systems

MDPI

Article

A Simulation Study of How Chinese Farmer Cooperatives Can Drive Effective Low-Carbon Production Systems Through a Carbon Transaction Incentive

Jian Feng [1], Haoyang Li [2], Nicola Cannon [2], Xianmin Chang [2] and Qianqian Chu [1,*]

[1] School of Economics and Management, Qingdao Agricultural University, Qingdao 266109, China; fengjian@qau.edu.cn
[2] School of Agricultural Science and Practice, Royal Agricultural University, Cirencester GL7 6JS, Gloucestershire, UK; haoyang.li@student.rau.ac.uk (H.L.); nicola.cannon@rau.ac.uk (N.C.); xianmin.chang@rau.ac.uk (X.C.)
* Correspondence: chuqianqian@qau.edu.cn

Abstract: This article aims to investigate the mechanisms of farmer professional cooperative (FPC) operations and to understand their role in promoting low-carbon production among small-scale farmers in China. Agricultural carbon emissions account for 17% of the total carbon emission in China; therefore, reducing agricultural carbon emissions is important for China to achieve carbon neutrality. Small-scale farmers face many obstacles in achieving the low-carbon transition of agriculture, which therefore makes them a priority target for the implementation of low-carbon production systems in China. Participating in FPCs is an effective support mechanism for them to conduct low-carbon production. In this paper, a system dynamics model is used to simulate the methods of how FPCs assist small-scale farmers to adopt low-carbon production practices within the framework of China's carbon trading system, through the year 2030. After attending the carbon transaction system, the agricultural carbon emissions are anticipated to decline by 10.21%, and FPCs' net income could increase by 11.85%. In a scenario where the price of their agricultural products increases, the reduction of carbon emissions and the increase of FPCs' net income will be beneficial. Under the operation of FPCs, the greatest profits will be generated from trading, and these will be distributed to small-scale farmers, thereby creating a positive feedback loop between carbon transactions and FPC operations. This article seeks determine the potential outcomes that can serve as a basis for informed decision-making within relevant policy-making agencies regarding agricultural carbon transactions by simulating the potential benefits to both small-scale farmers and FPCs from the integration of a carbon trading system.

Keywords: FPC; small-scale farmers; low-carbon production; carbon transaction system; system dynamics model

Academic Editor: Alberto Paucar-Caceres

Received: 2 March 2025
Revised: 22 March 2025
Accepted: 2 April 2025
Published: 7 April 2025

Citation: Feng, J.; Li, H.; Cannon, N.; Chang, X.; Chu, Q. A simulation Study of How Chinese Farmer Cooperatives Can Drive Effective Low-Carbon Production Systems Through a Carbon Transaction Incentive. *Systems* **2025**, *13*, 260. https://doi.org/10.3390/systems13040260

1. Introduction

Reducing carbon emissions has become a focal issue around the world due to the threat of global warming. As a large carbon emission country, China aims to peak its carbon emissions by 2030 and achieve carbon neutrality by 2060. In 2021, China initiated the implementation of the Measures for the Administration of Carbon Emission Trading. Currently, with the exception of the forestry sector, agriculture has not yet been incorporated into the carbon emission trading system. It is noteworthy that carbon emissions from agricultural production account for 17% of the total emissions in China, in contrast to 7% in the United States and 11% globally [1]. This indicates that reducing agricultural carbon emissions will significantly impact China's overall emission reduction goals. Therefore, to align with these carbon reduction objectives, it is essential to include agricultural production in the carbon emission trading system in China.

Small-scale farmers have the potential to make a significant contribution to low-carbon production systems in China; however, they currently encounter several challenges in transitioning towards low-carbon agricultural practices. Firstly, there is a general lack of awareness and willingness among these farmers regarding low-carbon production [2,3]. It is indicated that decision-making behavior among farmers is often constrained by various factors, including individual cognitive limitations, external environmental influences, and information asymmetry [4]. Consequently, it is challenging for individual farmers to develop awareness and motivation for low-carbon production when there are no financial incentives to mitigate eco-environmental losses [2]. Secondly, inadequate funding represents a major barrier to the autonomous implementation of low-carbon production systems by small-scale farmers [5,6]. Insufficient financial subsidies, inequitable subsidy structures, and limited investment in technological innovation hinder the adoption of low-carbon production techniques [7]. Thirdly, the absence of regulatory mechanisms for policy implementation significantly affects the situation [8]. Access to targets, as well as monitoring and verification technologies for emissions from agricultural sources, is limited. Additionally, the establishment and trading mechanisms for the agricultural carbon reduction markets are still in their early stages of development [9].

Modern farmer professional cooperatives (FPCs) originated in the 19th century [10]. The history of cooperatives can be traced back to the establishment of the Rochdale Equitable Pioneers Society Limited in 1844, located in the suburbs of Manchester [10]. FPCs are autonomous organizations governed by their members. Cooperatives have succeeded in establishing a democratic structure that promotes collaboration to meet the needs of their members, ultimately striving to enhance the quality of life for each individual. The democratic governance, autonomy, and empowerment positions cooperatives as effective vehicles for mutual assistance [11]. Since 2008, the Chinese government has actively worked to develop FPCs to enhance their reach among small-scale farmers. By the year 2020, there were nearly 2 million FPCs in China, and they spread over Chinese countryside. FPCs play a crucial role in enhancing food production in China by integrating smallholder farmers into contemporary agricultural systems [9,12]. These cooperatives increase productivity through collective purchasing of inputs, sharing of advanced technologies, and the implementation of standardized farming practices [10,11]. FPCs serve as a vital platform for facilitating the connection between small-scale farmers and the market, and they represent an essential organizational system that aids these farmers in overcoming information barriers and maintaining a competitive edge in the marketplace [12].

The operation of an FPC is a complex system that needs to consider the mechanisms of policy support, farmer behavior, markets, and the environment [13]. FPCs have received government support to unite numerous small-scale farmers to gain the benefits of improved markets for the buying of production materials and the sale of agricultural products. Since the enactment of the "Farmers Professional Cooperation Law of the People's Republic of China" in 2008, the Chinese government has promoted FPC development through multiple policy tools [13,14].

Firstly, the government has implemented financial support policies to enhance the services provided by FPCs, including agro-mechanical purchasing and technical training, aimed at improving cooperative production performance and profitability [15,16]. Secondly, multiple credit support policies have been introduced for the establishment and operation of FPCs; however, only a limited number have benefited from these initiatives [17,18]. Thirdly, talent support policies have been executed, significantly influencing the standardized and normalized development of FPCs [9,12,19]. Lastly, the FPC laws have been promulgated to provide a fair business environment for cooperatives to operate legitimately, regulate earnings distribution systems, and foster positive participation [20–22].

Supportive policies can enhance the development of FPCs and encourage greater participation from small-scale farmers, thereby expanding their operational scale [14,23]. The relationship between FPCs and smallholder farmers can be characterized as a principal–agent framework. Typically, FPCs are formed by multiple small-scale farmers who may not be able to engage comprehensively in all aspects of management and operations. Therefore, the appointment of a professional manager is essential for overseeing these tasks. For instance, in the context of land transfers, small-scale farmers participate in an FPC by delegating their land management rights to the FPC for consolidated administration. The primary incentive for small-scale farmers to engage with FPCs is the potential for a multitude of increased benefits [24]. FPCs are more likely to receive policy support, which aids small-scale farmers in achieving both economic and environmental advantages through coordinated procurement of production inputs, adoption of low-carbon technologies, standardized low-carbon production management, and uniform marketing of agricultural outputs [9,12]. In conclusion, the mechanism through which FPCs promote low-carbon production among small-scale farmers is a multifaceted economic system that encompasses policy support, FPC operations, farmer behavior, and the ecological environment.

Participating in an FPC presents an effective approach for small-scale farmers to engage in low-carbon production [9,25]. The involvement of small-scale farmers in FPCs indicates a transfer of production decision-making authority to these cooperatives, which play a critical role in guiding these decisions [26]. The primary sources of carbon emissions in agricultural production include synthetic fertilizers, pesticides, plastic films, diesel fuel, ploughing, and irrigation practices. FPCs can assist these farmers in reducing carbon emissions by minimizing the excessive use of productive inputs among small-scale farmers [2]. The Chinese government has leveraged FPCs as a means to offer policy and financial support, facilitating government funding and mitigating investment risks [27]. FPCs are particularly well-positioned to implement necessary changes due to their organizational advantages and collective institutional strengths, enabling them to address the challenges associated with low-carbon production among small-scale farmers [9,25,28,29].

While there is some literature addressing the factors influencing low-carbon production among small-scale farmers, as well as the mechanisms by which FPCs can impact low-carbon production, there appears to be a lack of studies employing systems dynamics simulation to model the operational mechanisms of FPCs driving low-carbon production in small-scale farming, particularly in the context of carbon trading systems. Furthermore, there is limited research on predicting the associated benefits. FPCs serve as agricultural entities that represent the interests of general farmers and can significantly influence public choice in China [24]. Grounded in the principle of equitable compensation, "those who protect should benefit, and those who pollute should bear the costs". This paper aims to explore how FPCs can facilitate low-carbon production among small-scale farmers within the carbon trading framework, as well as to evaluate the benefits to both farmers and FPCs.

In this study, a system dynamics model is developed to simulate how FPCs encourage small-scale farmers to adopt low-carbon production practices within the framework of the Chinese carbon trading system, projected through to the year 2030. The study also estimates the potential benefits that small-scale farmers and cooperative groups may realize following the integration of the agricultural sector into the carbon trading system. This article contributes to the existing body of literature in three significant ways. First, this article treats FPCs as a socially embedded system and employs a system dynamics model to explore their operational mechanisms, an approach that has been underrepresented in current research. Second, this article analyzes the mechanisms by which FPCs facilitate small-scale farmers' transition to low-carbon production in the context of a carbon trading system, a topic that has not been extensively examined in prior studies. Finally, this article projects the carbon trading quotas for agricultural production by 2030 and the subsequent benefits for FPCs and farmers within the carbon trading framework, an area that has not been previously documented. The outcomes of this article may serve as a foundation for in-formed decision-making within relevant policy-making agencies concerning agricultural carbon transactions.

This article aims to explore the mechanisms of FPC operations and their role in facilitating low-carbon production among small-scale farmers in China. By simulating the potential benefits for both small-scale farmers and FPCs following the integration of the agriculture sector into carbon trading systems, the mechanisms of FPC promoting low-carbon production among small-scale farmers are discovered. The study process of how an FPC drives low-carbon production for small-scale farmers is presented in Figure 1.

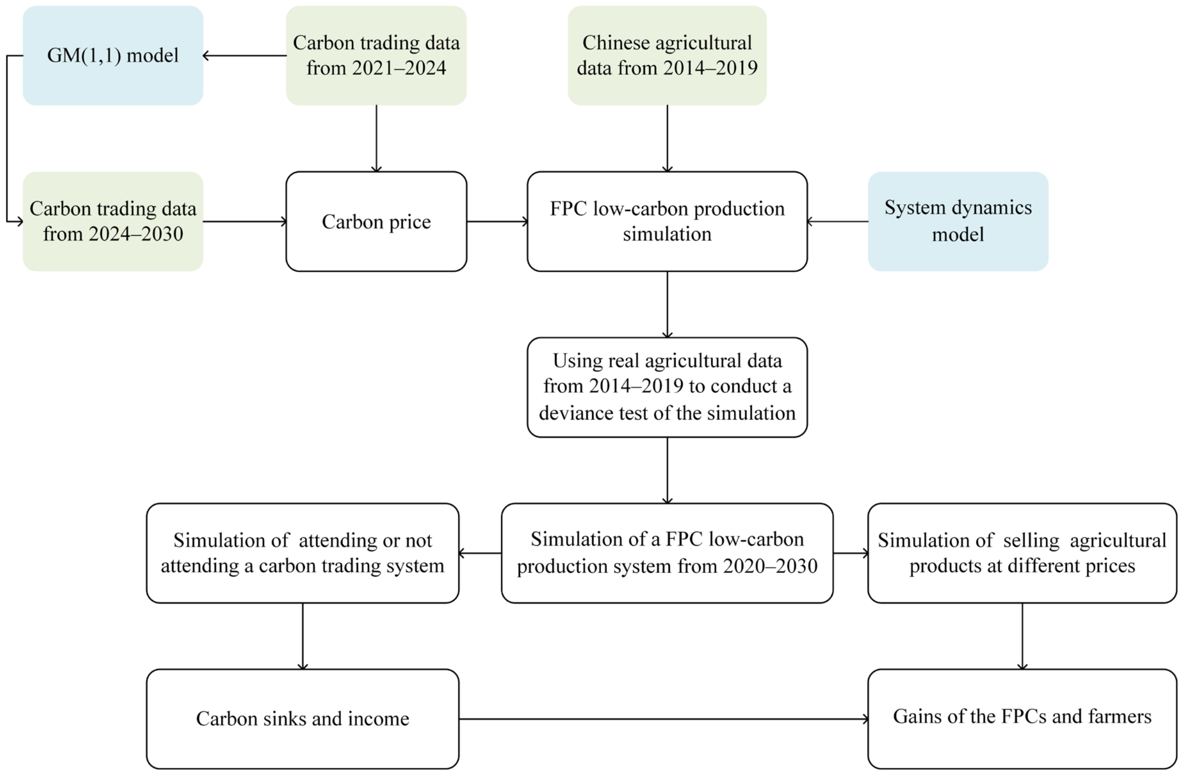


Figure 1. The study process of FPCs driving low-carbon production for small-scale farmers.

Figure 1 illustrates how this study utilizes Chinese agricultural data and carbon trading data, through the development of a system dynamics model, to simulate the mechanism by which FPCs promote low-carbon production among small-scale farmers. Real agricultural data from 2014 to 2019 is used to validate the simulation results. Upon successful validation, the simulation is extended to explore scenarios with and without carbon trading participation, as well as varying agricultural output prices. The final outcomes of the simulation reveal the ultimate benefits for both FPCs and farmers under different conditions, thereby elucidating the mechanism through which FPCs facilitate small-scale farmers' transition to low-carbon production practices.

2. Materials and Methods

2.1. Data

This study uses national level data encompassing 30 provinces (including cities and autonomous regions) within China. However, the access to data from the Tibet Autonomous Region, Hong Kong Special Administrative Region, Macau Special Administrative Region, and Taiwan Province of China is limited. The variables and parameters involved in the FPC Low Carbon Production System are presented in Table 1.

Table 1. Subsystems and variables of the FPC Low Carbon Production System.

Subsystem	Types of Variables	Stock, Flow, Ancillary Variables, and Parameters
Funding Input Subsystem	Endogenous variables	Funds (FD), inflow (IW), outflow (OW), self-funding (SF)
	Exogenous variables	Funding support factor (FSF), government support funds (GSF), unsupported ratio (UR), distribution (DN)
FPC Operation Subsystem	Endogenous variables	FPC surplus (FPCS), net income (NI), DN, FPC production scale (FPCPS), uniform purchasing production materials (UPPM), uniform sales agricultural products (USAP), distributable surplus (DS), return by transactions volume (RTV), brand management (BM), standardized production (SP)
	Exogenous variables	Adjustment distribution factor (ADF), legal regulation factors (LRF), farmers enter (FE), carbon income (CI)
Farmer Behavior Subsystem	Endogenous variables	FPC human capital (FPCHC), increase (IS), famer training (FT), FE
	Exogenous variables	Talent support factor (TSF), BM
Eco-Environmental Subsystem	Endogenous variables	Carbon fixation amount (CFA), carbon sinks (CSK), carbon source (CSC), reduction verification (RV), CI, fertilizer (FZ), film (FM), diesel (DL), pesticide (PD)
	Exogenous variables	FPCPS, verification factor (VF), carbon price (CP), carbon fixation factor (CFF), tilling emission coefficient (TEC), irrigation emission coefficient (IEC)

The majority of the data in this system have been sourced directly from "China's Statistical Annual Report on Rural Operation Management (2014–2018)", "China's Statistical Annual Report on Rural Cooperative Economy (2019)," and the "China Rural Statistical Yearbook (2014–2019)," as well as the China Carbon Trading Network. Additional data points have been derived from calculations based on the aforementioned sources. In the Funding Input Subsystem, the funding support factor (FSF) is calculated as the ratio of government input for the current year to government input for the previous year. The utilization rate (UR) is determined by the ratio of government support funds to self-funding of the FPC for each year, while the cost support factor (CSF) reflects the applicable interest rate. Within the FPC Operation Subsystem, the labor return factor (LRF) indicates the proportion of the FPC that returns distributable surplus at a trading volume of 60% (according to Chinese law). The additional distributable factor (ADF) is calculated by taking the difference between the value of the FPC returning distributable surplus at that trading volume and the total return of distributable surplus. In the Farmer Behavior Subsystem, the training support factor (TSF) is calculated based on the ratio between number of rural agricultural economics personnel who receive training and ordinary farmers. In the Eco-Environmental Subsystem, the value factor (VF) represents the proportion of sold residual value (RV), while the carbon fixation factor (CFF) reflects the carbon fixation coefficient relevant for organic agricultural cultivation, as outlined by Liu et al. in 2018 [30]. The technical efficiency coefficient (TEC) is derived from Duan et al. (2011), and the impact efficiency coefficient (IEC) is based on research from the China Agricultural University [31,32]. Carbon pricing is projected using the gray model, GM (1,1). Missing data are addressed through the interpolation method.

2.2. System Dynamics Model

The system dynamics (SD) model is a simulation methodology that captures the structure of complex systems by utilizing feedback loops from stocks, flows, and variables [33]. This framework allows us to investigate the underlying causes and effects of relevant dynamic trends and to design various policies aimed at enhancing system performance [33]. System dynamics models are particularly effective in analyzing complex systems that undergo temporal changes [33]. These models are frequently employed to address intricate challenges within the agricultural sector and support strategic decision-making processes [34–39]. The primary advantage of a system dynamics model is its capacity to offer a comprehensive view of the system, simulate complex relationships within it, and test various strategies without exposure to actual risks [33]. Consequently, this paper employs a model to analyze the implementation or non-implementation of carbon trading in the agricultural sector, as well as to investigate various pricing scenarios for organic agricultural products. However, it is important to acknowledge certain limitations of the model, including the intricacies involved in the modeling process and challenges associated with validation [34,36]. To address these concerns, this paper utilizes real data to validate the model, thereby enhancing its practical application.

The operation of FPCs is a socially embedded, complex economic system characterized by multi-actor interactions [13]. It encompasses various dimensions of factors and stakeholders. This study aims to explore the mechanisms through which an FPC facilitates low-carbon production practices among small-scale farmers. The system consists of four subsystems: the Funding Support Subsystem, the FPC Operation Subsystem, the Farmer Behavior Subsystem, and the Eco-Environmental Subsystem (illustrated in Figure 2). Given that numerous factors—such as policy, economics, and social dynamics—are interrelated and exert influence on the system, this research employs these factors as exogenous variables. The factors are integrated into the system as constants to ensure that its operation aligns closely with real-world data. Due to the complexity of FPC Low Carbon Production Systems, it is impractical to address every factor within the system comprehensively. This paper focuses on the core variables that significantly impact the system while excluding less critical elements, allowing for a clearer understanding of the primary contradictions in the process of conformational analysis. The model construction for this study is based on the following assumptions:

H1: *It is anticipated that the external economic environment will remain stable, with no fluctuations expected.*

H2: *The cropping industry will participate in a carbon trading system beginning in the year 2027.*

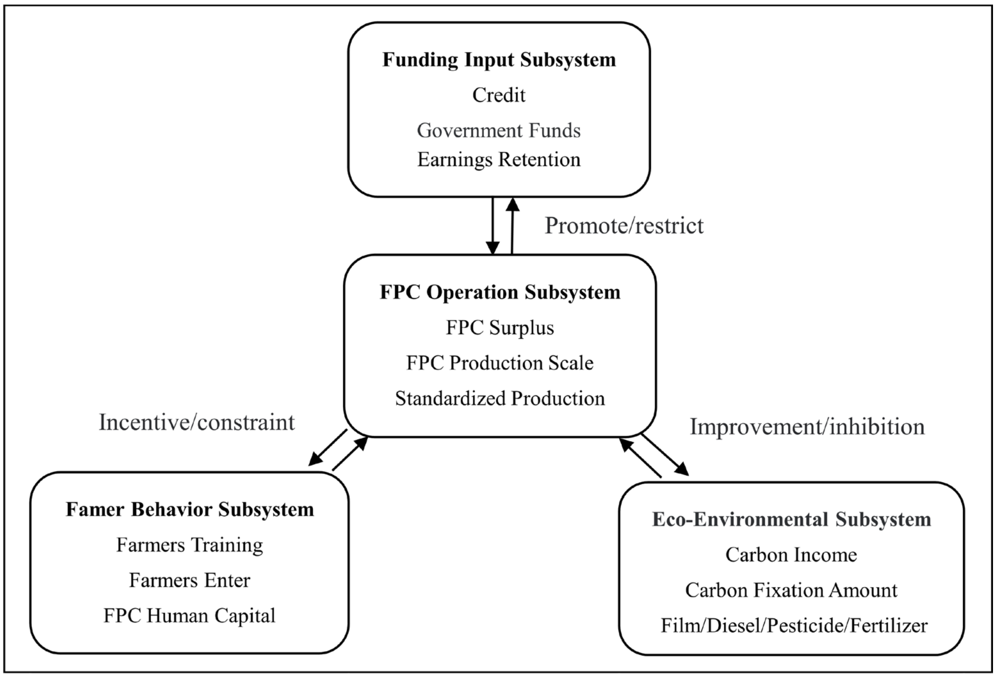


Figure 2. FPC Low Carbon Production System.

Figure 2 illustrates that there are four subsystems of the FPC Low Carbon Production System, as detailed below:

1. The Funding Input Subsystem: This subsystem focuses on analyzing the dynamics of changes in FPC investment, encompassing both government funding and self-funding, as well as the trends in the inflow and outflow of FPC funding. The model treats FPC funds as the primary stock variable to assess the dynamic effects of aggregate investments that arise from a combination of funding sources, including self-funds and government support, on the operations of the cooperative.

2. The FPC Operation Subsystem: This subsystem focuses on the operational scale, management system, and performance benefits of the FPC. The FPC Surplus serves as the primary stock variable within this framework. This subsystem specifically examines variations in factors such as investment and human capital, along with the dynamic development trends related to the operational scale, management system, and performance benefits of the FPC. The key feedback loops associated with the FPC Operation Subsystem are outlined in the following subsystems:

3. The Farmer Behavior Subsystem: This subsystem primarily investigates the impact of farmers' production behaviors on the operations of the FPC. Within this subsystem, the FPC human capital is identified as the primary stock variable, while supplementary factors, such as farmer training and farmer entry, are utilized to analyze the mechanisms that promote the relationship between farmers' production behaviors and FPC operations.

4. The Eco-Environmental Subsystem: This subsystem integrates the FPC carbon income into the operational subsystems of the FPC and analyzes the interactions between FPC operations and the ecological environment. Currently, agriculture, excluding forestry, has not been included in the carbon trading system; therefore, the ecological environmental subsystem is projected to commence in 2027.

2.3. The GM (1,1) Model

Grey system theory is particularly effective when working with small data sets or data that have limited information. This analytical approach can significantly reduce the level of unknowns by leveraging the available information, thereby providing a more accurate representation of the system's nature. Given the constraints on data availability, grey systems serve as a valuable model for short-term predictions. However, it is important to note that air quality and disease data may only be accessible for limited periods and locations, which can lead to potential incompleteness and inaccuracies. As proposed by Deng in 1982, grey system theory is well-suited for addressing these types of information challenges [40].

Let $X^{(0)} = (x^{(0)}(1), x^{(0)}(2), \cdots, x^{(0)}(n))$ be a sequence of raw data. Denote its accumulation generated sequence by $X^{(1)} = (x^{(1)}(1), x^{(2)}(2), \cdots, x^{(1)}(n))$.

$$x^{(0)}(k) + ax^{(1)}(k) = b \quad (1)$$

is referred to as the original form of the GM (1,1) model, where the symbol GM (1,1) stands for "first order grey model in one variable".

Let $Z^{(1)} = (z^{(1)}(2), z^{(2)}(3), \cdots z^{(1)}(n))$ be the sequence generated from $X^{(1)}$ by adjacent neighbor means. That is, $Z^{(1)}(k) = \frac{1}{2}(x^{(1)}(k) + x^{(2)}(k-1))$, $k = 2,3,\ldots n$.

$$x^{(0)}(k) + az^{(1)}(k) = b \quad (2)$$

is referred to as the basic form of the GM (1,1) model.

Let $X^{(0)}$,$X^{(1)}$, and $Z^{(1)}$ be the same as above, except that $X^{(0)}$ is non-negative. If $\bar{a} = (a, b)^T$ is a sequence of parameters, and

$$Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix}, \ B = \begin{bmatrix} -Z^{(1)}(2) & 1 \\ -Z^{(2)}(3) & 1 \\ \vdots & \vdots \\ -Z^{(0)}(n) & 1 \end{bmatrix} \quad (3)$$

then the least squares estimate sequence of the GM (1,1) model Equation (2) satisfies $\bar{a} = (B^T B)^{-1} B^T Y$, continuing all the notations from (3), if $(a, b)^T = (B^T B)^{-1} B^T Y$.

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = b \quad (4)$$

is referred to as a whitenization equation of the GM (1,1) model in Equation (2); then, the solution, also known as time response function, of the whitenization equation

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = b \quad (5)$$

is given by

$$x^{(1)}(t) = (x^{(1)}(1) - \frac{b}{a})e^{-at} + \frac{b}{a} \quad (6)$$

The time response sequence of the GM (1,1) model in Equation (2) is given below:

$$\bar{x}^{(1)}(k+1) = (x^{(0)}(1) - \frac{b}{a})e^{-ak} + \frac{b}{a}, k = 1,2, \cdots n \quad (7)$$

The restored values of $x^{(0)}(k)$ are given as follows:

$$x^{(0)}(k+1) = \bar{x}^{(1)}(k+1) - \bar{x}^{(1)}(k) = (1 - e^a)(x^{(0)}(1) - \frac{b}{a})e^{-ak}, k = 1,2, \cdots n \quad (8)$$

The parameters a and b of the GM (1,1) model are named as the development coefficient and grey action quantity, respectively.

3. Results

3.1. Construction of the FPC Low Carbon Production System

Based on the operational realities of an FPC we have developed a system dynamics model to illustrate how an FPC can promote low-carbon production among small-scale farmers. To provide a comprehensive and systematic overview of the components, operating mechanisms, and behavioral characteristics of the system, we utilized a system flow diagram. This diagram details the logistical relationships, feedback pathways, and interactions among the system variables, which include stock variables, flow variables, ancillary variables, and parameters. In total, the model encompasses 41 variables, categorized as follows: 4 stock variables, 7 flow variables, 18 ancillary variables, and the remainder as parameters. Using this subsystem classification and feedback loop analysis, this study interconnects and integrates four subsystems to construct a system dynamics model for FPC Low Carbon Production. The complete system flow diagram was created by using Anylogic 7.0.2 software, as illustrated in Figure 3.

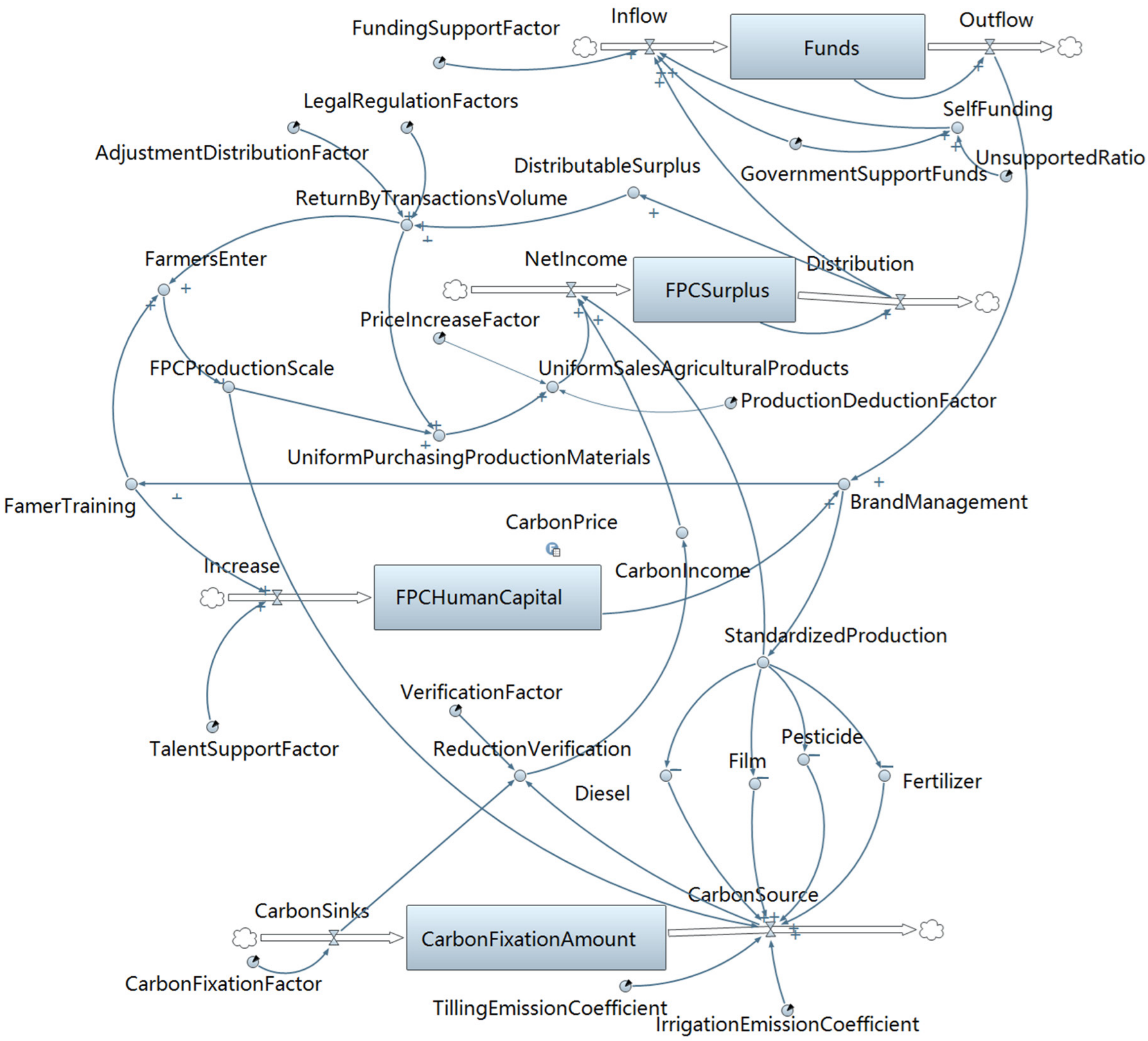


Figure 3. Causal loop diagram of the FPC Low Carbon Production System. Note: The data regarding the system of the FPC Low Carbon Production System is sourced from "China's Statistical Annual Report on Rural Operation Management (2014–2018)", "China's Statistical Annual Report on Rural Cooperative Economy (2019)", and the "China Rural Statistical Yearbook (2014–2019)", as well as the China Carbon Trading Network (http://www.tanjiaoyi.com, accessed on 1 January 2023). The relationships between them have been derived from calculations of regression analysis.

In alignment with the goal of achieving carbon peaking by 2030 and considering the current stage of the Chinese carbon trading system, the simulation period for this system has been established from 2014 to 2030, covering a total of 17 years with annual simulation intervals. The initial six years, from 2014 to 2019, serve as an examination phase, during which the correspondence between the simulation results and actual data have been assessed. Adjustments to the parameter settings were made based on the outcomes of this analysis, along with relevant theoretical insights. The subsequent period from 2020 to 2030 is designated for simulation, focusing on forecasting the developmental trends of the FPC. It is anticipated that the agricultural carbon trading mechanism will be integrated into the carbon trading system in 2027, allowing the Eco-Environmental Subsystem to begin participation at that time. The initial values for stock variables within the system are derived from statistical data from the year 2014.

The relationships among the variables in the system are established through theoretical analysis, regression analysis, formula derivation, and simulation adjustments to ensure optimal alignment between the system and real-world data. By integrating these methodologies, we have developed the primary variable equations for the FPC Low Carbon Production System (see Appendix A.1.)

3.2. Model Validity Testing

The system dynamics model developed serves as a simplified representation of the actual system, with the goal of capturing the overall operational characteristics. However, it is important to note that this model cannot replicate the real system precisely. Therefore, once the model is established, it is essential to assess its validity and rationality to ensure it accurately reflects the dynamic characteristics of the real system. This evaluation is crucial for guaranteeing that subsequent predictions and simulations objectively and realistically represent the state of the FPC Low Carbon Production System.

Methods for testing the model may include assessments of model structure and model behavior fit. The dimensional consistency test within the fit tests for model structure is a self-contained detection feature of the AnyLogic 7 software. AnyLogic 7 automatically reports errors and will pause the process until all issues are resolved, ensuring that model structure errors do not remain during the system commissioning phase. Typically, the fit test of model behavior involves comparing simulated data against actual historical data to evaluate the effectiveness of the model in representing the real system. In this analysis, we simulated data from 2014 to 2019 and calculated the degree of deviation, with results summarized in Table 2.

Table 2. Degree of Deviance Test of the Variables.

	BM ($\times 10^4$ Pieces)			FPCS ($\times 10^{11}$ RMB Yuan)		
	Real value	**Simulation value**	**Deviance degree**	**Real value**	**Simulation value**	**Deviance degree**
2016	8.14	7.81	4.05%	1.08	0.99	8.33%
2018	8.68	9.47	9.10%	1.16	1.25	7.76%
	RTV ($\times 10^{10}$ RMB Yuan)			**FPCPS ($\times 10^6$ hm^2)**		
	Real value	**Simulation value**	**Deviance degree**	**Real value**	**Simulation value**	**Deviance degree**
2016	5.68	5.16	9.15%	1.94	2.08	7.22%
2018	5.69	6.09	7.03%	2.10	2.09	0.48%
	SP ($\times 10^4$ pieces)			**USAP ($\times 10^{11}$ RMB Yuan)**		
	Real value	**Simulation value**	**Deviance degree**	**Real value**	**Simulation value**	**Deviance degree**
2016	8.95	8.80	1.68%	8.28	7.99	3.50%
2018	10.01	10.37	3.60%	8.18	8.31	1.59%

It can be seen from Table 2 that all the deviance degrees are under 10%, with half of them under 5%, so the model fits with the reality well.

To assess the impact of the FPC on promoting low-carbon production among small-scale farmers within the carbon transaction framework in China, we will conduct a continuous simulation of the system dynamics model covering the period from 2020 to 2030.

Based on the development phase of the carbon transaction mechanism in China, it is assumed that the agricultural sector will participate in the carbon transaction system starting in 2027.

3.3. Simulation Results

3.3.1. Simulation of the Carbon Reduction Mechanism

Fertilizer, film, diesel, pesticides, cultivation, and irrigation serve as significant carbon sources throughout the cropping process. Among these resources, cultivation and irrigation are relatively fixed based on land scale, while the others are primarily influenced by agricultural practices. The market prices for crops produced under organic standard conditions are typically 1 to 10 times higher than those of general crops [41–45]. Based on research data gathered from various online and offline supermarket chains in China, including JD online stores, Lida Supermarkets, and Hema Fresh Supermarkets (Available online: https://jd.com, http://qdlida.com.cn, and https://www.freshippo.com, accessed on 18 March 2025), the results are simulated using pricing levels that are 2, 3, and 5 times the baseline price, which are referred to as Price 1, Price 2, and Price 3, respectively. The adoption of organic production practices leads to a 15% reduction in productivity [46], which has been accounted for in the simulation modeling at the same time. The values of usages of fertilizer, film, diesel, pesticides and carbon emissions, when agricultural carbon emissions are not included in carbon trading system are presented as the original value. The outcomes of this simulation are detailed in Table 3.

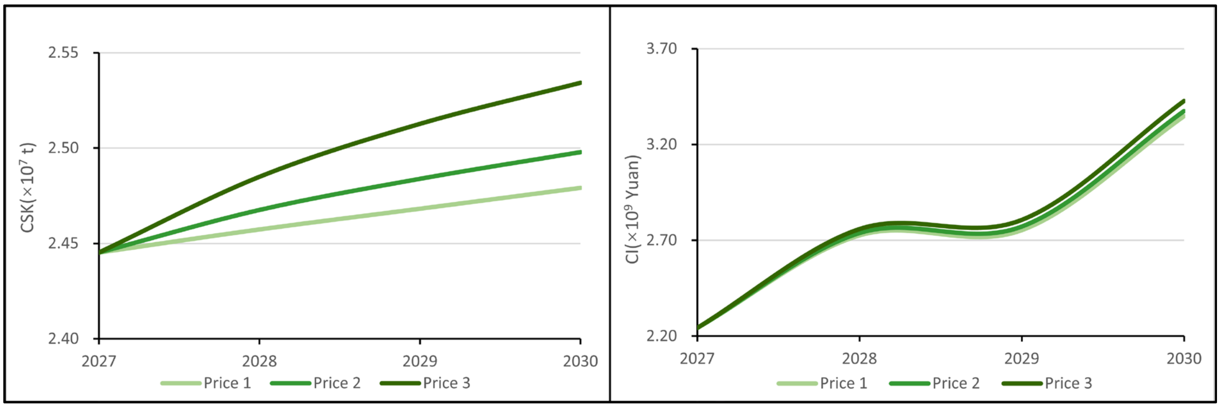
Table 3. Inputs of Fertilizer, Film, Diesel, and Pesticides with Different Prices.

	FZ (t/hm^2)				**FL (×10^{-1} t/hm^2)**			
	Original value	**Price 1**	**Price 2**	**Price 3**	**Original value**	**Price 1**	**Price 2**	**Price 3**
2030	0.5417	0.5106	0.5002	0.4713	0.2558	0.2416	0.2368	0.2233
	DL (t/hm^2)				**PD (×10^{-2} t/hm^2)**			
	Original value	**Price 1**	**Price 2**	**Price 3**	**Original value**	**Price 1**	**Price 2**	**Price 3**
2030	0.1832	0.1734	0.1699	0.1603	0.9501	0.8855	0.8672	0.8173

According to Table 3, in 2030, it is projected that the implementation of the carbon transaction mechanism starting in 2027 will lead to a reduction in the use of fertilizer, film, diesel, and pesticides compared to a scenario without this mechanism. Specifically, the usage of fertilizer is expected to decrease by 5.73%, film by 5.54%, diesel by 5.31%, and pesticides by 6.79%. In a scenario where prices increase to three times their original value, these reductions will be more significant, with fertilizer usage decreasing by 7.66%, film by 7.43%, diesel by 7.21%, and pesticides by 8.72%. In a scenario where prices increase to five times their original value, these reductions will be more significant, with fertilizer usage decreasing by 13.01%, film by 12.67%, diesel by 12.43%, and pesticides by 13.97%. Additionally, the overall carbon emissions are anticipated to decline by 10.21% from the predicted values, which corresponds to approximately 1.71 million tons of carbon dioxide at original prices. This percentage is expected to rise to 11.13% with the fivefold increase in prices.

3.3.2. Simulation of Carbon Sinks and Income

When the cropping industry has developed and adopted the carbon transition system in 2027, the amount of carbon sinks and carbon income are influenced by the pricing model and are shown in Figure 4.



(**a**) (**b**)

Figure 4. Carbon sinks and carbon income with different prices. (**a**) Simulation of carbon sinks with different prices. (**b**) Simulation of carbon income with different prices. Note: The data regarding carbon sinks and carbon income with different prices is sourced from the simulation.

According to Figure 4a, if the price of agricultural production increases to two times, the carbon sink is projected to reach 24.8 million tons by 2030; if the price increases to three times its original value, the carbon sink could potentially rise to 24.97 million tons, while if the price increases to five times its original value, the carbon sink could potentially rise to 25.34 million tons. Figure 4b illustrates that a higher price can also result in increased carbon income. The simulation results indicate that in 2030, carbon income based on general production prices is expected to reach 3.34 billion yuan, and it could rise to 3.42 billion yuan.

3.3.3. Simulation of the FPCPS, NI, FPCS, and RTV

In order to evaluate the benefits of farmers participating in the carbon trading mechanism through an FPC compared to those not participating, we conducted a simulation of the FPCPS, NI, FPCS, and RTV from 2020 to 2030. We assume that the cropping industry will engage in the carbon trading system starting in 2027. The results of the simulation are presented in Figure 5.

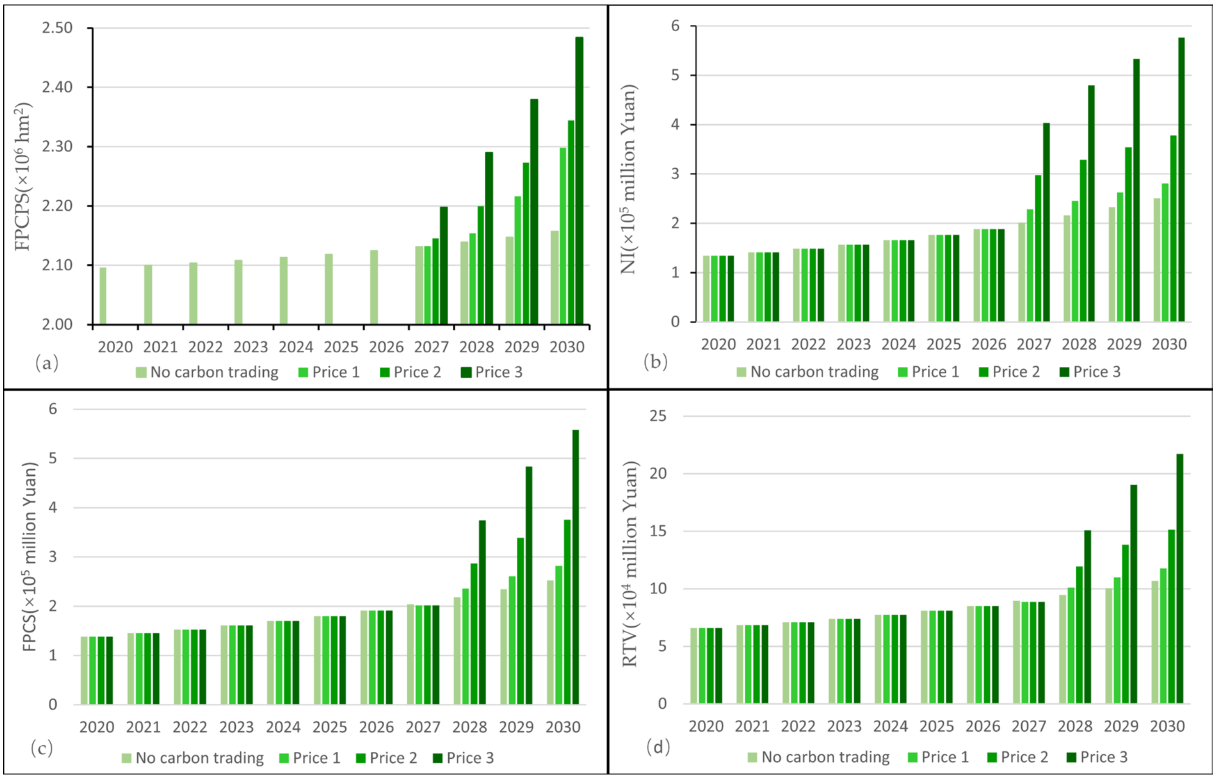


Figure 5. Simulation of the FPCPS, NI, FPCS and RTV with different prices. (**a**) Simulation of FPCPS with different prices. (**b**) Simulation of NI with different prices. (**c**) Simulation of FPCS with different prices. (**d**) Simulation of RTV with different prices. Note: The data regarding FPCPS, NI, FPCS and RTV with different prices is sourced from the simulation.

As illustrated in Figure 5, no carbon trading indicates the situation that the cropping industry is not participating in the carbon trading mechanism. Price 1, Price 2, and Price 3 reflect scenarios where the cropping industry engages in this trading mechanism, with Price 1 representing a price that is two times the original production price, Price 2 indicating a price that is three times the original, and Price 3 indicating a price that is five times the original.

As illustrated in Figure 5a, participation in carbon trading by 2030 can lead to an increase in FPCPS of 141 thousand (6.5%) hectares at Price 1, 187 thousand (8.6%) hectares at Price 2, and 32 thousand (15%) hectares at Price 3, compared to a scenario without carbon trading.

NI refers to the total net income generated by the FPC and the farmers. The trend in NI is illustrated in Figure 5b. By the year 2030, participation in carbon trading could enable the FPC to achieve an additional income of 29 billion yuan (11.85%) at Price 1, 126 billion yuan (50.58%) at Price 2, and 325 billion yuan (129.52%) at Price 3, compared to the scenario without carbon trading.

FPCS represents the total net income of the FPC after distributions have been made. As illustrated in Figure 5c, in the year 2030, the FPCS in the Price 1 scenario experiences an increase of 30 billion yuan (11.91%) and the Price 2 scenario shows a substantial increase of 123 billion yuan (48.92%), whereas the Price 3 scenario shows a substantial increase of 305 billion yuan (121%), when compared to the scenario without carbon trading.

RTV represents the funds returned based on transaction volume, specifically the surplus distribution from FPC to farmers. Figure 5d illustrates the comparison of RTV in scenarios without carbon trading versus scenarios that involve carbon trading at Price 1, Price 2, and Price 3. In 2030, compared to the scenario without carbon trading, RTV with Price 1 sees an increase of 10.8 billion yuan (10.14%) and Price 2 experiences a significant increase of 44.5 billion yuan (41.62%), while Price 3 experiences a significant increase of 110 billion yuan (103.06%).

4. Discussion

4.1. The FPC Low Carbon Production System

The FPC Low Carbon Production System comprises four interrelated subsystems: the Funding Input Subsystem, the FPC Operation Subsystem, the Farmer Behavior Subsystem, and the Eco-Environmental Subsystem. These subsystems function in a cohesive manner and exert mutual influence on one another. Among them, the Funding Input Subsystem is primarily responsible for identifying the main sources of funding for the FPC. Government funding serves as the principal external investment to facilitate the FPC's operations, particularly during the initial development phase. The factors contributing to funding support are crucial in determining the proportion of government support funds required for the successful implementation of the FPC project.

The Farmer Behavior Subsystem illustrates the behaviors of farmers regarding their participation in training programs aimed at enhancing the human capital of the FPC. This, in turn, contributes to effective brand management and improves production standards. Farmer training is also a key factor encouraging farmers to join an FPC, thereby increasing the scale of FPC production.

In the FPC Operation Subsystem, there are three reinforced loops designed to enhance the income of both the FPC and the farmers. For the FPC, the surplus primarily derives from uniform production sales, standardized production practices, and carbon credits. The crucial factor in these reinforced loops is to attract more farmers to participate in an FPC, thereby expanding its production scale. A key incentive for farmers to engage with an FPC is to maintain a high return rate of over 60% from transaction volume. This return is subject to legal constraints but can be leveraged through additional training for farmers. The uniform sale of production represents the largest revenue source for the net income of the FPC; therefore, increasing production prices can significantly elevate net income and surpluses for the FPC, ultimately increasing profits for farmers. This, in turn, amplifies the positive impact of these three loops compared to the general pricing of agricultural production.

Within the Eco-Environmental Subsystem, there is one strengthening loop and four weakening loops. The primary driver of the strengthening loop is the enhancement of carbon sinks in conjunction with the production scales of the FPC. Conversely, the main factors contributing to the weakening loops are the number of FPCs that continue to operate under standard production practices. An increase in the number of FPCs maintaining standard production, relative to the original situation, results in a decrease in carbon emissions from diesel, film, pesticides, and fertilizers used in the production process, thereby contributing to a higher carbon income. Additionally, a rise in the prices of agricultural products can significantly enhance carbon sinks, leading to increased carbon income. This occurs because higher agricultural prices can incentivize both the scaling up of FPC production and the maintenance of standard production practices, resulting in greater income compared to the average agricultural production price. The carbon fixation factor is an external parameter that can be changed by the mode of implantation and how it is structured.

In summary, the FPC Low Carbon Production System is a sophisticated framework designed to appeal to small-scale farmers, facilitating green standard production that delivers both economic advantages and environmental benefits.

4.2. Carbon Sinks and Income Analysis

In conjunction with Figure 4, the causal loop diagram for the FPC Low Carbon Production System illustrates that as the quantity of FPCs engaging in standard production increases, there is a corresponding decrease in the usage of fertilizer, film, diesel, and pesticides. However, many small-scale farmers may lack the resources to implement standard production independently, making participation in FPCs an advantageous option for them. This standard production model can enhance the surplus generated by FPCs, which in turn can facilitate the entry of more farmers into these cooperatives. This creates a reinforcing loop between FPCs conducting standard production and the influx of new farmer participants. Government support serves as a primary funding source for FPCs, enabling them to implement brand management strategies and promote standardized production. By adopting standardized practices, farmers can reduce their usage of fertilizers, films, diesel, and pesticides, leading to lower carbon emissions during the cropping process. Furthermore, higher market prices can contribute to a greater reduction in carbon sources, as they provide additional surplus for FPCs to invest in standard production initiatives.

The total carbon sink is significantly influenced by the land area of the FPC. As the number of farmers participating in the FPC increases, it becomes possible for the FPC to engage in standard production, thereby enhancing the carbon sink. According to the standardized production model of existing cooperatives, strictly controlling the use of fertilizer, pesticides, and growth regulator and transgenesis technology can result in the product reaching the required standards for Chinese organic food [27,47]. The price of organic products is higher than that of conventional products [41–45]. Consequently, within the framework of a carbon transition mechanism, standard production can yield both greater economic and ecological benefits, provided that all organic standards are adhered to. The higher pricing creates an additional surplus for the FPC, which can further incentivize more farmers to join the FPC to pursue low-carbon production and increase carbon sinks. This creates a positive feedback loop.

The adoption of a carbon trading mechanism within the cropping industry could facilitate greater participation of small-scale farmers in FPCs and enhance their income. Subsequently, FPCs may experience increased revenue, allowing them to promote low-carbon production, thereby reducing carbon emissions and attracting additional farmers to join FPCs to augment carbon sequestration efforts. Furthermore, low-carbon production frequently commands price premiums, which can bolster FPCs and further enhance farmers' earnings.

4.3. Gains of the FPC and Farmers

The FPCPS is a critical component of the FPC Low Carbon Production System. An increase in FPCPS indicates that FPC can cultivate a greater area of land dedicated to low-carbon production, thereby enhancing both economic and ecological benefits. This increase in FPCPS is primarily attributed to a rise in farmer participation, which is driven by the growing availability of RTV and famer training.

Cooperatives can encourage farmers to join by offering training and enhancing returns through increased transaction volume. As a unique form of organization, farmers' cooperatives require members to possess certain levels of scientific and cultural literacy, market transaction awareness, and exhibit a spirit of collaboration. However, many farmers may lack these essential skills and knowledge due to longstanding production techniques and traditional living habits. By providing specialized training, cooperatives can equip farmers with knowledge in areas such as organic agricultural practices, marketing strategies, and cooperative management, thereby helping to engage more farmers in the growth of cooperatives.

Return by transaction volumes is a key principle within the distribution system of the cooperative. This principle aligns with the organizational goals of cooperatives that aim to serve the common interests of all members. By distributing increased surpluses based on the proportion of returns in transaction volume, it can motivate farmers to engage more actively in cooperatives, thereby contributing to their growth. Additionally, this approach has strengthened farmers' loyalty to the cooperatives, making them more inclined to participate in their long-term development. Ultimately, this trend will lead to the overall expansion of the FPCS.

NI plays a significant role in the growth of FPC and is affected by USAP, SP, and CI. The cooperative can create a scale effect and enhance the market competitiveness of agricultural products through the unification of these products. This approach enables cooperatives to secure better pricing in the marketplace, ultimately increasing net income. Unified sales methods can also decrease the costs associated with locating buyers and negotiating prices. The reduction of these expenses results in a greater net income for the cooperatives. Furthermore, cooperatives establish stable sales channels for farmers, minimizing sales uncertainty arising from market fluctuations and assisting in the maintenance of consistent net income.

The adoption of standardized production practices within cooperatives enhances the quality and consistency of agricultural products, effectively addressing market demands for high-quality offerings. This, in turn, contributes to higher pricing and increased sales, ultimately boosting the net income of cooperatives. By implementing standardized production methods, cooperatives can optimize their production processes, minimize waste, and lower production costs. These cost reductions translate into increased net income for cooperatives. Furthermore, standardized production enhances the market competitiveness of agricultural products, resulting in additional increases in net income.

4.4. Future Research Directions

This article takes the national level as the research unit, analyzing the operational mechanisms of FPCs and the benefits they and the farmers can gain from participating in carbon emission transaction systems. The objective is to understand the role of FPCs in fostering low-carbon production among small-scale farmers in China and to identify potential outcomes that can inform decision-making within relevant policy-making agencies. However, limitations in data collection in certain regions may impact the accuracy of the research findings. Consequently, further analysis of the operational mechanisms of FPCs on a larger regional scale, along with the formulation of countermeasures and recommendations to enhance low-carbon production among small-scale farmers, remains an area for future research. Additionally, the fluctuating uncertainty of carbon prices is a factor which can affect the income of FPCs and small-scale farmers and this warrants further study.

5. Conclusions and Policy Implications

5.1. Conclusions

This article seeks to explore the mechanisms of FPC operations and to assess their role in facilitating low-carbon production among small-scale farmers in China. By utilizing a system dynamics model, we simulate the potential benefits for both small-scale farmers and FPCs following the integration of the agricultural sector into carbon trading systems. The findings are summarized as follows:

1. The implementation of a carbon transaction mechanism within the cropping industry is expected to result in a reduction in the use of fertilizers, films, diesel, and

pesticides. Notably, in scenarios where agricultural production prices rise, these reductions are projected to be more pronounced.

2. The establishment of a carbon transaction mechanism within the cropping industry is anticipated to enhance both carbon sinks and carbon income for FPCs and small-scale farmers. Similarly, in scenarios where agricultural products' prices increase, these enhancements are expected to be more significant.

3. Participation in carbon trading mechanisms can lead to an increase in the financial performance indicators of FPCs as well as enhance the net income and financial capacity of small-scale farmers. In a scenario where agricultural products' prices rise, these increases are likely to be more pronounced.

In conclusion, it is clear that integrating the agricultural sector into carbon trading systems could encourage small-scale farmers to join FPCs, thereby enhancing the overall production scale of these organizations. By participating in an FPC, both the organization and small-scale farmers stand to gain greater economic and ecological benefits. Furthermore, considering a scenario where elevated prices for organic agricultural products could result in a more substantial increase in carbon sinks, reductions in carbon emissions, expanded production capacity for FPCs, and increased income for both farmers and FPCs, highlights the potential for further economic and ecological advantages for both FPCs and small-scale farmers.

5.2. Policy Implications

From a global comparative perspective, China's FPCs demonstrate both the universal principles of cooperatives and distinctive institutional characteristics [5,12,48,49]. While sharing core functions with international models, including resource integration, agricultural input procurement, and market linkage, Chinese FPCs operate within a unique institutional framework featuring collective land ownership and significant government participation [14,15,48,49]. Comparative research indicates that successful international cooperative models in the EU and USA typically achieve sustainable development through member-driven governance, market-oriented operations, and robust legal safeguards [48,49]. By contrast, China's FPCs excel in technology adoption and policy implementation efficiency through government-led agricultural extension systems, enabling effective promotion of low-carbon agriculture [9,14,15,50]. However, their limitations in financial autonomy and operational flexibility may constrain capacity building for value-added agricultural processing and brand marketing, potentially preventing them from reaching the sophistication level of mature international cooperatives.

To promote low carbon agricultural production, it is crucial for the government to engage the cropping industry in the carbon trading system at the earliest opportunity [51]. Integrating the cropping industry into this system can yield significant economic and ecological benefits, thereby enriching both the FPC and farmers, promoting a collaborative economy and facilitating mutual growth. Additionally, this engagement would enable the government to allocate more funding, talent, and legal support to the development of FPCs. As evidenced by the FPC Low Carbon Production System, funding can provide essential operational resources, talent acquisition can encourage more farmers to participate in FPCs, and legal regulations can ensure the protection of farmers' interests. Given the important role that FPCs play in transitioning small-scale farmers to organic production, the government should explore strategies to strengthen their cooperative functions.

Attracting a greater number of small-scale farmers to engage in organic production aligned with carbon reduction targets is crucial for the success of FPC. The government currently offers various policy support mechanisms to facilitate the development of FPCs. It is essential for FPCs to leverage these resources effectively to recruit more small-scale farmers and scale up production. As the focus on carbon transactions continues to evolve, it is vital for FPCs to implement low-carbon production practices, which can yield significant economic and ecological benefits for both farmers and the organization. The economic advantages of organic production are anticipated to surpass the ecological benefits. Therefore, embracing low-carbon production not only supports the advancement of ecological goals but also enhances economic viability, particularly in the context of carbon transition.

Participation in an FPC presents a valuable opportunity for farmers to enhance their income. Due to limited financial resources and technological access, small-scale farmers often face challenges in implementing low-carbon production without formal assistance. Engaging in an FPC allows these farmers to improve their income potential through collective purchasing of production materials and increased sales of agricultural products, while also gaining access to essential funding and technological support. Moreover, by participating in FPCs' educational programs focused on low-carbon production, small-scale farmers can further increase their earnings. Nonetheless, adhering to the rigorous standards of organic production can pose challenges for these farmers. It is crucial for them to understand the importance of standardized organic practices and comply with established production protocols to ensure the quality of their outputs. Upholding these standards is essential for maintaining consumer trust and securing price premiums, as consumers increasingly value the integrity of organic products in the marketplace.

FPCs can serve as pivotal agents in low-carbon agricultural transformation by integrating carbon trading mechanisms with farming systems to establish a trilateral sustainable development model encompassing "policy implementation, emission reduction efficiency, and benefit sharing". Through legislative empowerment, fiscal support, and technological enablement, governments can develop FPCs into a tool that simultaneously advances climate governance and sustainable agriculture. These cooperatives can implement emission reduction initiatives by standardizing eco-friendly farming practices and establishing technical benchmarks. Additionally, they can serve as mechanisms for redistributing environmental benefits, thereby creating income-generating opportunities for small-scale farmers and helping to narrow the income gap. This innovative governance model not only contributes the achievement of national carbon reduction targets but also demonstrates China's replicable approach to global agricultural sustainability through the synergistic realization of environmental, economic, and social benefits.

Author Contributions: Conceptualization, Q.C. and J.F.; methodology, J.F.; software, H.L.; validation, Q.C. and X.C.; investigation, J.F. and H.L.; writing—original draft preparation, J.F.; writing—review and editing, N.C. and H.L.; and funding acquisition, J.F. and Q.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Qingdao Agricultural University High-level Talent Research Fund Projects (Fund Number: 663-1120703, 663-1119726） and the Shandong Province Youth Project for Education and Teaching Research (Fund Number: 2023JXQ004)

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We are very grateful for the valuable suggestions provided by the editors and reviewers.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1. Equations for the FPC Low Carbon Production System.

1. The Funding Input Subsystem

$$d(FD)/dt = IW - OW$$

$$IW = GSF \times FSF + SF + DN \times 0.20$$

$$OW = 0.80 \times Funds$$

$$SF = GSF \times UR$$

2. The FPC Operation Subsystem

$$d(FPCS)/dt = NI - DN$$

$$NI=19971.32 + 0.06 \times USAP + 5325.51 \times SP + CI$$

$$DN = FPCS \times 0.92$$

$$DS = 0.70 \times DN$$

$$RTV = DS \times LRF + ADF$$

$$FPCPS = 2050000.00+5.00 \times FE$$

$$UPPM = 95921.81 + 3.17 \times RTV + 0.03 \times FPCPS$$

$$USAP = 450111.13 + 1.11 \times UPPM$$

$$SP = 1.43 + 0.94 \times BM$$

$$BM = 6.47 + 0.0001 \times FPCHC + 0.000001 \times OW$$

3. The Farmer Behavior Subsystem

$$d(FPCHC)/dt = IS$$

$$IS = TSF \times FT$$

$$FE = -966.66 + 0.44 \times FT+0.10 \times RTV$$

$$FT = -1123.04 + 870.08 \times BM$$

4. The Eco-Environmental Subsystem

$$d(CFA)/dt = CSK - CSC$$

$$CSK = CFF \times FPCPS$$

$$CSC=TEC \times FPCPS + IECT \times FPCPS + 8956.00 \times FZ + 49341.00 \times PD + 51800.00 \times FM + 5927.00 \times DL$$

$$RV = CFA \times VF$$

$$CI = CP \times RV$$

$$DL = 73.96 - 1.16 \times SP$$

$$FL = 8.76 - 0.11 \times SP$$

$$PD = 6.10 - 0.14 \times SP$$

$$FZ = 204.29 - 2.93 \times SP$$

References

1. Huang, X.; Xu, X.; Wang, Q.; Zhang, L.; Gao, X.; Chen, L. Assessment of Agricultural Carbon Emissions and Their Spatiotemporal Changes in China, 1997–2016. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3105. https://doi.org/10.3390/ijerph16173105.
2. Wang, H.; Zhang, L. Research on Farmers' Low-Carbon Production Behavior: Introducing Green Cognition into the Theory of Planned Behavior. *Pol. J. Environ. Stud.* **2024**, *33*, 873–884. https://doi.org/10.15244/pjoes/172041.
3. Jiang, L.; Huang, H.; He, S.; Huang, H.; Luo, Y. What motivates farmers to adopt low-carbon agricultural technologies? Empirical evidence from thousands of rice farmers in Hubei province, central China. *Front. Psychol.* **2022**, *13*, 983597. https://doi.org/10.3389/fpsyg.2022.983597.
4. North, D.C. *Institutions, Institutional Change and Economic Performance*; Cambridge University Press: Cambridge, UK, 1990. https://doi.org/10.1017/CBO9780511808678.015.
5. Hao, J.; Bijman, J.; Gardebroek, C.; Heerink, N.; Heijman, W.; Huo, X. Cooperative Membership and Farmers' Choice of Marketing Channels–Evidence from Apple Farmers in Shaanxi and Shandong Provinces, China. *Food Policy* **2018**, *74*, 53–64. https://doi.org/10.1016/j.foodpol.2017.11.004.
6. Kang, M. A Brief Analysis of Low-Carbon Agriculture Development Pattern. *Bus. Manag. Res.* **2013**, *2*, 96. https://doi.org/10.5430/bmr.v2n2p96.
7. Cui, Y.; Khan, S.U.; Deng, Y.; Zhao, M.; Hou, M. Environmental Improvement Value of Agricultural Carbon Reduction and Its Spatiotemporal Dynamic Evolution: Evidence from China. *Sci. Total Environ.* **2020**, *754*, 7398. https://doi.org/10.1016/j.scitotenv.2020.142170.
8. Wang, Y.; Zhang, T.; Wang, X.; Jiang, B.; Wu, X.; Huang, X. Urbanization and Agricultural Carbon Emissions: The Mediation Effect of Agricultural Land Use Change. *Pol. J. Environ. Stud.* **2024**, *33*, 3927–3939. https://doi.org/10.15244/pjoes/177149.
9. Yu, L.; Chen, C.; Niu, Z.; Gao, Y.; Yang, H.; Xue, Z. Risk Aversion, Cooperative Membership and the Adoption of Green Control Techniques: Evidence from China. *J. Clean. Prod.* **2021**, *279*, 123288. https://doi.org/10.1016/j.jclepro.2020.123288.
10. Sambuo, D. Co-Operatology and the Science of Cooperative Societies: A Synthetic Review of Research on Cooperative Evolution. *J. Coop. Organ. Manag.* **2023**, *11*, 100190. https://doi.org/10.1016/j.jcom.2022.100190.
11. Spear, R. The Co-Operative Advantage. *Ann. Public Coop. Econ.* **2000**, *71*, 507–523. https://doi.org/10.1111/1467-8292.00151.
12. Ma, W.; Renwick, A.; Yuan, P.; Ratna, N. Agricultural Cooperative Membership and Technical Efficiency of Apple Farmers in China: An Analysis Accounting for Selectivity Bias. *Food Policy* **2018**, *81*, 122–132. https://doi.org/10.1016/j.foodpol.2018.10.009.
13. Ma, D.; Wang, X.; Guo, Z.; Yu, T. An evolutionary game theory–based study examining the relationship between fiscal policy, stability of farmers' cooperatives, and environmentally friendly digital management. *Environ. Sci. Pollut. Res.* **2024**, *31*, 909–930. https://doi.org/10.1007/s11356-023-31092-5.
14. Deng, H.; Huang, J.; Xu, Z.; Rozelle, S. Policy support and emerging farmer professional cooperatives in rural China. *China Econ. Rev.* **2010**, *21*, 495–507. https://doi.org/10.1016/j.chieco.2010.04.009.
15. Liu, Y.; Cao, L.; Wang, Y.; Liu, E. Viability, Government Support and the Service Function of Farmer Professional Cooperatives—Evidence from 487 Cooperatives in 13 Cities in Heilongjiang, China. *Agriculture* **2024**, *14*, 616. https://doi.org/10.3390/agriculture14040616.
16. Ma, G.; Chen, J. Study on development capability of small farmer cooperative organization in rural revitalization. In Proceedings of the International Academic Conference on Frontiers in Social Sciences and Management Innovation (IAFSM 2018), Chongqing, China, 17–18 November 2018; Atlantis Press: Dordrecht, The Netherlands, 2019; pp. 1–5. https://doi.org/10.2991/iafsm-18.2019.1.
17. Zheng, Y.; Lou, J.; Mei, L.; Lin, Y. Research on digital credit behavior of farmers' cooperatives—A grounded theory analysis based on the "6C" family model. *Agriculture* **2023**, *13*, 1597. https://doi.org/10.3390/agriculture13081597.

18. Yi, Z.; Wang, Y.; Chen, Y.J. Financing an agricultural supply chain with a capital-constrained smallholder farmer in developing economies. *Prod. Oper. Manag.* **2021**, *30*, 2102–2121. https://doi.org/10.1111/poms.13357.
19. Nzamurambaho, F.; Ekowati, T.; Gayatri, S. Factors Influencing the Profitability of Agricultural Cooperative Members: Case of Tuzamurane Cyeza Cooperative, Muhanga District, Rwanda. *Agro Ekon.* **2023**, *35*, 124–141. https://doi.org/10.22146/ae.90514.
20. Yu, X.; Liu, W.; Qing, L.; Zhang, D. Improving farm cooperatives' performance and sustainability: A study of agricultural managers' competencies based on the grounded theory and the fsQCA methods. *Sustainability* **2023**, *15*, 1263. https://doi.org/10.3390/su15021263.
21. Ran, G.; Wang, G.; Du, H.; Lv, M. Relationship of cooperative management and green and low-carbon transition of agriculture and its impacts: A case study of the western tarim river basin. *Sustainability* **2023**, *15*, 8900. https://doi.org/10.3390/su15118900.
22. Wang, J.; Zhang, X.; Li, R. The Role of Farmers' Cooperatives in Promoting Agricultural Green Development: Empirical Evidence from China. *J. Clean. Prod.* **2022**, *330*, 129862. https://doi.org/10.1016/j.jclepro.2021.129862.
23. Wang, H.; Qiu, T. The effects of farmer cooperatives on agricultural carbon emissions reduction: Evidence from rural China. *J. Clean. Prod.* **2024**, *450*, 141881. https://doi.org/10.1016/j.jclepro.2024.141881.
24. Sun, X.; Liu, W.; Xu, D. Agricultural Cooperatives and Their Contribution to Farmers' Sustainable Development—A Case Study of Organic Tea Growers in China. *Sustainability* **2019**, *11*, 2631. https://doi.org/10.3390/su11092631.
25. Ajates, R. An Integrated Conceptual Framework for the Study of Agricultural Cooperatives: From Repolitisation to Cooperative Sustainability. *J. Rural Stud.* **2020**, 78, 467–479. https://doi.org/10.1016/j.jrurstud.2020.06.019.
26. Zhao, L.; Yang, B. The Impact of Cooperative Membership on Farmers' Adoption of Low-Carbon Agricultural Practices. *J. Rural Stud.* **2022**, *90*, 117–128. https://doi.org/10.1016/j.jrurstud.2022.04.003.
27. Zou, J.; Shen, L.; Wang, F.; Tang, H.; Zhou, Z. Dual carbon goal and agriculture in China: Exploring key factors influencing farmers' behavior in adopting low carbon technologies. *J. Integr. Agric.* **2024**, *23*, 3215–3233. https://doi.org/10.1016/j.jia.2024.07.016.
28. Hou, J.; Hou, B. Farmers' adoption of low-carbon agriculture in China: An extended theory of the planned behavior model. *Sustainability* **2019**, *11*, 1399. https://doi.org/10.3390/su11051399.
29. Li, F.; Tang, X.; Zhang, P. The Impact of Cooperative Participation on Farmers' Adoption of Green Production Technologies. *Sci. Total Environ.* **2021**, *771*, 145418. https://doi.org/10.1016/j.scitotenv.2021.145418.
30. Xie, J.; Wang, Z.; Huang, X. Farmers' Cooperatives and Rural Environmental Governance: A Study Based on Chinese Agricultural Carbon Emissions. *J. Rural Stud.* **2023**, *98*, 34–47. https://doi.org/10.1016/j.jrurstud.2023.01.005.
31. Huo, Y.; Mi, G.; Zhu, M.; Chen, S.; Li, J.; Hao, Z.; Cai, D.; Zhang, F. Carbon footprint of farming practices in farmland ecosystems on the North and Northeast China plains. *J. Environ. Manag.* **2024**, *354*, 120378. https://doi.org/10.1016/j.jenvman.2024.120378.
32. Feng, J.; Zhao, L.D.; Zhang, Y.B.; Sun, L.X.; Yu, X.; Yu, Y. Can climate change influence agricultural GTFP in arid and semi-arid regions of Northwest China? *J. Arid Land* **2020**, *12*, 837–853. https://doi.org/10.1007/s40333-020-0073-y.
33. Forrester, J.W. Learning through system dynamics as preparation for the 21st century. *Syst. Dyn. Rev.* **2016**, *32*, 187–203. https://doi.org/10.1002/sdr.1571.
34. Saysel, A.K.; Barlas, Y.; Yenigün, O. Environmental sustainability in an agricultural development project: A system dynamics approach. *J. Environ. Manag.* **2002**, *64*, 247–260. https://doi.org/10.1006/jema.2001.0488.
35. Winz, I.; Brierley, G.; Trowsdale, S. The use of system dynamics simulation in water resources management. *Water Resour. Manag.* **2009**, *23*, 1301–1323. https://doi.org/10.1007/s11269-008-9328-7.
36. Rozman, Č.; Pažek, K.; Prišenk, J.; Škraba, A.; Kljajić, M. System dynamics model for policy scenarios of organic farming development. *Organizacija* **2012**, *45*, 212–218. https://doi.org/10.2478/v10051-012-0016-2.
37. Li, F.J.; Dong, S.C.; Li, F. A system dynamics model for analyzing the eco-agriculture system with policy recommendations. *Ecol. Model.* **2012**, *227*, 34–45. https://doi.org/10.1016/j.ecolmodel.2011.12.005.
38. Bastan, M.; Khorshid-Doust, R.R.; Sisi, S.D.; Ahmadvand, A. Sustainable development of agriculture: A system dynamics model. *Kybernetes* **2018**, *47*, 142–162. https://doi.org/10.1108/K-01-2017-0003.
39. Egerer, S.; Cotera, R.V.; Celliers, L.; Costa, M.M. A leverage points analysis of a qualitative system dynamics model for climate change adaptation in agriculture. *Agric. Syst.* **2021**, *189*, 103052. https://doi.org/10.1016/j.agsy.2021.103052.
40. Deng, J.L. Introduction to grey system theory. *J. Grey Syst.* **1989**, *1*, 1–24. https://dl.acm.org/doi/10.5555/90757.90758.
41. Niu, B.; Dong, J.; Dai, Z.; Jin, J.Y. Market expansion vs. intensified competition: Overseas supplier's adoption of blockchain in a cross-border agricultural supply chain. *AgriSciRN Agric. Coop.* **2021**, *51*, 101113. https://doi.org/10.1016/j.elerap.2021.101113.

42. Li, W.; Clark, B.; Taylor, J.A.; Kendall, H.; Jones, G.; Li, Z.; Jin, S.; Zhao, C.; Yang, G.; Shuai, C.; et al. A hybrid modelling approach to understanding adoption of precision agriculture technologies in Chinese cropping systems. *Comput. Electron. Agric.* **2020**, *172*, 105305. https://doi.org/10.1016/j.compag.2020.105305.
43. He, Y.Q.; Zhu, S.; Zhang, Y.; Zhou, Y.C. Calculation, elasticity and regional differences of agricultural greenhouse gas shadow prices. *Sci. Total Environ.* **2021**, *790*, 148061. https://doi.org/10.1016/j.scitotenv.2021.148061.
44. Chen, Q.; Huang, J.; Mirzabaev, A. Does fuel price subsidy work? Household energy transition under imperfect labor market in rural China. *Energy Econ.* **2022**, *107*, 105845. https://doi.org/10.1016/j.eneco.2022.105845.
45. Ullah, A.; Arshad, M.; Kachele, H.; Khan, A.; Mahmood, N.; Müller, K. Information asymmetry, input markets, adoption of innovations and agricultural land use in Khyber Pakhtunkhwa, Pakistan. *Land Use Policy* **2020**, *90*, 104261. https://doi.org/10.1016/j.landusepol.2019.104261.
46. Samuel, K.; Van der Heide, M.G.A. A Global Meta-Analysis of Yield Stability in Organic and Conservation Agriculture. *Nat. Commun.* **2018**, *9*, 3632. https://doi.org/10.1038/s41467-018-05956-1.
47. Zhang, B.; Fu, Z.T.; Huang, J.; Wang, J.Q.; Xu, S.Y. Consumers' perceptions, purchase intention, and willingness to pay a premium price for safe vegetables: A case study of Beijing, China. *J. Clean. Prod.* **2018**, *197*, 1498–1507. https://doi.org/10.1016/j.jclepro.2018.06.273.
48. Grashuis, J.; Ye, S.U. A Review of the Empirical Literature on Farmer Cooperatives: Performance, Ownership and Governance, Finance, and Member Attitude. *Ann. Public Coop. Econ.* **2018**, *90*, 77–102. https://doi.org/10.1111/apce.12205.
49. Candemir, A.; Duvaleix, S.; Latruffe, L. Agricultural Cooperatives and Farm Sustainability—A Literature Review. *J. Econ. Surv.* **2021**, *35*, 1118–1144. https://doi.org/10.1111/joes.12417.
50. Dong, C.; Wang, H.; Long, W.; Ma, J.; Cui, Y. Can Agricultural Cooperatives Promote Chinese Farmers' Adoption of Green Technologies? *Int. J. Environ. Res. Public Health* **2023**, *20*, 4051. https://doi.org/10.3390/ijerph20054051.
51. Black, H.; Reed, M.; Kendall, H.; Parkhurst, R.; Cannon, N.; Chapman, P.J.; Orman, M.; Phelps, J.; Rudman, H.; Whalley, S.; et al. What makes an operational farm soil carbon code? Insights from a global comparison of existing soil carbon codes using a structured analytical framework. *Carbon Manag.* **2022**, *13*, 554–580. https://doi.org/10.1080/17583004.2022.2135459.