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Article

Microalgae photosynthetic carbon sequestration technology, financing subsidies and carbon trading mechanism: An evolutionary game mechanism modeling study from a biomechanical perspective

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Abstract: The global consensus to move towards carbon neutrality has been growing amidst turbulence, and the issue of carbon emissions has been an unavoidable topic for achieving the goal of carbon neutrality. The introduction of microalgae photosynthetic carbon sequestration technology optimizes the culture environment of microalgae through hydrodynamics and enhances the efficiency of light and carbon dioxide transfer, thus increasing the rate of photosynthesis and carbon sequestration effect of microalgae. Based on the biomechanical perspective, this study constructed a three-party dynamic evolution game model including agricultural subjects, enterprises and local governments, analyzed the mechanism of photosynthetic carbon sequestration by microalgae, the financing subsidy system and the carbon trading mechanism, and explored the strategic choices and behavioral evolution process of the agricultural subjects and local enterprises in the face of different policy incentives, and verified the conclusions by numerical simulation analysis. The study shows that: (1) the implementation of financial subsidy policies by local governments significantly increases the willingness of agricultural producers and enterprises to apply microalgae photosynthetic carbon sequestration technology, thus accelerating the process of agricultural carbon emission reduction; (2) the integration of energy enterprises and microalgae industry in the carbon trading market is conducive to the generation of renewable energy, and realizes a win-win situation for the government's environmental benefits and the enterprise's economic benefits; (3) the adoption of microalgae carbon sequestration by agricultural producers (3) The adoption of microalgae carbon sequestration technology by agricultural producers is conducive to the promotion of the virtuous cycle of soil microbial communities and the realization of crop income. This study evaluates the potential impacts of different policy combinations on agricultural carbon emission reduction based on the carbon trading mechanism, which can help promote the application of microalgae carbon sequestration technology and the implementation of agricultural carbon emission reduction.

Keywords: biomechanics; microalgae photosynthetic carbon sequestration technology; carbon trading mechanisms; agricultural carbon emission reduction; financing subsidy policies; strategy options

1. Research background

Global climate change is one of the most urgent and challenging issues facing the world today. The Chinese Government has set the goal of achieving carbon peaking by 2030 and striving to achieve carbon neutrality by 2060 [1]. Currently, the basic strategy to reach the dual-carbon target can be divided into two aspects: on the one hand, it is the conversion of biomass resources into usable energy through the use of bioenergy, and on the other hand, to offset the carbon emissions generated by cultivating and developing carbon sink industries [2]. In recent years, the Government of China has attached great importance to agricultural carbon emission reduction and the promotion of sustainable agricultural development. Against this background, the carbon emissions trading market has emerged as an important link in promoting carbon emission reduction in agriculture. The carbon emissions trading market guides enterprises to reduce emissions and promotes the rational allocation of carbon emissions rights through the establishment of a carbon emissions rights trading mechanism [3–5]. At the same time, microalgae bio sequestration technology and financial subsidy systems, as major technological and policy tools, also play an important role in agricultural carbon reduction.

Microalgae photosynthetic carbon sequestration technology refers to the process of utilizing microalgae cells to absorb atmospheric CO_2 through photosynthesis and convert it into biomass. The application of this technology is mainly reflected in the reduction of atmospheric CO_2 concentration through the biomass production of microalgae, while the microalgal biomass can be used as fertilizer, feed or biomass energy source to realize the decarbonization of agricultural production and resource recycling [6]. By establishing microalgae culture system around the farmland, it can not only reduce the carbon emissions generated by agricultural activities, but also enhance the overall carbon sink capacity of the agroecosystem, which provides an effective means of ecological engineering technology for agricultural carbon emission reduction. The financial subsidy system refers to the government's financial support for agricultural carbon emission reduction activities, in order to incentivize the main body of agricultural carbon emissions to reduce carbon emissions, and to promote the development and application of agricultural carbon emission reduction technology. The financial subsidy system can provide economic incentives for agricultural carbon emission reduction and reduce the emission reduction cost of agricultural carbon emission main body [7]. Therefore, the research motivation of this paper has the following points: 1) clarify the relationship between carbon emission reduction and microalgae photosynthetic carbon sequestration technology, the impact of financial subsidy system and the implementation of rural revitalization strategy is closely related to the solution of this problem can effectively promote the implementation of the strategy; 2) microalgae photosynthesis and carbon sequestration technology as a current research problem in the field of biology needs to be solved, has attracted the attention of many scholars, but has not yet made a definitive conclusion on its practical application; 3) the current research on the impact of microalgae carbon sequestration technology and financial subsidy system on agricultural carbon emission reduction is relatively limited, especially in the context of the carbon emissions trading market, the interaction between the three and the evolution of the game process is still worth exploring.

Therefore, this paper will start from the perspective of biomechanics, take the carbon emissions trading market as the background, and use the evolutionary game theory to study the impacts and interactions between microalgae photosynthesis carbon sequestration technology and financial subsidy system on agricultural carbon emission reduction, with the aim of providing theoretical references and practical guidance for policy makers and relevant departments. Therefore, in this paper, we will start from the biomechanical perspective, take the carbon emissions trading market as the background, and apply the evolutionary game theory to study the impacts and interactions of microalgae photosynthesis carbon sequestration technology and the financial subsidy system on carbon emission reduction in agriculture, with the aim of providing theoretical references and practical guidance for policy makers and relevant departments. We hope to make the following contributions to the study: 1) This study provides a systematic analysis of the application of microalgae photosynthetic carbon sequestration technology, combining the financing subsidy and carbon trading mechanism, and explores how to promote technological innovation and widespread application through economic policies and market mechanisms. It further reveals the interaction between policy tools and technological development, and provides theoretical guidance for the formulation of more effective policy combinations; 2) based on a biomechanical perspective, the study further analyzes the strategic interactions and evolutionary paths of different stakeholders in the process of carbon emission reduction through the construction of an evolutionary game model, which provides a new theoretical tool for the understanding of technological diffusion and policy formulation; 3) the article provides an assessment of the sustainability of microalgae photosynthesis carbon sequestration The article assessed the sustainability of microalgae photosynthetic carbon sequestration, including environmental impacts, economic costs and long-term carbon sequestration effects. This assessment helps to clarify the potential value and limitations of microalgae carbon sequestration technology in addressing climate change, and provides important theoretical references for future research directions and technology applications. It was found that the application of microalgae photosynthetic carbon sequestration technology can effectively increase the economic benefits of stakeholders in the model system, while at the same time, the government can significantly promote the widespread application of this technology through the provision of financing subsidy policies, which can help to reduce CO_2 emissions and increase the environmental benefits of the government.

2. Literature review

The research direction of this paper is the influence mechanism of microalgae photosynthetic carbon sequestration technology and financial subsidy policy on agricultural carbon emission reduction. The research involves exploring the strategic choices and interactions among agricultural subjects, enterprises and local governments in the process of carbon emission reduction under the background of carbon emission trading market from a biomechanical perspective, and is closely related to the literature on carbon emission reduction policy, agricultural subsidy system and microalgae bio-application. The following is a review of the relevant literature in three parts.

1) Carbon emission reduction policies aim to reduce greenhouse gas emissions through laws and regulations, economic incentives and policy instruments. They include measures such as implementing carbon emissions trading, promoting clean energy, raising energy efficiency standards and providing financial subsidies and tax incentives to facilitate the economic and social transition to a green and low-carbon economy. Regarding carbon emission reduction, early

studies have focused on the mechanism of external incentives on farmers' transition to low-carbon agriculture, P. Smith and T.J.F. Smith [8] Research on this issue was conducted in 2000, and they concluded that the cost of transporting carbon could generate higher net carbon benefits in the area of agricultural carbon abatement. The study by Aysha et al. [9] included the role of co-benefits and economic incentives in facilitating the transition of farmers to low-carbon agriculture. Other scholars have addressed the issue of regional and temporal heterogeneity by suggesting the need for carbon emission reduction market trading mechanisms and compensatory policies. Cui et al. [10] suggested that differentiated carbon emission reduction policies should be formulated based on regional and time differences, while regional cooperation should be strengthened to create a synergistic carbon reduction effect. Scholars Yang et al. [11] have proposed policies on reducing agricultural carbon emissions and growing agroecological efficiency from the perspectives of regional heterogeneity and green-oriented policies for public investment in agriculture. Different from them, our study is based on the carbon insurance perspective and analyzes the impacts on agricultural carbon emission reduction in two scenarios of agricultural subjects and enterprises purchasing and not purchasing carbon insurance, respectively. In contrast, our study is based on a biomechanical perspective and analyzes the impacts on agricultural carbon emission reduction under two scenarios, namely, whether or not the agricultural entity and the enterprise apply microalgae carbon sequestration technology, respectively. With the depth of research, scholars have expanded their studies to include the impact of digital construction on agricultural carbon emission reduction. By studying the correlation between digital village construction and local agricultural carbon emissions, Ma et al. [12] found that the impact of the digital economy on carbon emissions in the region showed an inverted U-shaped relationship of stimulation followed by inhibition, with spatial spillover effects. Ma et al. [13] through the establishment of "Internet + agricultural machinery operation" platform, in order to promote the development of mechanized agriculture and low-carbon economy. With the in-depth development of international trade liberalization, some scholars have done further research on the role of agricultural trade liberalization on the development of low-carbon agriculture. A study by He et al. [14] suggested that agricultural trade liberalization is conducive to the promotion of low-carbon agriculture. Li et al. [15] showed that agricultural trade liberalization (ATL) has a significant impact on reducing China's agricultural carbon emission intensity (ACEI). Some other scholars have also conducted relevant research on the role mechanism of digital finance-enabled carbon emission reduction by constructing mathematical models based on panel data. For example, Liu et al. [16] people based on the panel data of 30 provinces in China from 2011 to 2019, using two-way fixed effect model and threshold effect model, concluded that financial agglomeration has a stronger effect on reducing agricultural carbon emissions when the industrial structure is more rational or digital finance is more developed. Li and Jiang [17] used balanced panel data to empirically analyze the impact of rural inclusive finance on agricultural carbon emission reduction in 30 provinces in China from 2010 to 2021, and the results of the study show that rural inclusive finance mainly promotes agricultural carbon reduction through the effects of agricultural technological advancement, redistribution of factors of production, and pollution mitigation. In contrast, our study constructs a tripartite evolutionary game model of agricultural subjects, enterprises and local governments based on the carbon emissions trading market, which is used to simulate the behavioral dynamics and strategic choices of the three subjects under the influence of carbon emission reduction policies. This approach better captures the dynamics and complexity of the policy implementation process, and provides a theoretical basis for understanding the interactions among policy instruments.

2) The agricultural subsidy system refers to a series of economic compensation measures that the Government provides to farmers through the provision of financial resources in order to support agricultural development. These measures include cost subsidies for agricultural production materials, market price support for agricultural products, and subsidies for agricultural insurance costs, with the aim of reducing the burden on farmers, stabilizing their incomes, encouraging agricultural production, and guaranteeing national food security and sustainable agricultural development. Early studies on the agricultural subsidy system mainly included the distribution of agricultural subsidies and the reasons why abnormal agricultural subsidies constrain the advancement of China's urbanization process. Ane Kirstine et al. [18] who studied the Danish country as an example of a high nature value (HNV) agricultural indicator, concluded that priority should be given to the allocation of agricultural subsidies to high nature value areas. The study by Murray et al. [19] proposed to increase the funding for agricultural subsidies to climate friendly and biodiverse agricultural areas first. Ray et al. [20], based on the large regional variations in the 1995 reforms, found that the elimination of agricultural subsidies would have harmful spillover effects on the local non-farm economy. Based on county-level data from 1878 counties in China, Huang et al. [21] people found that abnormal agricultural subsidies are an important constraint on China's under-urbanization. Different from the earlier studies, this study further investigates the relationship between the impact of agricultural subsidy system and the implementation of carbon emission reduction policies in China from the perspective of carbon emission reduction. As the study progresses, scholars gradually expand their research from the impact of agricultural subsidies on farmers to the impact on the environment. For example, Guo et al. [22] who constructed a structural equation modeling (SEM) framework using the control function (CF) method based on heteroskedasticity identification strategy concluded that agricultural subsidies can reduce fertilizer use by promoting the adoption of agricultural technologies and expanding the area under cultivation. Bai et al. [23] who studied the exploration of the role of agricultural subsidy policy on sustainable agriculture using data mining techniques in big data analytics approach. Jeremiás Máté [24] further explored the impact of agricultural subsidy policy on sustainable agricultural development through panel regression modeling, and the results of the study showed that direct agricultural subsidies reduced agriculture-related carbon emissions. In addition, some other

scholars have provided further explanations for the role of agricultural subsidies in promoting the efficiency of production technology. Fan et al. [25] who applied the Difference in Differences（DID）method to conclude that the new agricultural subsidies increased the area planted to food crops. The study of Abdullah [26] included the effect of agricultural input subsidies on output growth and labor productivity. Liu et al. [27] who used stochastic frontier production function, instrumental variable method and threshold regression model and found that agricultural subsidies help to improve the efficiency of production technology.

3) The application of microalgae biology refers to the utilization of the biological properties of microalgae and their application in several fields, such as biofuel production, food supplements, animal feeds, environmental remediation, carbon dioxide fixation, and extraction of biologically active substances, in order to achieve sustainable resource utilization and environmental protection. In the environmental field, Diego et al. [28] found that microalgal ecosystems can replace biofuels, optimize productivity per unit area of land, reduce CO_2 emissions, and improve the efficiency of energy use; Surkatti and Al-Zuhair [29] explored the use of Chlorella vulgaris in industrial wastewater treatment Applications. Similarly, scholars El Bakraoui et al. [30] further investigated the mechanism of action of microalgae for the removal of wastewater pollutants. In the commercial field, Gaignard et al. [31] found that red marine microalgae are particularly suitable for applications in the production of high-value pigments and hydrocolloids; Till et al. [32] found that feeding microalgae to high-yielding dairy cows significantly increased the milk and cheese content of DHA; Rao et al. [33] explored the role of microalgal carotenoid pigments in the production of milk and cheese. carotenoid pigments from microalgae in food, feed, pharmaceutical, and cosmetic industries. In the field of medicine, scholars Thomas et al. [34] found that cyanobacteria are the richest source of vitamin K 1 and play an important role in the prevention of chronic diseases by studying different strains of microalgae, and Araceli et al. [35] found that marine microalgal organisms are beneficial in the prevention of acute hepatopancreatic necrotic disease in their study. In the field of food, Samuel et al. [36] explored the application of microalgal organisms in functional foods; further scholars Ma et al. [37] in their study found that microalgae cells are rich in a large number of proteins of which microalgae proteins and their derivatives can be used as a source of novel foods. Different from the above studies, our study investigated the mechanism of microalgae biological carbon sequestration technology in agricultural carbon emission reduction based on the biomechanical perspective, further expanding the technological applications of microalgae biology.

The existing research results of scholars at home and abroad have laid an important foundation for this study, but the overall number of research results is still relatively small, and they are all still in the exploratory stage, and many important issues have not yet been solved. In view of this, we will further analyze the evolution paths and strategy choices of agricultural producers and enterprises for the application of microalgae carbon sequestration technology under different economic and policy environments based on the carbon emissions trading market, taking agricultural cultivation as an example, and provide theoretical guidance for policy makers to understand the dynamic changes and strategy adjustments in the development of the technology by constructing a three-party dynamic evolution game model. Through this study, we hope to further expand the application of microalgae photosynthetic carbon sequestration technology in agriculture, and utilize the photosynthetic mechanism of microalgae to fix CO_2 to further mitigate the global greenhouse effect with its technological advantages of being economical, sustainable and with minimal side effects.

3. Modeling and analysis

3.1. Description of relevant symbols and problem assumptions

China is actively promoting the construction of a carbon emissions trading market system and is committed to developing low-carbon agricultural technologies. To this end, the Government has carried out a series of policy innovations and practical explorations, including the provision of financial subsidies and tax exemptions for agricultural producers adopting low-carbon technologies; the implementation of a number of green financial policies, such as the promotion of the application of services such as carbon financial credits, carbon funds and carbon insurance; and the strengthening of the Government's mechanism for pursuing legal accountability for and penalizing damage to the environment and agricultural resources.

Based on the above research background, this paper constructs a three-party evolutionary game model, in which local governments, agricultural producers, and firms are groups that choose pure strategies and have a sufficiently large and limited number of individuals, respectively. Referring to Zhang et al. [38] and Liu et al. [39] studies on the topic using the three-way evolutionary model, the probabilities of local governments choosing to provide subsidies and not providing subsidies in this study are set as x and $1 - x(x \sim U(0,1))$; The probability that an agricultural producer chooses low-carbon production and traditional production methods, respectively, is y and $1 - y(y \sim U(0,1))$; As for the probability that a firm chooses to adopt microalgae sequestration technology and not to adopt microalgae sequestration technology respectively, they are z and $1-z$, Which still obey the (0, 1) uniform distribution. Taking rice, corn and wheat as the main agricultural products, the market prices of low-carbon and traditional production of agricultural products are set to be P_1 and P_2, the production costs are set to be C_1 and C_2, the annual outputs are set to be M_1 and M_2, and the annual carbon emissions are set to be Q_1 and Q. The revenues and costs of operating a business are Y and C, respectively. The local government provides subsidies to agricultural producers engaging in low-carbon production, and subsidies are provided to enterprises adopting microalgae sequestration technology when implementing the subsidies, and refers to the study on the impacts of agricultural subsidies on stakeholders under different strategies conducted by Nan et al. [40]on the impact of agricultural subsidies on stakeholders under different strategies, so as to set the agricultural subsidy coefficient in this study as a, where $0 < a < 1$.

In order to reduce the complexity of the model for better exploration of the research purpose, this paper makes several assumptions based on the actual situation as follows:

Hypothesis 1: This study assumes that local governments, agricultural producers, and enterprises are all limited rational decision makers, and that they will adjust their strategies over time in the interaction process according to the theory of evolutionary games until they reach an equilibrium state of strategy combinations, i.e., each participant is unable to unilaterally obtain more benefits by changing his or her strategy.

Hypothesis 2: Compared with traditional agricultural production technologies, low-carbon agricultural production technologies are technological innovations, and the adoption of low-carbon agricultural production technologies will generate additional low-carbon technology costs and carbon emission reduction effects, i.e., $C_1 > C_2$, $Q_1 < Q$,. At the same time, there is a premium in the unit price of blue carbon P_0 relative to the carbon tax P, that is to say, $P_0 > P$.

Hypothesis 3: The local government does not subsidize agricultural producers if they choose traditional farming methods when the local government implements the subsidy. When agricultural producers enter into transactions with firms, they receive environmental benefits from them regardless of whether the local government chooses to subsidize them B_1. Local governments also receive financial support from the central government when they choose to subsidize them B_2.

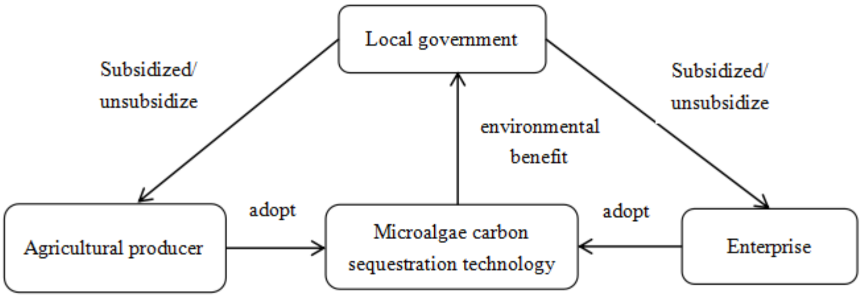


Figure 1. Relationship model of the three parties.

Table 1. Explanation of related symbols.

Parameters	**Explanation**
x	The probability of the local government choosing to provide subsidies
y	The probability of agricultural producers choosing low-carbon production
z	The probability of enterprises choosing to adopt microalgae technology.
a	Subsidy coefficient
P_1、P_2	The market price of low-carbon and traditional agricultural production
Q_1、Q	The carbon emissions of low-carbon and traditional agricultural production
C_1、C_2	The production costs of low-carbon and traditional agricultural production
M_1、M_2	The annual output of low-carbon and traditional agricultural production
S_1、S_2	Subsidies provided to producers and to enterprises adopting technology.
E_{11}、E_{12}	The expected benefits of governments choosing to subsidize and not subsidize
E_{21}、E_{22}	The expected benefits of low-carbon and traditional production for producers
E_{31}、E_{32}	The expected benefits of companies adopting technology and not adopt

Based on these three assumptions, we constructed a relationship diagram of the three subjects as shown in **Figure 1**, and provided further explanatory notes on the relevant symbols that appeared in this study (as shown in **Table 1**):

3.2. Participants' expected returns and replicated dynamic equations

Since each participating subject has two choices, the three subjects form a total of six strategy combinations, and under each strategy combination, the description of each parameter and the returns of the three subjects are shown in **Figure 2**, respectively:

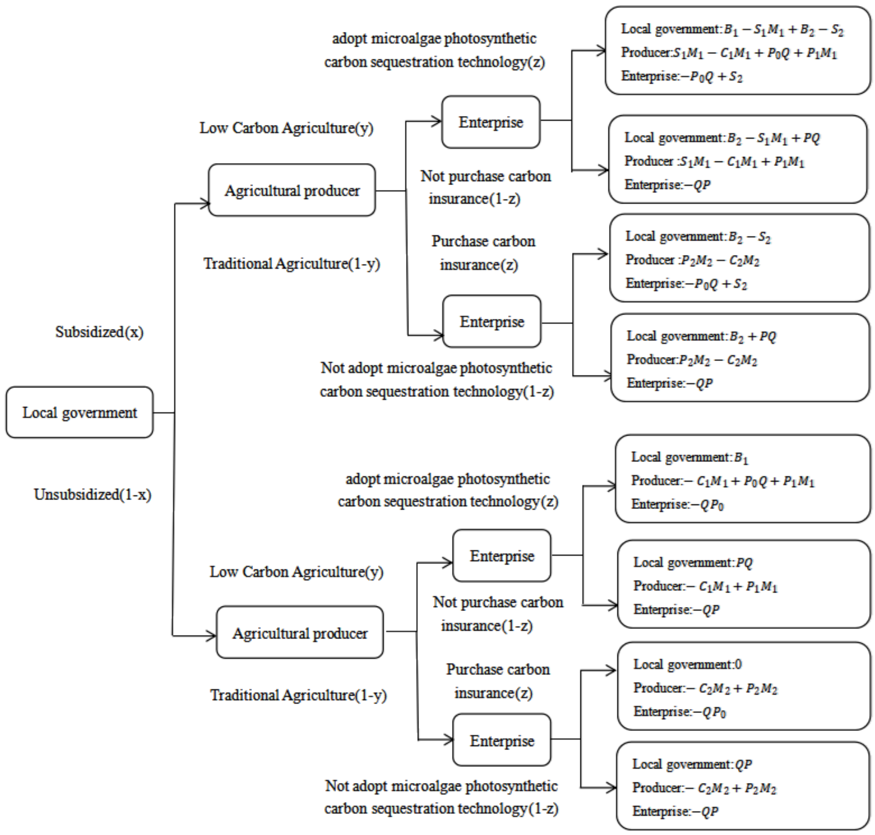


Figure 2. Expected returns for each party under the combination of eight strategies.

3.2.1. Average expected returns and replicated dynamic equations for local governments

For local governments, the expected benefits of their choices to subsidize and not to subsidize are, respectively:

$$E_{11} = yz(B_1 + B_2 - S_1M_1 - S_2) + y(1-z)(B_2 - S_1M_1 + PQ) + (1-y)z(B_2 - S_2) + (1-y)(1-z)(PQ + B_2) \tag{1}$$

$$E_{12} = yzB_1 + y(1-z)PQ + PQ(1-y)(1-z) \tag{2}$$

Description: The local government chooses to provide financial subsidies for agricultural subjects and enterprises, which means that the local government hopes to further stimulate agricultural producers and enterprises to implement low-carbon production methods by means of agricultural subsidies, thus creating more environmental benefits for the government. The expected benefits for the local government include the accumulation of four scenarios: 1) agricultural producers choose low-carbon production and enterprises choose to adopt microalgae photosynthetic carbon sequestration technology, the two subjects reach a deal, the local government at this time to obtain the benefits for the environmental benefits generated by the agricultural subjects and enterprises of low-carbon transactions plus the central government's financial support(B_1+B_2), and at the same time, to deduct the financial subsidies provided by the local government for agricultural producers and enterprises ($S_1M_1+S_2$); 2) farmers choose low-carbon production but enterprises do not choose to adopt microalgae photosynthetic carbon sequestration technology, the two research subjects did not reach a deal between them, at this time, the local government receives the benefits of the central government's financial subsidies plus the carbon tax paid by the enterprises, minus the agricultural subsidies given to the agricultural producers (B_2-S_1M_1+PQ); 3) farmers choose the traditional cultivation methods but enterprises choose to adopt microalgae photosynthetic carbon sequestration technology, at this time, the local government receives the benefits of the central government's financial support minus the financial subsidies it financial subsidies provided to enterprises (B_2-S_2); 4) agricultural producers adopt traditional cultivation methods and enterprises do not adopt microalgae photosynthetic carbon sequestration technology, in which case the government receives the carbon tax paid by enterprises and the financial subsidies from the central government ($PQ+B_2$).

On the contrary, if the local government does not provide financial subsidies to agricultural producers and enterprises, its expected benefits include the following three scenarios: 1) farmers choose low-carbon production and enterprises adopt microalgae photosynthetic carbon sequestration technology, in which case the local government receives only the environmental benefits generated by the deal between farmers and enterprises (B_1); 2) farmers choose low-carbon production but enterprises do not adopt microalgae photosynthetic carbon sequestration technology, in which case it receives the benefits from the carbon tax paid by the enterprise (PQ); 3) the farmer engages in traditional farming methods and the enterprise does not adopt microalgae photosynthetic carbon sequestration technology, in which case the local government gains only the carbon tax paid by the enterprise (PQ).

According to Equations (1) and (2) the average expected return of the loc-al government can be obtained as shown in Equation (3):

$$E_1 = xE_{11} + (1 - x)E_{12} \tag{3}$$

Based on Equations (1) and (3), the dynamic equation of local government replication can be obtained as shown in Equation (4):

$$f(x) = x(E_{11} - E_1) \tag{4}$$

3.2.2. Average expected returns of agricultural producers and replication of dynamic equations

For agricultural producers, the expected benefits of their choices of low-carbon and traditional agricultural production are, respectively:

$$E_{21} = xz(P_1M_1 - C_1M_1 + S_1M_1) + x(1-z) \times (P_1M_1 - C_1M_1 + S_1M_1) + (1-x)z \times (P_1M_1 - C_1M_1) + (1-x)(1-z)(P_1M_1 - C_1M_1) \tag{5}$$

$$E_{22} = xz(P_2M_2 - C_2M_2) + x(1-z) \times (P_2M_2 - C_2M_2) + (1-x)z \times (P_2M_2 - C_2M_2) + (1-x)(1-z)(P_2M_2 - C_2M_2) \tag{6}$$

Description: When agricultural producers choose to adopt low-carbon production methods, it means taking a series of environmental protection measures to reduce greenhouse gas emissions in the agricultural production process, which not only helps to mitigate climate change, but also improves the health of the soil, promotes biodiversity, and enhances the market competitiveness of agricultural products. The expected benefits for agricultural producers include the accumulation of four scenarios: 1) the local government chooses to provide agricultural subsidies and the enterprise chooses to adopt microalgae photosynthetic carbon sequestration technology, in which case the benefits for agricultural producers are the proceeds from the sale of agricultural products plus the government's financial subsidies (P_1M_1+S_1M_1), while at the same time, the costs incurred in the process of low-carbon production (C_1M_1) are deducted; 2) the local government chooses to provide agricultural subsidies but the enterprise has not adopted microalgae photosynthetic carbon sequestration technology, in which case agricultural producers receive the same benefits as in Case 1; 3) the local government does not provide agricultural subsidies but the enterprise chooses to adopt microalgae photosynthetic carbon sequestration technology, at this time, agricultural producers receive the benefits of agricultural sales proceeds minus the cost of low-carbon production (P_1M_1-C_1M_1); 4) the local government does not provide agricultural subsidies and the enterprise does not adopt microalgae photosynthetic carbon sequestration technology, at this time, agricultural producers receive the same benefits as in Case 3.

On the contrary, if the agricultural producer chooses to produce in the traditional way, the expected benefits include the same as the above four scenarios of choosing to produce in the low-carbon way, and the expected benefits in each case are the proceeds from the sale of agricultural products minus the costs of production in the traditional way (P_2M_2-C_2M_2).

According to Equations (5) and (6), the average expected return of agricultural producers is shown in Equation (7):

$$E_2 = yE_{21} + (1-y)E_{22} \tag{7}$$

According to Equations (5) and (7), the equation of replication dynamics o-f agricultural producers is shown in Equation (8):

$$f(y) = y(E_{21} - E_2) \tag{8}$$

3.2.3. Average expected returns of firms and replication dynamic equations

For firms, the expected benefits of their choice to adopt microalgae photosynthetic carbon sequestration technology and not to adopt microalgae photosynthetic carbon sequestration technology are, respectively:

$$E_{31} = xy(-QP_0 + S_2) + x(1-y)(-QP_0 + S_2) + (1-x)y(-QP_0) + (1-x)(1-y)(-QP_0) \tag{9}$$

$$E_{32} = xy(-QP) + x(1-y)(-QP) + (1-x)y(-QP) + (1-x)(1-y)(-QP) \tag{10}$$

Description: By choosing to adopt microalgae photosynthetic carbon sequestration technology, enterprises mean that they are purchasing protection against potential carbon price volatility or carbon emission overruns, and such insurance can help to reduce the financial burden on enterprises in the face of a shortage of carbon credit allowances or an increase in carbon taxes. At the same time, it can incentivize companies to take steps to reduce their carbon emissions in order to lower the cost of insurance and enhance their green image and competitiveness in the marketplace. In this case, the expected benefits of enterprises include the accumulation of four scenarios: 1) the local government chooses to provide financial subsidies and agricultural producers choose low-carbon production, in which case the enterprises obtain the benefits of the financial subsidies of the local government minus the enterprises' carbon emission expenditures in the production process ($-QP_0+S_2$); 2) the local government chooses to provide agricultural subsidies and agricultural producers carry out traditional planting production, in which case the local enterprises obtain the benefits as the same as in scenario 1; 3) the local government does not provide agricultural subsidies and agricultural producers choose low-carbon production methods, at this time, the enterprise obtains the benefits of sales revenue minus carbon emissions expenditure and cost variables ($-P_0Q$); 4) the local government does not provide agricultural subsidies and agricultural producers choose traditional production methods, at this time, the agricultural producers obtain the benefits of the same as in case 3.

On the contrary, if the agricultural producer chooses traditional cultivation, its expected benefits include the same as the above four scenarios of choosing low-carbon production, and the expected benefits of each scenario are the sales revenue minus the carbon emission expenditure and the cost variable ($-P_0Q$).

According to Equations (9) and (10), the average expected return of the firm is shown in Equation (11):

$$E_3 = zE_{31} + (1-z)E_{32} \tag{11}$$

Based on Equations (9) and (11), the replication dynamics equation of the firm is shown in Equation (12):

$$f(z) = z(E_{31} - E_3) \tag{12}$$

3.3. System stability analysis

In the process of evolutionary game involving three-party subjects, when the replicated dynamic equations of each participant have reached equilibrium (i.e., they are all zero), eight pure-strategy equilibrium points can be obtained. These equilibrium points are $E_1(0,0,0)$, $E_2(0,0,1)$、$E_3(0,1,0)$、$E_4(1,0,0)$、$E_5(0,1,1)$、$E_6(1,0,1)$、$E_7(1,1,0)$ and $E_8(1,1,1)$. Since stable solutions usually correspond to strict Nash equilibria in evolutionary games, we only need to analyze these equilibrium points. To determine the stability of these equilibrium points, we solved the replicated dynamic equations for each participant in terms of first-order partial derivatives and constructed the Jacobi matrix accordingly (shown in Equation (13)).

$$J = \begin{bmatrix} \frac{d(f(x))}{dx} & \frac{d(f(x))}{dy} & \frac{d(f(x))}{dz} \\ \frac{d(f(y))}{dx} & \frac{d(f(y))}{dy} & \frac{d(f(y))}{dz} \\ \frac{d(f(z))}{dx} & \frac{d(f(z))}{dy} & \frac{d(f(z))}{dz} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \tag{13}$$

Substituting these eight pure strategy equilibria into Equation (13), we can calculate the eigenvalues of the Jacobi matrix corresponding to each equilibrium, and the specific results are shown in **Table 2**:

Table 2. Eigenvalues corresponding to each equilibrium point.

Stable point	Eigenvalue 1	Eigenvalue 2	Eigenvalue 3
$E_1(0,0,0)$	B_2	$C_2M_2 - C_1M_1 + M_1P_1 - M_2P_2$	$-Q(P_0 - P)$
$E_2(0,0,1)$	$B_2 - S_2$	$QP_0 - C_1M_1 + C_2M_2 + M_1P_1 - M_2P_2$	$Q(P_0 - P)$
$E_3(0,1,0)$	$B_2 - S_1M_1$	$C_1M_1 - C_2M_2 - M_1P_1 + M_2P_2$	$-Q(P_0 - P)$
$E_4(1,0,0)$	$-B_2$	$C_2M_2 - C_1M_1 + M_1P_1 - M_2P_2 + S_1M_1$	$Q(P_0 - P) + S_2$
$E_5(0,1,1)$	$B_2 - S_1M_1 - S_2$	$C_1M_1 - QP_0 - C_2M_2 - M_1P_1 + M_2P_2$	$Q(P_0 - P)$
$E_6(1,0,1)$	$S_2 - B_2$	$QP_0 - C_1M_1 + C_2M_2 + M_1P_1 - M_2P_2 + S_1M_1$	$-Q(P_0 - P) - S_2$
$E_7(1,1,0)$	$S_1M_1 - B_2$	$C_1M_1 - C_2M_2 - M_1P_1 + M_2P_2 - S_1M_1$	$Q(P_0 - P) + S_2$
$E_8(1,1,1)$	$S_1M_1 - B_2 + S_2$	$C_1M_1 - QP_0 - C_2M_2 - M_1P_1 + M_2P_2 - S_1M_1$	$-Q(P_0 - P) - S_2$

According to the Liapunov discriminant, we can conclude that $E_1(0,0,0)$ is an unstable point, and the remaining 7 points $E_2(0,0,1)$、$E_3(0,1,0)$、$E_4(1,0,0)$、$E_5(0,1,1)$、$E_6(1,0,1)$、$E_7(1,1,0)$ and $E_8(1,1,1)$are asymptotically stable points. In this paper, we study the dynamic evolution game under microalgae photosynthetic carbon sequestration technology and financial subsidy system, so we only need to discuss the three case $E_4(1,0,0)$,$E_7(1,1,0)$ and $E_8(1,1,1)$ under microalgae photosynthetic carbon sequestration technology and financial subsidy system.

Case 1: $E_4(1,0,0)$, for it to be an evolutionary equilibrium, the conditions to be satisfied are Equations (14) and (15):

$$(P_1 - C_1 + S_1)M_1 < (P_2 - C_2)M_2 \tag{14}$$

$$P < (1 - a)P_0 \tag{15}$$

Note: If $E_4(1,0,0)$ becomes the Nash equilibrium point, it means that the government is willing to provide financial subsidies to agricultural producers and enterprises, at this time also need to meet the conditions: 1) agricultural producers traditional cultivation to obtain the expected return is higher than that obtained by the low-carbon production; 2) the enterprise to pay the carbon tax price is higher than the price of carbon trading unit.

By adjusting the plotting parameters to conform to the inequality conditions described above, the tripartite evolution results shown in **Figure 3**. were obtained. These results show that in the case where the income from traditional agriculture exceeds the total income from low-carbon agriculture plus financial subsidies, and the unit price of low-carbon agricultural products after financial subsidies is higher than the unit price of traditional agricultural products, local governments tend to implement subsidy policies, agricultural producers will choose to continue traditional agriculture, and enterprises will not choose to t adopt microalgae photosynthetic carbon sequestration technology.

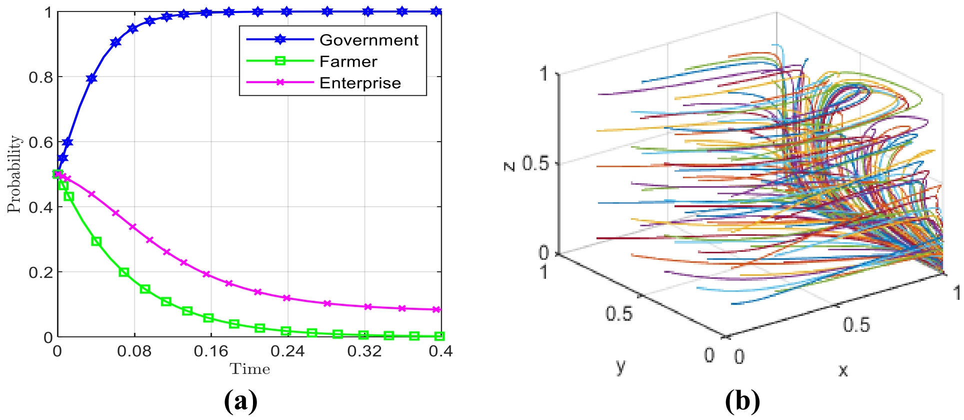


Figure 3. Evolutionary trajectory diagram of the equilibrium point $E_4(1,0,0)$: **(a)** Two-dimensional evolutionary trajectory diagram of the equilibrium point E_4; **(b)** Three-dimensional evolutionary trajectory diagram of the equilibrium point E_4.

Note: In **Figure 3b**, "*x*" represents agricultural producers, "*y*" represents local government, and "*z*" represents enterprises， the same applies below.

Case 2: $E_7(1,1,0)$, for it to be an evolutionary equilibrium, the conditions to be satisfied are Equations (16)–(18):

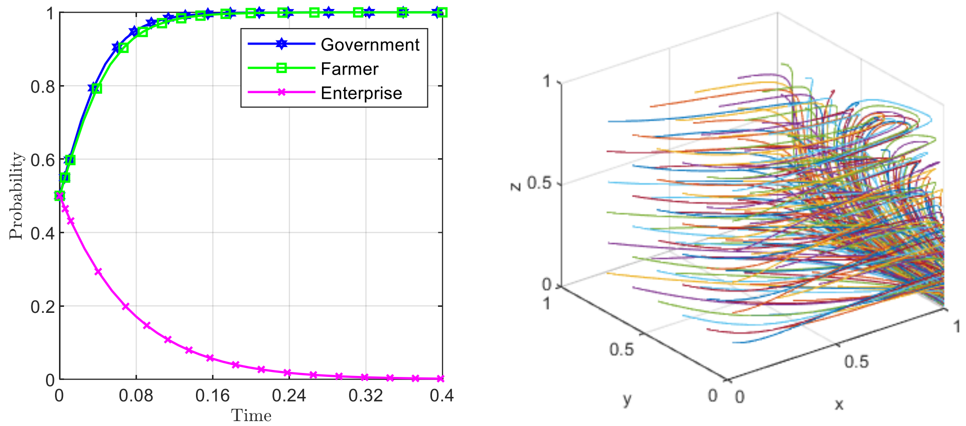
$$M_1 S_1 < B_2 \tag{16}$$

$$(P_2 - C_2)M_2 < (P_1 - C_1 + S_1)M_1 \tag{17}$$

$$P < (1 - a)P_0 \tag{18}$$

Note: If $E_7(1,1,0)$ is the Nash equilibrium point, it means that local governments are willing to provide financial subsidies to agricultural producers and enterprises, and at the same time, agricultural producers are willing to adopt low-carbon production methods, but enterprises are not willing to adopt microalgae photosynthetic carbon sequestration technology. At this point, the conditions to be met are: 1) the financial support provided by the central government to the local government is higher than the agricultural subsidies given by the local government to the agricultural producers and enterprises; 2) the expected return of the agricultural producers from low-carbon production planting is higher than that of the traditional planting; and 3) the unit price of the carbon tax paid by the enterprises is higher than that of the carbon trading.

By adjusting the plotting parameters to validate the previous inference, the tripartite evolution results were obtained as shown in **Figure 4**. These results indicate that in the case where the financial subsidy support provided by the central government exceeds the cost of local government subsidies for low-carbon agriculture, and the total income from low-carbon agriculture plus subsidies exceeds the income from traditional agriculture, and the unit price of low-carbon agricultural products after financial subsidies is higher than the unit price of traditional agricultural products, local governments tend to implement subsidy policies, agricultural producers tend to choose low-carbon agriculture, and enterprises don't choose to adopt microalgae photosynthetic carbon sequestration technology.



(a) **(b)**

Figure 4. Evolutionary trajectory diagram of the equilibrium point $E_7(1,1,0)$: **(a)** Two-dimensional evolutionary trajectory diagram of the equilibrium point E_7; **(b)** Three-dimensional evolutionary trajectory diagram of the equilibrium point E_7.

Case 3: $E_8(1,1,1)$, for it to be an evolutionary equilibrium, the conditions to be satisfied are Equations (19)–(21):

$$S_2 < B_2 \tag{19}$$

$$(P_1 - C_1 + S_1)M_1 < (P_2 - C_2)M_2 \tag{20}$$

$$(1 - a)P_0 < P \tag{21}$$

Note: If $E_8(1,1,1)$ is the Nash equilibrium point, it means that the local government is willing to provide financial subsidies to agricultural producers and enterprises, and at the same time, agricultural producers are willing to adopt low-carbon production methods and enterprises will choose to adopt microalgae photosynthetic carbon sequestration technology. The conditions to be met are: 1) the financial support provided by the central government to the local government is higher than the financial subsidies given by the local government to the enterprises purchasing carbon insurance; 2) the expected return from traditional production and cultivation of the agricultural producers is higher than that from low-carbon cultivation and production; and 3) the unit price of carbon trading is higher than that of the carbon tax paid by the enterprises in the course of operation.

By adjusting the plotting parameters to conform to the previously mentioned inequality conditions, tripartite evolutionary results were obtained as shown in **Figure 5**. These results show that in the case where the financial support provided by the central government exceeds the subsidies provided to enterprises purchasing carbon insurance, and the income of agricultural producers from traditional agriculture is higher than the sum of income from low-carbon agriculture and government subsidies, while the unit price of low-carbon agricultural products after financial subsidies is lower than the unit price of traditional agricultural products, the local government tends to implement the subsidy policy, and agricultural producers choose to continue to engage in traditional agriculture, while enterprises choose to adopt microalgae photosynthetic carbon sequestration technology.

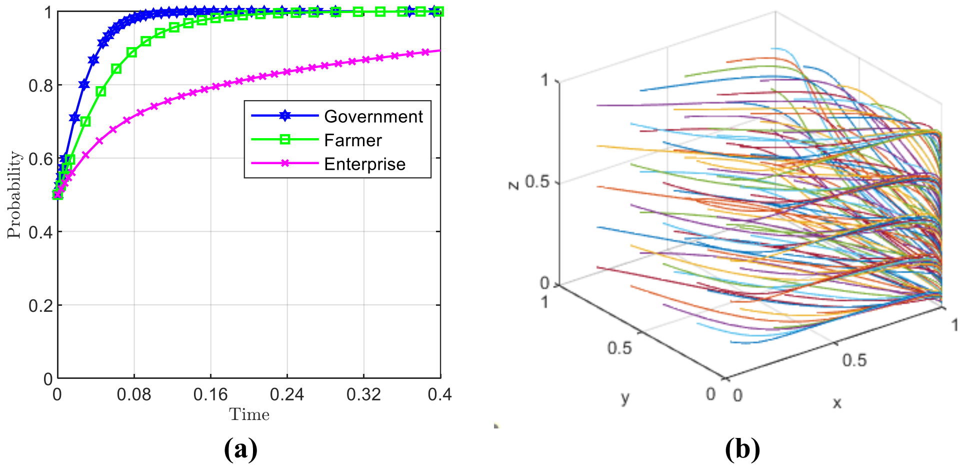


Figure 5. Evolutionary trajectory diagram of the equilibrium point $E_8(1,1,1)$: **(a)** Two-dimensional evolutionary trajectory diagram of the equilibrium point E_8; **(b)** Three-dimensional evolutionary trajectory diagram of the equilibrium point E_8.

4. Simulation and result analysis

4.1. Initial scenario parameterization and evolutionary results

4.1.1. Initial scenario parameter setting

The average trading price of low-carbon agriculture and traditional agriculture (based on the main agricultural rice, corn and wheat, hereinafter) is reasonably set with reference to the market trading price of agricultural products in 2023 in the Chinese Academy of Agricultural Sciences (CAAS). According to the carbon trading in China's pilot carbon market in 2021, the carbon trading unit price is set at RMB 42.85/t [41]. Based on the World Bank's series of research reports, as well as the findings of Liu Yu's team and Ma Xiaozhe's team, we set a baseline scenario in which the carbon tax is levied at a rate of \$100/t of CO_2 equivalent [42–44]. Based on the compilation of data from the National Compendium of Cost and Benefit Information of Agricultural Products, we can know that the average annual output and average production cost of traditional agriculture are and 1361.91 yuan/t respectively [45]. According to the data compiled in the China Agricultural and Rural Development Report 2023, we learned that China's agricultural carbon emissions reached 8.3×10^8 t [46]. According to the latest notice issued by Ping An Property and Casualty Insurance, subsidies are provided to enterprises that adopt microalgae photosynthetic carbon sequestration technology, with subsidies amounting to a maximum of Yuan 4×10^5 yuan. The average annual production and average cost of low-carbon agriculture, government subsidies for agricultural producers practicing low-carbon agriculture, financial support from the central government, environmental benefits to local governments, and low-carbon subsidy coefficients are rationally set with reference to relevant literature [47–50]. The numerical settings of the initial parameters of the model are shown in **Table 3**:

Table 3. Initial scenario parameter settings.

Parameters	Value/Unit	Data Source
P_1	10yuan/kg	Chinese Academy of Agricultural Sciences (CAAS)
P_2	6yuan/kg	Chinese Academy of Agricultural Sciences (CAAS)
P_0	42.85yuan/t	Related research
P	100yuan/t	Related research
M_1	3.2×10^6t	Related research
M_2	2.7×10^6t	National Compilation of Cost and Benefit Data for Agricultural Products
C_1	1879.20yuan/t	Related research
C_2	1361.91yuan/t	National Compilation of Cost and Benefit Data for Agricultural Products
Q	8.3×10^8t	2023 Report on Low Carbon Development in China's Agriculture and Rural Areas
S_1	10yuan/kg	Related research
S_2	4×10^5yuan	Ping An Property
B_1	6.5×10^8yuan	Formula calculation
B_2	2.5×10^7yuan	Related research
a	0.15	Related research

4.1.2. Initial scenario evolution results

After inputting the initially set scenario parameters into the model, we observed the evolution process as shown in **Figure 6**. The results show that in the initially set scenario, even if the local government implements a subsidy policy, agricultural producers eventually tend to return to traditional agriculture, while enterprises tend to choose to adopt microalgae photosynthetic carbon sequestration technology. This result does not meet our expectation. In view of this, subsequent studies will mainly focus on adjusting the parameters in order to push the system evolution game towards the ideal state.

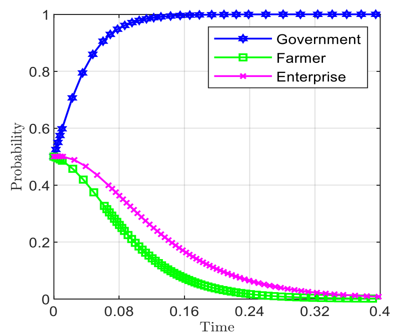


Figure 6. Two-dimensional evolutionary results of the initial scenario.

4.2. Parameter sensitivity analysis

4.2.1. Impact of low carbon subsidy coefficients on system stability

For enterprises, **Figure 7*a*** shows that when the low carbon subsidy coefficient is at the initial level a =0.15, enterprises will choose to engage in traditional production industries. When the subsidy coefficient is increased to a =0.2, enterprises are relatively hesitant between choosing to engage in traditional industries and green industries, and when the low-carbon subsidy coefficient reaches a = 0.25~0.4, enterprises will choose to transform to engage in green and low-carbon industries. The results of the study show that local government financial subsidies are an important variable influencing enterprises to make major decisions, and as the coefficient of subsidies increases, the stronger the willingness of enterprises to transform to be in the green and low-carbon industry, but this practice will also bring a heavy financial burden to the local government.

For agricultural producers, **Figure 7b** shows that when the low-carbon subsidy coefficient is at the initial level a =0.15, agricultural producers will choose to continue to engage in traditional agricultural cultivation. When the subsidy coefficient is increased to a =0.2, agricultural producers are indecisive between engaging in traditional agriculture and low-carbon agriculture, when the low-carbon subsidy coefficient is increased to between a =0.25 and 0.3, the decision of agricultural producers is more inclined to low-carbon agriculture, and when the subsidy coefficient reaches a =0.35~0.4, agricultural producers will ultimately choose to engage in low-carbon agricultural cultivation. The results of the study show that the financial subsidy support of local governments directly affects the planting methods of agricultural producers, and as the low-carbon subsidy coefficient increases, agricultural producers slowly tend to change their agricultural production methods to low-carbon planting production.

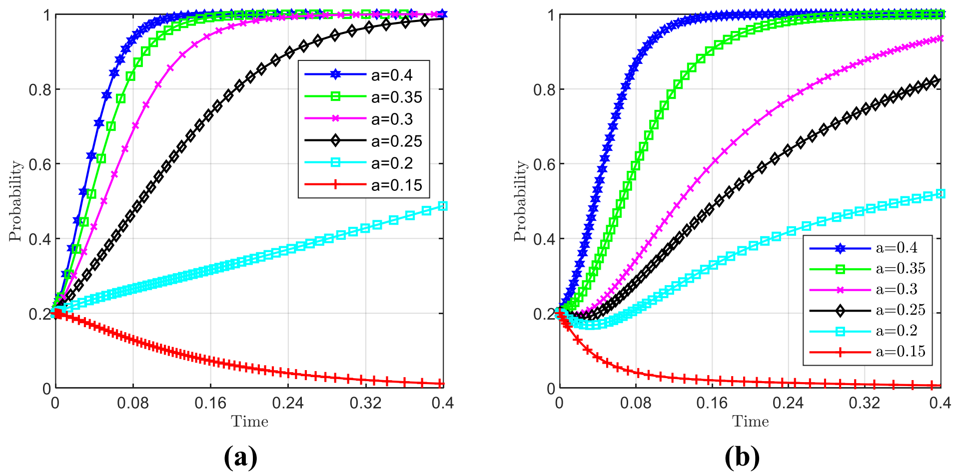


Figure 7. Impact of different low-carbon subsidy factors on the system: **(a)** The impact of different low-carbon subsidy coefficients on enterprises; **(b)** The impact of different low-carbon subsidy coefficients on agricultural producers.

4.2.2. The impact of carbon sequestration technology on the stability of agricultural carbon reduction systems

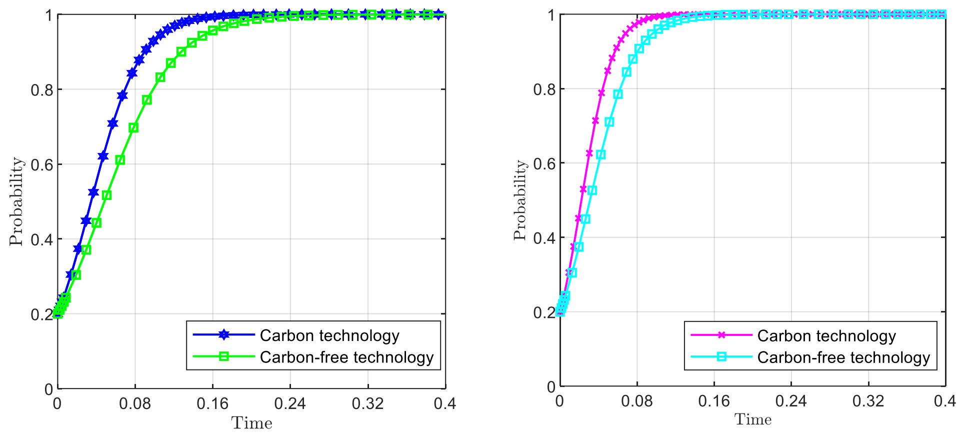
The research in this paper involves the following two scenarios:

Not carbon sequestration technology (baseline scenario): agricultural producers and enterprises do not adopt microalgae photosynthetic carbon sequestration technology.

Have acarbon sequestration technology: agricultural producers and enterprises adopt microalgae photosynthetic carbon sequestration technology.

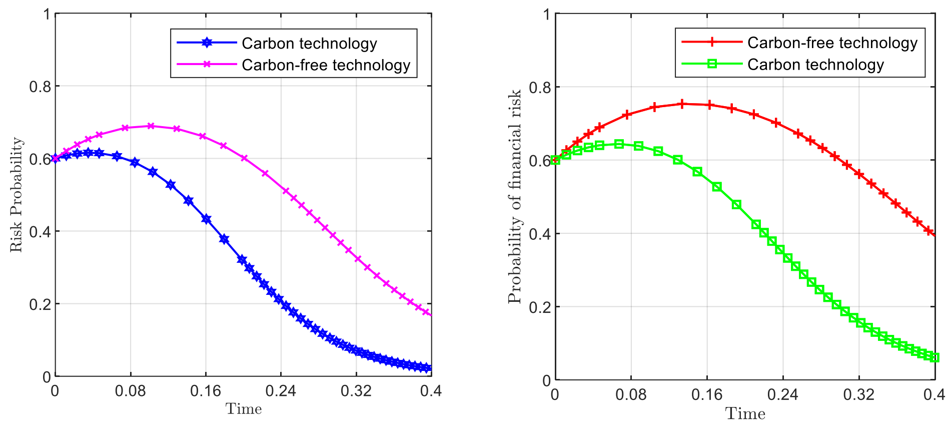
Microalgae carbon sequestration technology is an important tool for carbon risk control. **Figure 8** shows a comparative analysis between the two scenarios of agricultural producers with and without microalgae carbon sequestration technology at different production scales. Observations show that with microalgae carbon sequestration technology premium subsidies, microalgae carbon sequestration technology promotes the diffusion of low-carbon agricultural technologies and has a catalytic impact on the advancement of carbon emission reduction in agriculture. Further analysis of the impact of risk probability on the evolution of participants' behavior reveals that agricultural producers are more sensitive to the cost of microalgae carbon sequestration technology. The results of the study show that when agricultural producers adopt microalgae photosynthetic carbon sequestration technology, the favorable impact of the cost of insurance outweighs the benefits gained through risk aversion, and thus microalgae carbon sequestration technology has a favorable impact on agricultural emission reduction in general. Looking at agricultural operators of different production sizes, agricultural producers with larger production sizes are more sensitive to the cost of microalgae carbon sequestration technology, and therefore the favorable impact of microalgae carbon sequestration technology is more significant.

Microalgae carbon sequestration technology, as the main carbon risk management tool, has an important impact on the profitability of enterprises. **Figure 9** illustrates the risk diversification ability and potential financial risk performance of firms under two scenarios: with and without microalgae carbon sequestration technology. The results of the study show that, on the one hand, adopting the microalgae carbon sequestration technology can help enterprises diversify and transfer potential financial risks arising from carbon emissions exceeding the prescribed limit, such as fluctuations in carbon prices in the carbon trading market, and increases in costs due to climate change or policy changes. On the other hand, enterprises may face fines or compensation for exceeding the carbon emission limits, and these costs may have a significant impact on their financial position. In addition, in the absence of government financial subsidies, high microalgae carbon sequestration technology costs can likewise increase the operating costs of enterprises and reduce their productivity in the course of their operations.



(a) **(b)**

Figure 8. The impact of microalgae photosynthetic carbon sequestration on carbon emission reduction by agricultural producers with premium subsidies: **(a)** Agricultural producers, $Q = 10$; **(b)** Agricultural producers, $Q = 50$.



(a) **(b)**

Figure 9. The impact of microalgae photosynthetic carbon sequestrationon the probability of risk occurrence and financial risk assumption by the company: **(a)** The risks that exist within a company; **(b)** The level of financial risk undertaken by the company.

5. Conclusions and recommendations

Microalgae photosynthetic carbon sequestration technology and financial subsidy system, as the main management tools in the field of agricultural carbon emission reduction, play an important role in creating environmental benefits. In actual production life, local governments, agricultural producers and enterprises form an interactive system in the process of agricultural carbon emission reduction. In order to balance the interests of the three parties, reasonable policies and subsidy mechanisms can be designed to promote the realization of carbon emission reduction goals. By analyzing the impact of each subject's strategic choices on the stability of the system, we draw the following conclusions: (1) local governments can effectively guide agricultural producers to low-carbon production through the implementation of financial subsidies, which significantly increases the willingness of enterprises and agricultural producers to apply microalgae photosynthesis and sequestration technology, reduces the adoption cost of carbon emission reduction technology, and thus accelerates the process of agricultural carbon emission reduction; (2) Without financial subsidies for agricultural producers, the high cost of microalgae carbon sequestration technology has become an obstacle to the adoption of low-carbon technologies, and small and medium-sized agricultural producers are even less receptive to the application of microalgae carbon sequestration technology due to financial constraints, so subsidy policies targeting this group are particularly important; (3) By applying microalgae photosynthesis and sequestration technology in the carbon emissions trading market, enterprises can effectively manage the risk of exceeding carbon emissions and safeguard the sustainable operation of the enterprise. risk and guarantee the sustainable operation of enterprises, financial subsidies can reduce the decision-making threshold of enterprises, and enterprises with microalgae carbon sequestration technology are more competitive in the market and can attract more investors and consumers who pay attention to sustainable development.

Based on the above findings, this paper gives the following policy recommendations: (1) For local governments, establish and improve the financial subsidy system, design differentiated subsidy policies, and ensure the accuracy and effectiveness of subsidies. Increase subsidies for carbon insurance, reduce the premium burden of agricultural producers, and encourage more agricultural producers to participate in carbon emission reduction. Strengthen the construction of laws and regulations, formulate and improve laws and regulations related to carbon emission reduction, and clarify the responsibilities and obligations of local governments, agricultural producers and enterprises in carbon emission reduction; (2) for agricultural producers, on the one hand, we can establish demonstration bases for carbon emission reduction of agricultural producers, promote the application of successful microalgae carbon sequestration production technology on the ground, and give incentives to agricultural producers who carry out low-carbon production, such as tax incentives and loan (3) For enterprises, policy support is given to enterprises that actively participate in the carbon emissions trading market, such as tax breaks and financial incentives. Enterprises are encouraged to manage the risk of carbon emissions in the process of enterprise operation and improve market competitiveness by purchasing and applying microalgae carbon sequestration technology, and at the same time, enterprises should strengthen their innovation ability and actively research, develop and apply low-carbon technologies.

Our study has not yet considered the impact of the application environment of microalgae sequestration technology on the application of microalgae sequestration technology by agricultural producers and enterprises in our modeling assumptions. Future research could be conducted on the direction of R&D and innovation of microalgae sequestration technology by energy companies, and the management mechanism of the carbon emissions trading market.

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editing, BZ and MG; visualization, CD; supervision, BZ; project administration, BZ; funding acquisition, BZ. All authors have read and agreed to the published version of the manuscript.

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