, in this study, the share of agricultural income in the disposable income of rural residents was chosen as an indicator of the ability to pay for agriculture.

c) Financial support. Agriculture is naturally weak and cannot do without government financial support. To a certain extent, the government's financial expenditures on agriculture promote the development of agriculture, and the inputs used for agricultural infrastructure are closely related to whether the technology applied to agricultural production can be upgraded periodically and whether there are basic conditions for the operation of large-scale machinery and equipment in the field, which is closely related to the technical efficiency of agricultural production. Subsidies for agricultural support policies have an economic impact on the production behaviour of farmers, adjusting their decision-making on production behaviour. Ecological compensation for farmers' green production behaviour is conducive to adjusting the current producers' "rough" agricultural production and management behaviour and improving the agro-ecological environment. Therefore, this study chooses the proportion of agricultural financial expenditure to regional GDP as an indicator to quantify the strength of financial support.

d) Urbanisation level. Urbanisation is a law of social development, and the promotion of urbanisation has accelerated the transfer of rural labour to towns and cities and the gradual transformation of the status of farmers into citizens, with a significant trend towards the part-time and non-agriculturalisation of farmers, which has provided the prerequisites for the transfer of land. On the one hand, the part-time employment of farmers has led to an increase in the demand for agricultural socialisation services in agricultural production, which has improved the efficiency of agricultural production. The non-farming of farmers has also led to a certain degree to the abandonment of arable land or a decline in the efficiency of agricultural output due to insufficient inputs into agricultural production. On the other hand, the transfer of land helps to integrate decentralised and fragmented land, to carry out large-scale and intensive operations, to generate economies of scale, and to transform the status quo of agricultural production efficiency that is difficult to be improved due to the limitations of fragmented arable land. This scale of operation also helps to improve the efficiency of the use of agricultural production materials such as chemical fertilisers and pesticides, and circumvents the increase in agricultural carbon emissions caused by the over-application of small farmers' production and operation. Therefore, the proportion of urban population to total population is used as an indicator to quantify the level of urbanisation.

e) Level of agricultural mechanisation. Agricultural mechanisation is the basis for the modernisation of agriculture, and the substitution of machinery for human labour is an innovation in productivity at the traditional stage of agriculture, creating a

Table 2
Model variables.

Independent variable	Description of variables
Agricultural cropping structure (X_1)	Area sown in grain/area sown in crops
Agricultural payment capacity (X_2)	Agricultural income/disposable income of rural inhabitants
Financial support (X_3)	Agricultural fiscal expenditure/total fiscal expenditure
Urbanisation level (X_4)	Share of urban population/total population
Level of agricultural mechanisation (X_5)	Total power of agricultural machinery/area sown with crops

realistic possibility for large-scale production. With the rapid development of agricultural technology, the substitution of agricultural machinery for human labour in agricultural production, especially in the production of bulk agricultural products, has basically achieved full substitution. In the exogenous application of agricultural production materials can also use agricultural machinery to achieve a more scientific and efficient use of agro-environmental technology to improve efficiency. From another perspective, the popularisation of agricultural machinery has also led to an increase in the demand for agricultural diesel, which has increased agricultural carbon emissions and offset some of the positive externalities associated with the use of agricultural machinery in the agricultural production chain. The ratio of total power of agricultural machinery to the area sown to crops is therefore used as an indicator to quantify the level of agricultural mechanisation.

4. Results

4.1. Analysis of the results of measuring the technical efficiency of the agricultural environment

Measures of technical efficiency in agriculture in Jilin Province were carried out and compared without the inclusion of agricultural carbon emissions and with the inclusion of agricultural carbon emissions as a non-desired output, respectively (Formulas 1 to 3). The results show that the years in which technical efficiency is achieved without agricultural carbon emissions are still technically efficient when agricultural carbon emissions, an element of non-desired output, are taken into account. In terms of the technical efficiency of agricultural production in other years, the combined technical efficiency declined after taking into account the agricultural carbon emissions generated in the agricultural production chain. Overall, Jilin Province's agri-environmental technical efficiency fluctuates less during the period from 2000 to 2008, while it shows greater fluctuations during the period from 2000 to 2021, especially at a lower level during the period from 2015 to 2019, but shows a rebound from 2020 onwards (Tables 3 and 4). The conclusions of this study verifying the decline in agri-environmental technical efficiency due to agricultural carbon emissions from agricultural inputs such as fertilisers, pesticides, and diesel fuel are basically consistent with the findings of the established literature [53,54]. In terms of the research object, previous studies have focused on eco-efficiency studies of dairy products [55,56], and less attention has been paid to the study of grain-producing areas, and the results of this study are an expansion of the measurement of the technical efficiency of the agricultural environment in the main grain-producing areas.

4.2. Analysis of factors influencing the efficiency of agricultural environmental technology

The analysis of the influencing factors of agro-environmental technical efficiency in Jilin Province found that agricultural payment capacity (Formulas 5), financial support and agricultural mechanisation level are significant at 10%, 1% and 10% significance level respectively, which are the main influencing factors affecting agro-environmental technical efficiency in Jilin Province. While agricultural planting structure and urbanisation level did not pass the significance test and are not the main influencing factors, but show positive correlation with agri-environmental technical efficiency (Table 5).

Among the main factors affecting agri-environmental technology efficiency in Jilin Province, agricultural payment capacity is

Table 3
Technical efficiency of agricultural production in Jilin Province from 2000 to 2021.

Year	TE	S_land	S_labor	S_capital	S_mechanical	S_output
2000	0.847163	1081.0533	150.55495	2.45E−07	117.4662	9.41E−07
2001	1.000000	0.0000318	3.72E−06	0.00115099	2.27E−06	3.56E−06
2002	0.956297	260.67822	32.187434	14637.181	9.60E−12	1.28E−08
2003	1.000000	2.60E−06	5.91E−07	0.00021441	2.28E−07	0.00180061
2004	0.981883	238.5985	13.415255	6.10E−08	5.42E−10	4.48E−07
2005	0.969698	248.75527	14.980889	7.66E−08	65.48458	1.28E−08
2006	1.000000	5.94E−10	2.43E−13	8.62E−07	1.12E−09	3.02E−08
2007	0.965276	28.24149	3.82E−11	90127.483	34.79195	2.33E−06
2008	1.000000	6.28E−11	6.70E−12	1.02E−08	5.54E−11	9.50E−11
2009	0.836763	1223.4199	183.68657	17718.715	84.529792	84157.285
2010	0.820644	1081.358	260.623	200241.79	74.474488	19455.351
2011	0.91478	494.655	161.33897	1.48E−06	4.85E−12	1.95E−08
2012	1.000000	5.65E−10	9.03E−10	1.67E−07	9.00E−11	1.89E−07
2013	1.000000	1.49E−11	8.43E−13	9.66E−08	5.37E−12	5.57E−09
2014	1.000000	1.68E−10	2.37E−11	2.38E−08	1.26E−10	2.15E−09
2015	0.919074	346.87954	56.955695	675855.84	5.10E−10	0.00831075
2016	0.733556	1453.3186	208.09325	2060273.9	10.62374	218149.34
2017	0.682998	1182.1241	166.82108	1883216.7	0.00210687	1368970.3
2018	0.756047	1365.4563	162.69748	1,851,969	300.19997	437.68933
2019	0.757417	941.76634	110.00141	1776399.1	185.56267	757088.61
2020	0.907762	278.1098	34.992595	1442091.7	4.36E−09	8.86E−06
2021	1.000000	1.35E−10	1.12E−11	2.64E−08	8.41E−11	2.92E−09

Note: results of the model analysis.

Table 4
Technological efficiency of agri-environment in Jilin Province from 2000 to 2021.

Year	TE	S_land	S_labor	S_capital	S_mechanical	S_output	S_CO_2
2000	0.781029	1081.0533	150.55495	117.4662	5.19E−06	4.26E−07	30.714271
2001	1.000000	4.13E−06	4.59E−07	2.56E−07	0.00001626	0.0005056	5.88E−08
2002	0.939077	290.78356	36.104387	0.00018013	11129.217	0.00086037	7.5772067
2003	1.000000	2.25E−10	4.56E−11	3.13E−11	3.52E−09	1.38E−08	4.17E−12
2004	0.923738	238.5985	13.415255	1.94E−12	3.76E−08	1.08E−07	30.694081
2005	0.957586	248.75527	14.980889	65.48458	5.66E−08	2.35E−06	5.7477007
2006	1.000000	3.75E−07	2.04E−08	2.48E−07	6.49E−06	0.00006027	1.72E−08
2007	0.94604	249.23677	27.645341	60.909387	0.00196551	0.00019259	10.958429
2008	1.000000	9.50E−11	4.69E−14	1.30E−10	1.02E−07	2.33E−08	1.01E−11
2009	0.757062	1294.6043	197.23834	76.655816	0.00001404	0.00006304	62.211006
2010	0.755033	1163.2335	286.00955	4.64E−09	96446.416	4.32E−07	57.675462
2011	0.87002	494.655	161.33897	7.79E−12	4.06E−07	1.65E−08	32.233439
2012	1.000000	1.37E−08	3.20E−08	5.09E−10	0.0000111	6.12E−06	8.36E−09
2013	1.000000	6.07E−08	2.03E−08	2.43E−09	0.00012398	3.50E−06	1.13E−09
2014	1.000000	8.37E−11	3.49E−11	1.47E−13	5.57E−08	9.20E−09	1.13E−11
2015	0.877637	346.87955	56.955697	7.48E−11	675855.84	0.00003211	33.613311
2016	0.633623	1556.9104	215.69182	80.092944	2,137,681	8.54E−08	112.88048
2017	0.580707	1832.2024	214.50498	435.94787	2368976.2	6.70E−08	125.78728
2018	0.667128	1365.6641	162.71272	300.33935	1852124.3	2.19E−06	93.167424
2019	0.675787	1301.2825	136.37228	426.65596	2045041.1	0.00134625	83.392547
2020	0.880048	278.1098	34.992594	2.33E−07	1442091.7	0.00030802	21.52639
2021	1.000000	8.59E−07	8.36E−08	4.10E−07	0.00006514	0.00005967	1.71E−08

Note: results of the model analysis.

Table 5
Factors affecting the efficiency of agri-environmental technology in Jilin Province.

CO_2	Coefficient	Robust std. err.	t	P>|t|	[95% conf. interval]	
X_1	2.700	2.452	1.10	0.286	−2.473	7.873
X_2	0.746	0.388	1.92	0.072*	−0.074	1.565
X_3	−1.704	0.270	−6.30	0.000***	−2.274	−1.134
X_4	1.047	2.598	0.40	0.692	−4.435	6.529
X_5	0.105	0.053	1.98	0.064*	−0.007	0.217
_cons	−2.472	2.511	−0.98	0.339	−7.769	2.826

Note: results of the model analysis. *** and * indicate significance at the 1 per cent and 10 per cent significance levels, respectively.

positively correlated with agri-environmental technology efficiency. Considering from the perspective of agricultural micro-operators, when agricultural income is the main source of household income, farmers as rational economic people tend to control the production inputs on the basis of increasing the value of agricultural outputs, which in turn achieves the purpose of increasing agricultural income. At this stage, when the maximum value of crop output has basically reached a critical point, the only way to further increase agricultural productivity is to improve agricultural productivity as an entry point. An increase in agricultural income will further stimulate operators to invest in agricultural production, upgrade and transform existing productivity and production tools, tap the potential for technical efficiency in agricultural production, replace outdated production methods, help to improve the efficiency of the use of inputs, reduce non-desired outputs, mainly in terms of agricultural carbon emissions, and complete the Pareto improvement of technical efficiency in the agricultural environment.

There is a negative correlation between the level of financial support and agri-environmental technology efficiency. As a weak industry, agriculture is supported by policies in most countries around the world, and agricultural policy subsidies are generally the main means to support agricultural development, and such economic incentives are more likely to realize some of the original policy intentions in the short term. In the case of Jilin Province, the agricultural policy that has had a greater impact on agricultural production from 2000 to 2021 is the temporary corn storage policy, which was subsequently adjusted to a price-compensation separation policy. This policy was designed to boost grain production and motivate farmers to grow grain. The government provided subsidies to grain farmers in the form of temporary storage prices, generating a large amount of financial expenditure, and the actual implementation of this policy has indeed resulted in successive increases in grain production. However, since the implementation of this policy, corn planting in Jilin Province also appeared disorderly expansion of the situation, non-corn advantageous production areas of farmers also in order to obtain the corresponding agricultural subsidies and switch to corn, in the same level of inputs, but difficult to obtain the same corn advantageous production areas of the same agricultural output. On the other hand, under this policy, the final return of planting other crops lacks comparative advantage compared with that of maize, and from the perspective of economic efficiency, this policy guides farmers to choose maize in their production behaviour for a long period of continuous cropping, which is not in line with the law of sustainable development of agriculture. Such long-term cropping leads to an imbalance in soil organic matter, so that farmers can only guarantee yields by adding exogenous means of agricultural production, such as chemical fertilisers, in order to ensure stable agricultural incomes. This kind of production behaviour, which neglects the maintenance of arable land, can only end up in a vicious circle of relying on high inputs of chemical fertilizers in exchange for high outputs, and the increased application of chemical fertilizers not only increases the inputs of agricultural production, but also increases carbon emissions from chemical fertilizers, resulting in a decrease in the efficiency of agro-environmental technologies.

The level of agricultural mechanisation is positively correlated with the technical efficiency of the agricultural environment. The application of agricultural machinery has achieved the substitution of human labour in agricultural production, greatly improving the efficiency of agricultural production, and the popularisation and application of agricultural machinery is one of the important measures to promote the first to realize agricultural modernisation in Jilin Province. The improvement of mechanisation level promotes the rise and improvement of agricultural social service organizations, in the context of the phenomenon of rural labour part-time phenomenon caused by the rapid advance of urbanisation, agricultural social service fills the part-time farmers in the agricultural production of time and labour inputs, and improves the efficiency of agricultural production. With the continuous upgrading of agricultural science and technology, the application of agricultural machinery has also been extended to the application of fertilisers, pesticide spraying and other production processes, relying on machinery to achieve more accurate and efficient use of production materials, reducing the increase in agricultural carbon emissions caused by excessive application, and thus improving the efficiency of agro-environmental technology.

The analysis of the factors affecting the efficiency of agricultural environmental technology in Jilin Province takes into account the special characteristics of agricultural production in Jilin Province on the basis of the theoretical basis for the selection of the factors affecting the existing literature. The literature usually only considers the impact of the proportion of agriculture in agriculture, forestry, animal husbandry and fishery on the efficiency of agricultural environmental technology, while this study considers the impact of the agricultural planting structure on the efficiency of agricultural environmental technology in the light of the dominant characteristics of food in the agriculture of Jilin Province. There is also literature in the analysis of influencing factors did not consider the role of household income [57], even if there is considered but not specific to the agricultural ability to pay [58], so this study analyses the agricultural ability to pay for agricultural households to produce the impact of the mechanism, farmers as the micro-participation in agricultural production and management of the main body of the ability to pay for the relationship between the deployment of resources for agricultural production, which has an impact on the agricultural environment and technological efficiency.

5. Conclusion

China's main grain-producing regions have natural resource endowments for agricultural development, which determines their important position in China's agricultural development and food production. Agriculture as a weak industry, policy support is indispensable, China's main grain-producing areas, especially in northeastern China's main grain-producing areas as a tilted area of agricultural policy, the implementation of the relevant policies to a certain extent to promote the rapid development of agriculture, but at the same time, the spillover effect formed by the policy is also very easy to cause the main grain-producing areas of agriculture to form a single planting structure, the inappropriate mode of agricultural production to the agro-ecological environment to bring the negative effects.

Through the measurement of agricultural environmental technical efficiency in Jilin Province, it was found that in recent years, it has shown a trend of increasing from a lower level year by year, compared with the general input-output measurement of agricultural technical efficiency, taking into account the carbon emissions generated by the agricultural production link this non-desired outputs after the agricultural technical efficiency are lower than the former, indicating that the agricultural carbon emissions on the agricultural production of the technical efficiency of the existence of a significant impact.

In order to further analyse the influencing factors of agri-environmental technology efficiency, this study selects the factors related to agricultural production links and agricultural carbon emissions for empirical analysis, and the results show that agricultural payment capacity, financial support and agricultural mechanisation level are the main factors influencing the agri-environmental technology efficiency in Jilin Province, while the agricultural cultivation structure and the urbanisation level have not yet become the main influencing factors.

Based on the results of the study in Jilin Province, and taking into account the general characteristics and patterns of the main grain-producing areas, the following policy recommendations are proposed in order to improve the technical efficiency of the agricultural environment in China's main grain-producing areas and other agricultural areas, and to promote the green transformation of agricultural production while increasing the efficiency of agricultural production in the main grain-producing areas.

The first step should be to guarantee a reasonable level of income for agricultural producers and to increase the resilience of the agricultural economy. Agriculture is an industry in which natural risks are intertwined with market risks, and the impact of the occurrence of risks on producers' income may be enormous. To cope with unpredictable natural risks, the agricultural insurance system should be further improved. The types of agricultural insurance should be increased, the details of insurance should be clarified and reasonable rules on claims should be formulated, so as to avoid any conflict between insurance companies and producers due to the lack of clarity in the rules. For market risk, price fluctuations are to a certain extent due to the imbalance between supply and demand in the market caused by producers' blind production decisions, so the government should actively guide producers' production behaviours, release the correct relationship between supply and demand in the market and regulate the production behavioural decisions to producers. Ensuring the stability of agricultural producers' incomes will help to safeguard agriculture's ability to pay, increase its willingness to reinvest in agriculture, and make adjustments to existing productive forces and production relations in order to optimise the technological efficiency of the agri-environment.

Furthermore, financial support for agriculture should be kept at a moderate level. On the one hand, fiscal spending on agricultural infrastructure should be maintained in order to provide favourable conditions for agricultural production and to facilitate the application of advanced agricultural production technologies and productivity to agricultural production. On the other hand, in terms of agricultural subsidies, the dependence of agricultural production on economic compensation should be avoided. After achieving a certain policy objective by supporting agricultural development through economic means, agricultural policy should be gradually decoupled from agricultural development, so as to ultimately place agricultural development on the track of the law of the market, and to avoid inefficient production caused by excessive policy intervention.

Finally, it is necessary to further enhance the level of agricultural mechanisation. On the one hand, increase the research and development of advanced agricultural production tools, combined with regional development needs, to improve the applicability of agricultural machinery production; on the other hand, accelerate the establishment of agricultural socialized service organizations and promote their market-oriented development, improve the agricultural socialized service links, so that small farmers can also be achieved in all aspects of agricultural production with the help of agricultural socialized services, replacing the relatively inefficient productivity of the main productivity of the family labour force. This will enable small farmers to use agricultural socialisation services in all aspects of agricultural production, replacing the relatively inefficient productivity of family labour and promoting the precise and efficient application of production materials.

6. Further discussion

The innovation of this study is that carbon emission, which is the current concern in green agricultural production, is incorporated into the consideration of agricultural production efficiency in China's main grain producing areas, which complements the content and object of the study. Secondly, in terms of research theory, the non-desired output is quantified in the form of carbon emission, which is more objective and scientific, and provides a theoretical reference for the optimisation of the efficiency of agricultural environmental technology. Furthermore, in terms of conclusions and countermeasures, targeted opinions with implementation feasibility are proposed from the dual perspective of external and internal factors. The limitation of this study is that the exogenous and endogenous factors in the estimation model are not identified, so in the future research on agri-environmental technical efficiency, we should focus on distinguishing between exogenous and endogenous factors in the influencing factors, and it also necessary to pay attention to the influence mechanism of the micro-production and management subjects on the efficiency of agri-environmental technology.

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Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

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