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A Cooperative-Dominated Model of Conservation Tillage to Mitigate Soil Degradation on Cultivated Land and Its Effectiveness Evaluation

Yubo Liao [1,2], Bangbang Zhang [3], Xiangbin Kong [1,2,*], Liangyou Wen [1,2], Dongheng Yao [1,2], Yuxuan Dang [1,2] and Wenguang Chen [1,2]

[1] College of Land Science and Technology, China Agricultural University, Beijing 100193, China; bs20203210964@cau.edu.cn (Y.L.); wenly@cau.edu.cn (L.W.); b20203210945@cau.edu.cn (D.Y.); b20193030285@cau.edu.cn (Y.D.); bs20213211014@cau.edu.cn (W.C.)
[2] Key Laboratory of Agricultural Land Quality, Ministry of Natural Resources, Beijing 100193, China
[3] College of Economics and Management, Northwest A&F University, Xianyang 712100, China; bangbang.zhang@nwafu.edu.cn
* Correspondence: kxb@cau.edu.cn

Abstract: Sustainable agricultural production systems are important for ensuring food security. However, they are severely threatened by soil degradation and carbon emissions resulting from traditional farming practices. A cooperative-dominated conservation tillage model attempts to mitigate these issues, yet it is not clear how this model has been implemented and how well it performs in practice. This study takes Lishu County in Jilin Province in Northeast China as a case study to explore the implementation of a cooperative-dominated conservation tillage (CDCT) model and its practical effectiveness. In contrast to the traditional production model, this model uses cooperatives as the direct managers of cultivated land and promotes the construction of new production units and large-scale and mechanized operations to standardize the application of conservation tillage technology in agricultural production. Scientific research institutes, governments, and enterprises are supporters of cooperatives, empowering them in terms of technology, capital, products, and services. The evaluation results show that, unlike the traditional production model, which caused a decrease in the soil organic carbon content, the organic carbon content of the topsoil of cultivated land under this model increased by an average of 6.17% after 9 years of conservation tillage application. Furthermore, the soil structural stability index of the cultivated land increased from 3.35% to 3.69%, indicating that the degree of soil structural degradation was alleviated to a certain extent. The CDCT model effectively enhanced the operational efficiency and fertilizer use efficiency, and the carbon footprint of maize production was also reduced by 15.65% compared to the traditional production model. In addition, the total production cost was reduced by 1449 CNY/ha and profit increased by 2599 CNY/ha on average, indicating higher economic returns under the CDCT model due to increased yields and lower input costs. Farmers who are freed from agricultural production activities by transferring their farmland can also gain two types of income—land revenue and labor wagesi—thus mproving their living conditions. The CDCT model can deliver multigoal benefits and be of great value in its extension to other regions. This study may provide lessons for the sustainable use of cultivated land in China and other developing countries, contributing to agricultural development with lower environmental costs.

Keywords: soil degradation; carbon emissions; cooperative-dominated conservation tillage model; multi-agents; effectiveness evaluation; sustainable cultivated land use

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1. Introduction

Meeting the growing population's demand for agricultural products and ecosystem services is a considerable challenge [1,2]. To ensure food production, the agricultural production mode characterized by high-intensity utilization has led to severe soil degradation and substantial carbon emissions [3,4]. According to previous studies, approximately one-third of the planet's soil is degraded [5], and agriculture emits 24% of the total anthropogenic greenhouse gases [6]. It is urgent to curb soil degradation and control agricultural carbon emissions [7,8], which are vital components of achieving the United Nations' Sustainable Development Goals.

China is one of the countries most affected by soil degradation [9], especially Northeast China [10,11]. As one of the four black soil regions in the world, Northeast China has a cultivated area of 35.84 million ha, accounting for one-quarter of the grain output and one-third of the commodity grain transferred in China; thus, this region is referred to as the grain production base of China or the bread basket of China [12]. However, long-term extractive agriculture dominated by smallholder farmers has led to soil degradation on cultivated land, such as topsoil loss, a decline in the soil organic matter content, and soil structure deterioration [13–15]. For instance, the thickness of black soil in this region has decreased from 60–70 cm in the 1950s to 20–30 cm at present, and in some places, the loess parent material has been exposed [16,17]. The content of organic matter in black soil decreased from 60–80 g/kg during the initial stage of reclamation to an average of 30.56 g/kg in 2014 [18]. These problems have severely threatened the sustainability of agricultural production in the region [19,20]. Meanwhile, the cost of carbon emissions from traditional agricultural practices characterized by high investment [21,22] may also affect the achievement of China's carbon neutralization goal [23]. Therefore, in Northeast China, overcoming the disadvantages of the traditional agricultural production model implemented by smallholder farmers for a long time, effectively alleviating soil degradation, and controlling agricultural carbon emissions are important priorities for the development of sustainable agriculture.

At present, a cooperative-dominated model being explored and experimented with in Northeast China involves the application of conservation tillage (CT) to agricultural production practices through large-scale and standardized land management, with the goal of addressing the soil degradation and carbon emissions caused by conventional agricultural production. CT is a farming system that minimizes the degree and frequency of tillage passes to reduce soil disturbance and ensure that at least 30% of the soil surface remains covered with crop residues for soil conservation [24,25]. Due to its ability to improve soil structure, reduce soil organic carbon loss and greenhouse gas emissions, and alleviate soil erosion [26–28], CT is widely regarded as an effective way to reverse soil degradation and reduce carbon emissions [29–31]. A large number of studies based on field experiments have explored the effects of conservation tillage on soil physicochemical properties [32,33], soil biological properties [34,35], crop yield [36,37], and greenhouse gas emissions [38,39]. However, the implementation effect of CT is affected by factors such as the environment (e.g., terrain, soil properties, and climate), the maturity of supporting machinery, farm size, and management practices (e.g., tillage duration, machinery operation level, and straw mulching ratio) [40–43], causing the actual application effect to be different from the field experiment effect [44,45]. Specifically in China, the scattered management of land by smallholder farmers has become a major factor restricting the implementation of CT [46]. Through subjects such as agricultural cooperatives, we can move toward large-scale farming [47,48], thus making it possible to address the relevant constraints to applying CT. However, several questions remain: how is this cooperative-dominated conservation tillage model implemented, and how does the model perform in practice? The answers are not yet clear, and there is a lack of empirical studies, hindering the understanding and promotion of the model.

This study takes a cooperative-dominated conservation tillage (CDCT) model implemented in Lishu County in Jilin Province as a case study, explains in depth and analyzes the implementation process of the model and the roles played by the relevant agents involved, and evaluates the effectiveness of the model in terms of the soil condition, carbon emissions, production efficiency, and cost–benefit by comparing it with the traditional production model. It is hoped that this study will improve our knowledge of the CDCT model and provide new insight into the adoption and promotion of CT in agricultural production in Northeast China and other regions to promote the sustainable utilization of cultivated land resources and sustainable agricultural development.

2. Materials and Methods

2.1. Study Area

Lishu County is located in southwestern Jilin Province (123°45′–124°53′ E, 43°02′–43°46′ N) and the hinterland of the Songliao Plain in Northeast China. The southeast of the county is dominated by low mountains and hills. The central part of the county is a platform alluvial plain with slightly undulating terrain, dominated by denudation. The northern part is an alluvial plain with low-lying and flat terrain, alternating with aeolian sand and saline–alkali soil, dominated by aeolian alluvial terrain. The county has a temperate semi-humid continental monsoon climate. The temperature increases early but is unstable in spring, and there are many droughts and concentrated precipitation in summer. The annual average temperature is 6.5 °C, the annual sunshine duration is 2541 h, and the annual average rainfall is 553 mm. In general, there is sufficient sunshine and precipitation during crop growth. The soil types are mainly black soil, chernozem, meadow soil, aeolian sandy soil, and brown soil (Figure 1). The cultivated land area of Lishu County is 2.64×10^5 ha, accounting for 63% of the total land area, and is mainly planted with maize. Agriculture is an important supporting industry in Lishu County. The county is a national key commodity grain base county, where the annual grain output is stable at more than 2.5 million tons, and the three indicators (per capita grain possession, per unit area yield, and grain commodity rate) are among the best in China. Additionally, the production and operation of agriculture cooperatives in Lishu County have developed rapidly in the past ten years. At present, the number of cooperatives registered in the county exceeds 2000.

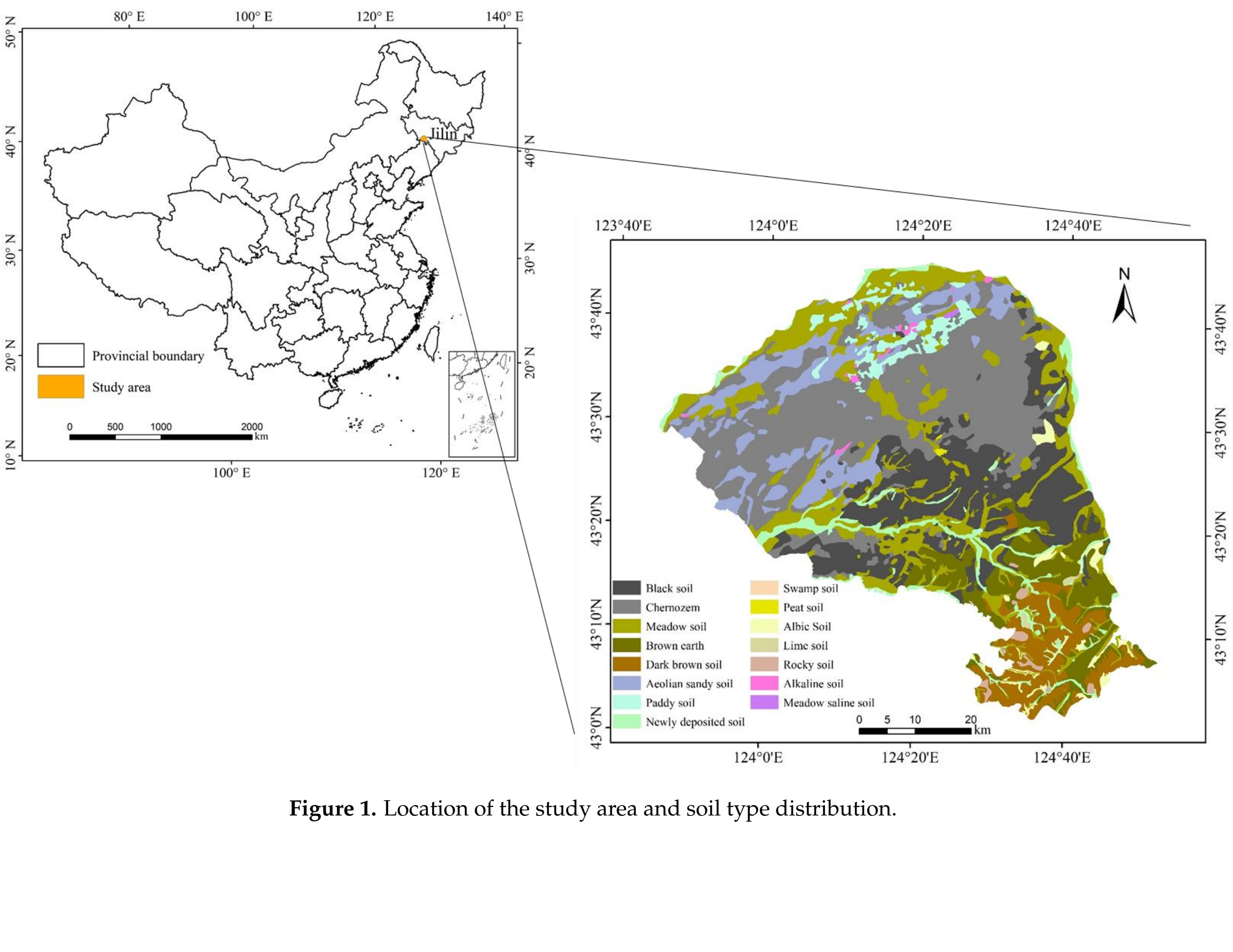

Figure 1. Location of the study area and soil type distribution.

2.2. Methodology

Based on field sampling and household surveys, this study calculated and compared the relevant indicators under the CDCT model to evaluate the effects of the model in terms of soil condition, carbon emissions, production efficiency, and economic benefits. Two key indicators—the soil organic carbon and the soil structural stability index—were used to measure the soil condition of the cultivated land. The measurements of carbon emissions, production costs, and economic benefits were mainly based on the data collected from the survey.

2.2.1. Measurement of SOC and the Soil Structural Stability Index

Soil organic carbon (SOC) is the basis of physical, chemical, and biological transformations and reactions in the soil and is recognized as the most significant single soil quality indicator [49]. The soil structural stability index (STI) was used to evaluate soil degradation and the stability of soil structure [15,50]. Therefore, SOC and STI were used to measure the soil conditions of the cultivated land in this paper.

The H Cooperative, a representative agricultural cooperative under the CDCT model, operates 500 hectares of cultivated land and has been using conservation tillage for maize production since 2012. We measured and calculated the changes in the SOC content and STI of cultivated land in the H Cooperative after 9 years of adopting conservation tillage. Soil samples were collected from the cultivated land operated by the H Cooperative in the harvest seasons of 2011 and 2020, and 42 composite samples (17 for 2011 and 25 for 2020) were obtained twice for the measurements of SOC and soil particle composition. The H Cooperative used conventional ridge tillage (CRT) for maize production before 2012 and adopted straw return and reduced tillage and no-tillage methods in production practices from 2012. The cooperative successively adopted two types of conservation tillage—no tillage with straw mulching (NTS) and strip rotary tillage with straw mulching (SRTS)—during the nine years from 2012 to 2020. The former tillage method was to crush the straw after the last season's maize harvest, cover it evenly on the surface of the farmland, and apply fertilizer and sow seeds with no-till seeders the following year, without soil disturbance throughout the growing season. The latter tillage method was to crush the straw and cover the ground surface with it during the maize harvest and then distribute the straw to the rows (to keep the coming year's uncultivated belts covered with straw) and rotary tillage the coming year's sowing belts with strip rototillers, finally conducting no-till seeding in due time in the coming year.

In each sampling plot, five soil samples were collected from the 0–20 cm soil layer and combined to form a composite sample for the measurement of the SOC content and soil particle composition. After being transported to the laboratory, the soil samples were air-dried. The first sub-sample was ground to pass through a 2 mm sieve for the analysis of soil particle composition, and the other was ground to pass through a 0.25 mm sieve for the measurement of SOC. The SOC content was determined using the rapid dichromate oxidation method [51]. Due to sample preservation, the total number of samples used for the analysis of the soil particle composition was 33, i.e., 13 for 2011 and 20 for 2020. The soil particle composition was measured using the laser diffraction method [15].

The STI (%) for a 0–20 cm soil layer depth was calculated using the following formula proposed by Pieri [50]:

$$\text{STI} = \frac{\text{SOM } (\%)}{\text{Clay}(\%) + \text{Silt}(\%)} \times 100 \tag{1}$$

where SOM (%) is the content of soil organic matter that was converted from the SOC content with a conversion factor of 1.724, and Clay (%) and Silt (%) represent the content of clay and silt particles in the soil, respectively. The smaller the STI, the higher the risk of structural degradation, and the STI $\leq 5\%$ indicates soil structural degradation [50]. The one-way variance analysis (ANOVA) was used to test the significance of SOC and STI before and after CT.

2.2.2. Measurement of Carbon Emissions

After obtaining effective data on the production and operation of 23 cooperatives and neighboring smallholder farmers in Lishu County, this study used the life cycle assessment method to calculate the carbon emissions from maize production under the CDCT model and traditional production model. Since the cooperatives surveyed currently mainly use SRTS, it was regarded as the representative tillage method under the CDCT model. In the traditional production model, the farming method adopted by smallholder farmers was CRT.

The system boundaries of the life cycle assessment in this study consisted of two phases—pre-farm and on-farm, i.e., the manufacture of agricultural material inputs and maize cultivation, respectively. In the on-farm phase, all parts of the maize cultivation process were included (Figure 2). The carbon emission coefficients of the inputs, such as diesel, fertilizer, and pesticides, are shown in Table 1. Seeds and human labor were not taken into account because of their small contribution to the overall carbon emissions. The investigation showed that the fertilizers used by the cooperatives in maize production were compound fertilizers, so this study calculated the amount of nitrogen (N), phosphorus (P), and potassium (K) fertilizer according to the amount of compound fertilizers and the proportion of each nutrient. The pesticides used include herbicides and insecticides. In this study, the dosages of the two types of pesticides were calculated according to the dosage of the pesticide products and the percentage contents of active ingredients, but the specific model of a certain type of pesticide was not distinguished. In addition, the energy consumed for mechanical operation in maize production was only diesel. Rainfed agriculture is a common practice in maize production in Lishu County; thus, the energy consumption of irrigation was not considered in this study.

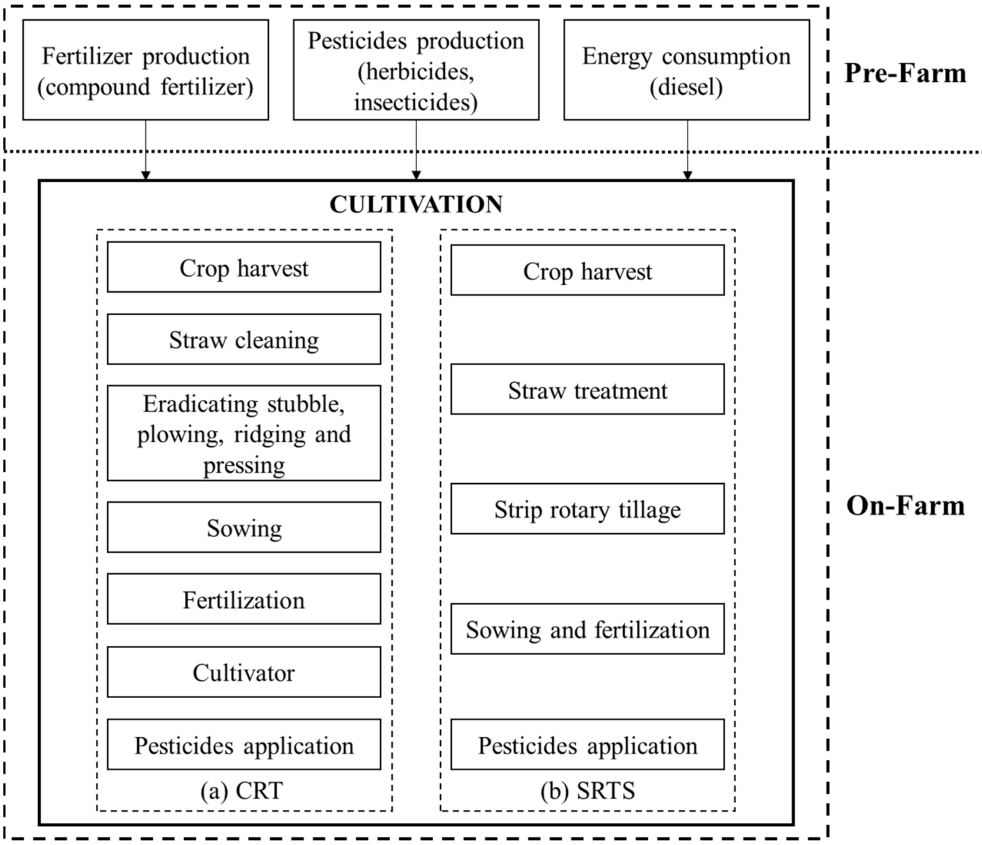

Figure 2. System boundaries of maize production using conventional ridge tillage (CRT) or strip rotary tillage with straw mulching (SRTS) in Lishu County.

Table 1. Carbon emission coefficients of the inputs considered in maize cultivation.

Inputs	Unit	kg CO_2-eq $Unit^{-1}$	References
Diesel	Liter	2.56	IPCC (2006) [52]
Fertilizer			
N	kg	13.5	Zhang et al. (2013) [53]
P	kg	2.332	Chen et al. (2015) [54]
K	kg	0.660	Chen et al. (2015) [54]
Pesticides			
Herbicides	kg	17.242	West and Marland (2002) [55]
Insecticides	kg	18.084	West and Marland (2002) [55]

The cumulative carbon footprint was the sum of the carbon emissions of the various inputs in each link of maize production defined in the system boundaries. The calculation formula is as follows:

$$\text{CCF} = \sum_i Input_i \times \delta_i \quad (2)$$

where CCF (kg CO_2-eq per f.u.) refers to the cumulative carbon footprint; $Input_i$ is the consumption of the i th input (fertilizer, pesticide, diesel, etc.); f.u. is the functional unit (ha or kg); and δ_i (kg CO_2-eq per unit) is the carbon emission coefficient of the i th input.

2.2.3. Measurement of Production Efficiency

As the application of the CDCT model would cause changes in production efficiency, this study selected fertilizer use efficiency (FUE) and the efficiency of straw handling, rotary tillage, sowing, and fertilization to characterize the production efficiency of cultivated land. FUE (kg kg^{-1}) is the partial productivity of fertilizer, i.e., crop yield divided by the pure nutrient input of chemical fertilizer [56]. The efficiencies of straw handling, rotary tillage, sowing, and fertilization were all calculated as follows:

$$\text{E} = O_s / T \quad (3)$$

where E is the operational efficiency, which is defined as the effective operational area per unit time, and O_s and T are the operational area and working time, respectively.

2.2.4. Economic Benefits Assessment

A cost–benefit analysis was used to evaluate the economic benefits of the CDCT model. In terms of costs, agricultural material inputs (seeds, fertilizers, and pesticides), mechanical operations, and labor costs were considered; the benefits considered were the income from the direct sales of maize. As the objective was not the absolute financial result but the economic impact of the CDCT model, the land transfer cost was not included in the cost components, and the relevant subsidies from the government were not included in the benefits when comparing the profits of the CDCT model and the traditional production model in this study.

2.3. Data Sources

The qualitative and quantitative data for the whole process and the effects involved in the application of the CDCT model were obtained from the directors and members of 23 cooperatives (the H Cooperative and 22 other cooperatives), two leaders of the General Agricultural Technology Extension Station in Lishu County, and relevant teachers and postgraduates (from various scientific research institutes) of the Lishu Experimental Station through semi-structured interviews in August 2020 and June 2021. At the same time, to obtain more detailed quantitative data on the traditional production model for comparison, a questionnaire survey method was used to investigate 23 farmers who were adjacent to the cooperatives but did not join them. Specifically, the data sets included agricultural inputs, outputs, production efficiency, costs, income, and other benefits. The data used to measure the changes in cultivated land soil conditions were obtained from soil sampling and laboratory tests. All the data sets on the evaluation of the model effects were processed by SPSS statistical software. The maps were processed using ArcGIS v10.2 and Origin 2021 software.

3. Results

3.1. Cooperative-Dominated Conservation Tillage Model

3.1.1. Conceptual Framework of the Cooperative-Dominated Conservation Tillage Model

The polycentric governance theory proposed by Elinor Ostrom and Vincent Ostrom emphasizes the optimal use of resources or services through multi-agent participation and cooperation [57]. Cultivated land is a basic resource for human survival; thus, addressing the problem of soil degradation to promote the protection of cultivated land also requires the support of governments, cultivated land managers, social organizations, and other forces, among which the role of those that directly manage cultivated land cannot be neglected. However, in the process of actually utilizing cultivated land, policies and financial support from government departments, intellectual support from scientific researchers, and the services of various enterprises are often difficult to effectively link with farmers' production activities to form a joint force. CT is a sustainable farming method, but the key to its application in agricultural production practice is related to three core conditions: the technical system, supporting agricultural machinery, and land size. The CDCT model can effectively meet these conditions, in that scientific research institutes, governments, and enterprises empower agricultural cooperatives in terms of technology, capital, products, and services, and agricultural cooperatives, as the direct managers of cultivated land and the core of the model, promote the construction of new production units and large-scale and mechanized management to realize the standardized application of CT technology in agricultural production (Figure 3). The essence of this model is to promote the deep combination of scientific research innovation, policy management, transfer of land property rights, key agricultural machinery support, and standardized operations and management through the carrier of cooperatives to achieve an efficient connection between CT and agricultural production practices.

Agricultural cooperatives use the production team leaders of their administrative village as a communication bridge or a direct connection with farmers to attract farmers to transfer their land through land equity, land lease, or land trusteeship, and the cooperatives take the lead in removing the boundaries of cultivated land plots among farmers to centralize scattered cultivated land and form a spatial pattern of cultivated land at a certain scale. In addition, the cooperatives change and standardize the crop planting row spacing to complete the construction of new production units, thereby meeting the mechanical operation conditions for the application of conservation tillage technology. Then, the cooperatives implement unified operation and management of the new production units, including the unified purchase of agricultural materials, unified mechanized and standardized production, and unified grain storage and sales, which reduce production investment. Among these actions, unified mechanization and standardized production provide the foundation for the adoption of conservation tillage with straw mulching and reduced or no tillage as the core. Based on natural endowment characteristics, such as different soil types and topographies of cultivated land resources, cooperatives choose appropriate CT technology for maize production, which increases the accumulation of soil organic carbon and controls soil erosion. In the CDCT model, scientific research institutes are the agents that conduct research and localize CT technologies. They carry out technological innovation and clarify the technological mechanisms and relevant parameters of CT application on the basis of systematic analysis of foreign CT technologies and long-term local experiments. Site-specific CT technical packages suitable for different regions in Northeast China have been developed based on this approach. These research institutes provide training and guidance for cooperatives in applying relevant technologies to production management. In addition, related governmental departments participated in the cooperative research and development of technology and provided financial subsidies and technical training support to agricultural cooperatives. Various enterprises provided agricultural machinery products, agricultural materials products, agricultural insurance products, grain storage, and preferential financial services for the operation of cooperatives. In general, through the connection between cooperatives and scientific research institutes, governments, and enterprises, the constraints of land scale, technical systems, and supporting agricultural machinery have been addressed, thus promoting CT in agricultural production practice and ensuring its practical effects in terms of improving cultivated land soil conditions, reducing carbon emissions, enhancing production efficiency, and promoting economic benefits.

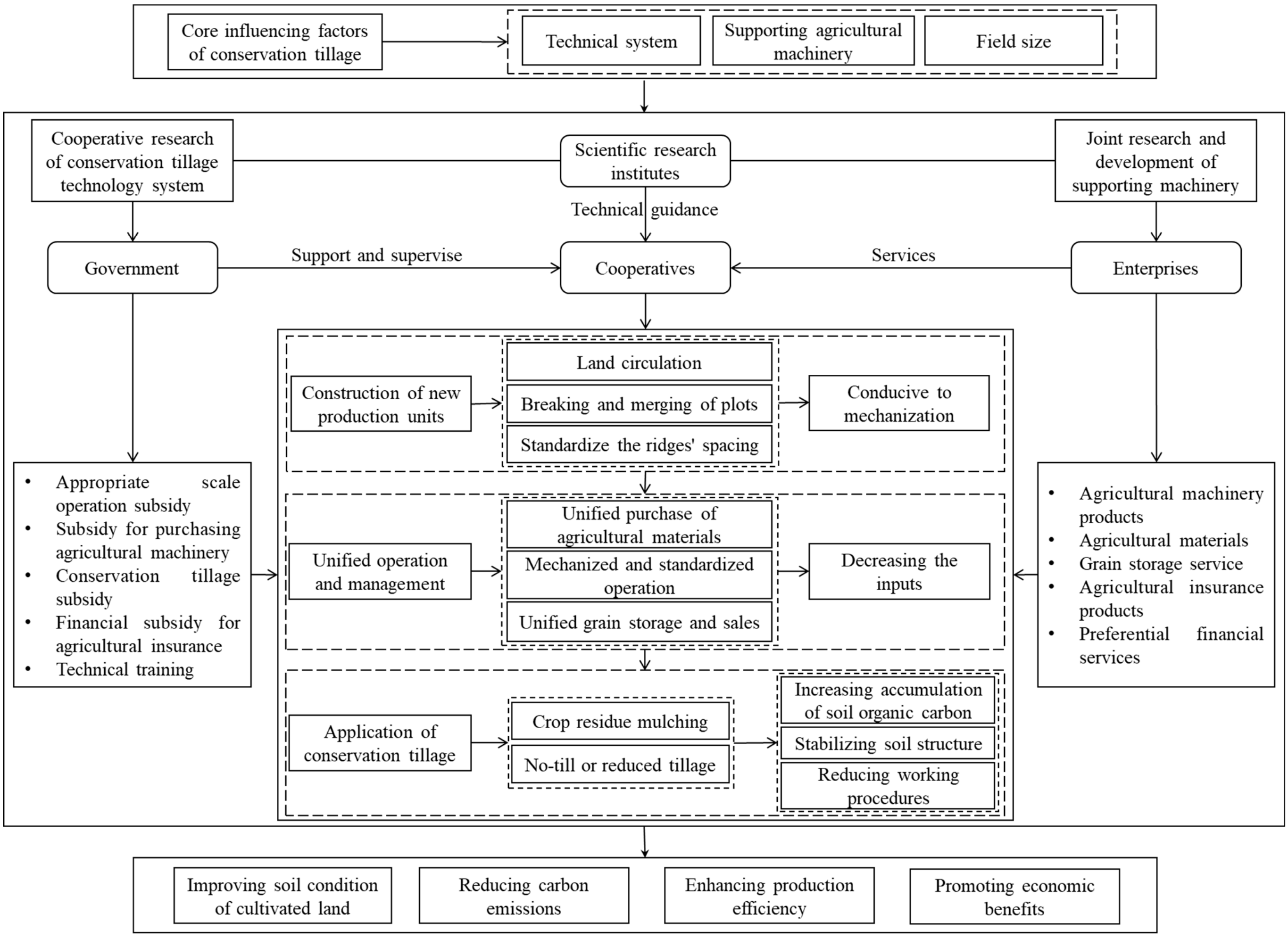

Figure 3. Conceptual framework of the cooperative-dominated conservation tillage model (CDCT model).

3.1.2. Role of Different Agents in the Cooperative-Dominated Conservation Tillage Model

The CDCT model mainly involves four different agents, i.e., scientific research institutes, governments, enterprises, and cooperatives (Figure 4). The role of scientific research institutes is to develop CT technology and supporting agronomic technology that is applicable to different regional characteristics, integrate technical systems, jointly develop agricultural machines with agricultural enterprises, and provide relevant technical training and guidance to cooperatives. After more than ten years of exploration, the Chinese Academy of Sciences, China Agricultural University, and other scientific research institutes have jointly developed a CT technology system suitable for Northeast China, including no tillage with straw mulching (NTS), strip rotary tillage with straw mulching (SRTS), ridge tillage with straw retention (RTS), and ridge side cultivation with high stubble (RSCHS).

At the same time, these scientific research institutes have improved supporting agronomic technologies, including the proportion of planting row spacing under no-tillage conditions, the duration and depth of strip rotary tillage, and the proportion of straw mulch; thus, they have further realized the integration of technical systems. To meet the mechanical conditions of technology implementation, the Northeast Institute of Geography and Agroecological Application of the Chinese Academy of Sciences have cooperated with agricultural machinery manufacturing enterprises to develop supporting machinery, such as high-performance no-tillage seeders and strip tillage machines. Additionally, the professors and postgraduates at these scientific research institutes have cooperated with the technicians of the Lishu Agricultural Technology Extension Station to provide technical training and guidance to the managers of cooperatives on the technical process of CT and precautions in CT implementation and to obtain feedback from the cooperatives after the application of technology. Then, they improved and perfected the CT technology system according to the practical feedback received from the cooperatives to improve the regional adaptability of the technology.

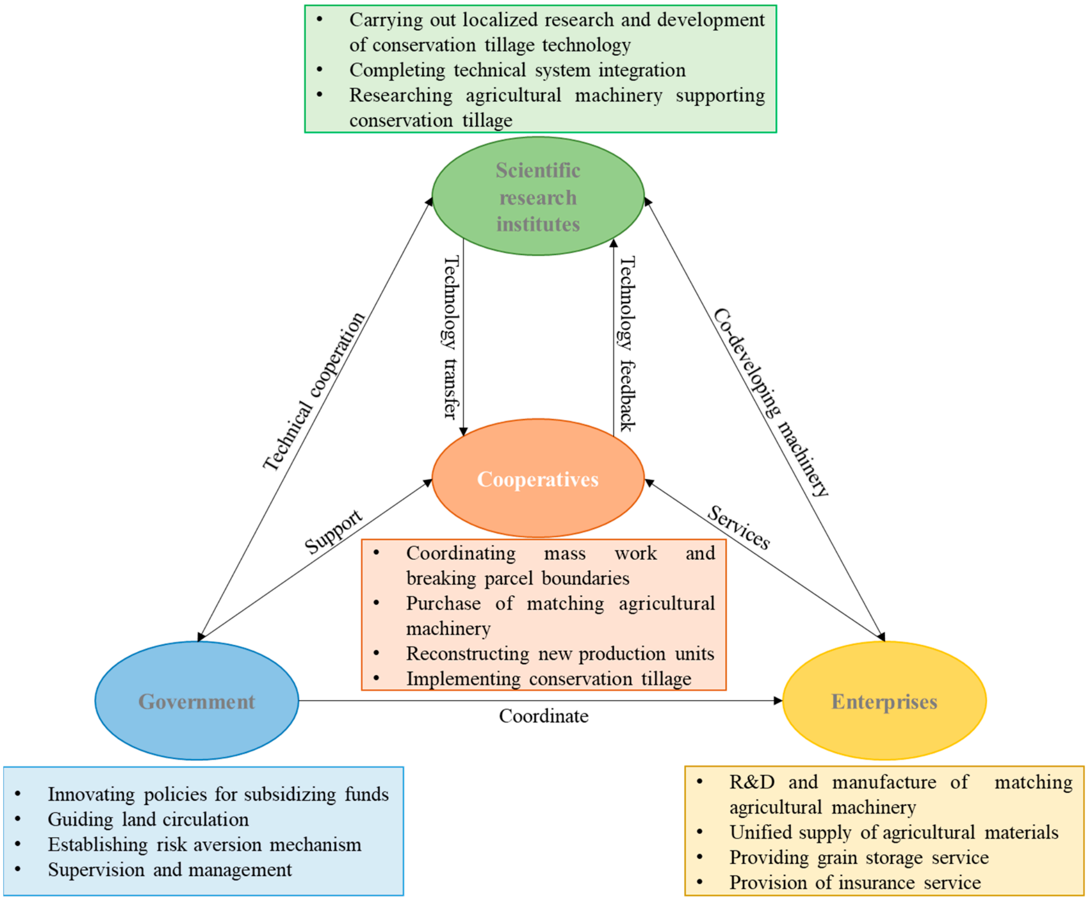

Figure 4. Role of different agents and their synergistic relationship in the cooperative-dominated conservation tillage model.

The role of local governments is to develop innovative subsidy policies, guide farmer land transfers, and establish risk-averse mechanisms that provide policy guarantees for cooperatives to implement conservation farming. Starting in 2016, Jilin Province started carrying out a province-wide reform of the "three subsidies" of agriculture, reorganizing 20% of the former comprehensive agricultural subsidies to support moderate-scale agricultural operations to guide farmers to circulate their land in an orderly manner. At present, government subsidies for cooperatives include moderate-scale operation subsidies, subsidies for CT, and subsidies for the purchase of agricultural machinery. Moreover, in 2020, the Lishu County government guided an insurance company to design and provide a maize yield insurance product for plots in which CT technology was implemented. The county treasury provided subsidies for premiums to help cooperatives avoid the risks arising from natural disasters and grain price fluctuations.

Under the coordination and guidance of government departments, such as the General Agricultural Technology Extension Station in Lishu County, enterprises, including agricultural machinery manufacturing companies, agricultural material supply companies, grain trading companies, insurance companies, and banks, provide cooperatives with supporting agricultural machinery products, agricultural products (e.g., seeds, fertilizers, and pesticides, etc.), grain storage services, maize revenue insurance products, and preferential financial services (e.g., interest rate reduction loans) relating to all aspects of the services to ensure the stability of cooperative production and operation.

Cooperatives, as the core of the model, mainly coordinate mass work, break the boundaries of cultivated land transferred from farmers, acquire supporting agricultural machinery, construct new production units, and implement conservation farming as a unified operation. Lishu County can be divided into four zones according to its soil and climate characteristics, namely, the mountainous and semi-hilly area in the southeast, the black soil plain area in the central area, the low-lying area in the northeast, and the aeolian sandy soil and saline–alkali soil area in the northwest. The cooperatives in the corresponding zones adopt different CT methods for their maize production. For instance, the southeastern region is dominated by the RSCHS method; the central region and northwestern region mainly apply the NTS and SRTS methods; and in the northeastern region, the NTS and RTS are mainly adopted. Taking the G Cooperative in Lishu County as an example, the cooperative currently operates 150 ha of cultivated land through both farmer land shareholding and land leasing. The G Cooperative signed a written land transfer contract with the farmers who joined the cooperative to determine the area of transferred cultivated land and promised that the cooperative could break the boundaries of the plots for consolidation based on the operational needs, change the spacing of planting ridges, and reconstruct the production units for a unified operation. In addition, the cooperative signed an agreement directly with an agricultural company to purchase seeds and other agricultural materials in a unified manner, realizing the planting of improved seeds. On the other hand, because the cooperative constructed new production units of a large scale that meet the operational requirements of supporting agricultural machinery and trained agricultural machinery operators with a high professional level for unified operation, the planting technology of SRTS that is suitable for the area where the cooperative is located was applied in a standardized way.

Indeed, the CDCT model also involves farmers who have transferred their contracted farmland to cooperatives for unified management, and these farmers are also considered part of the cooperatives. Those who have labor can choose to work for the cooperatives or find work outside. As a result, they can benefit from earning double incomes, one from land revenue (including rent and dividends) and one from wages, which will help them out of poverty and improve their living conditions.

3.2. Effectiveness Evaluation of the Cooperative-Dominated Conservation Tillage Model

3.2.1. Changes in the Soil Condition of Cultivated Land under the CDCT Model

The organic carbon content in the surface soil of the cultivated land plots where farmers adopted the conventional ridge tillage (CRT) method for maize production decreased by 2.03 g/kg from 2008 to 2015 (Li et al., 2020); namely, there was an annual average decrease of 0.29 g/kg in the SOC content under the traditional production model (Figure 5c). In contrast, the implementation of conservation tillage in maize production under the CDCT model effectively alleviated the most prominent soil degradation problems in Northeast China, such as the decline in organic matter and soil structural degradation. From 2011 to 2020, the SOC content in the surface layer (0–20 cm) of cultivated land operated by the H Cooperative with conservation tillage, including NTS and SRTS, increased from 11.67 g/kg to 12.39 g/kg on average (Figure 5a); namely, after 9 years of CT, the SOC content increased by 6.17%, and the average annual increase was 0.08 g/kg (Figure 5c). On the one hand, compared to CRT, there were no tilling links of ridging and mid-till cultivation in the NTS or SRTS, which reduced tillage times. The lower tillage intensity reduced soil disturbance and soil aggregate damage, resulting in less loss of organic carbon in the cultivated soil layer. Moreover, the cultivated belts and the uncultivated belts (planting belts in the coming year) were alternately distributed, which had a fallow effect and realized the combination of utilization and maintenance of cultivated land resources. On the other hand, approximately 30–50% of maize straw was returned to and covered the field after the harvest, which increased the organic carbon accumulation on the topsoil and improved the soil fertility. These practices also increased the time soil was covered and protected from wind- or runoff-induced erosion. Thus, the STI of cultivated land in the H Cooperative increased from 3.35% to 3.69% on average after the application of CT (Figure 5b), which was a small increase, but it also indicates that the degradation of the soil structure was alleviated to a certain extent and the risk of soil degradation was reduced. Overall, the soil condition of cultivated land was effectively improved under the CDCT model.

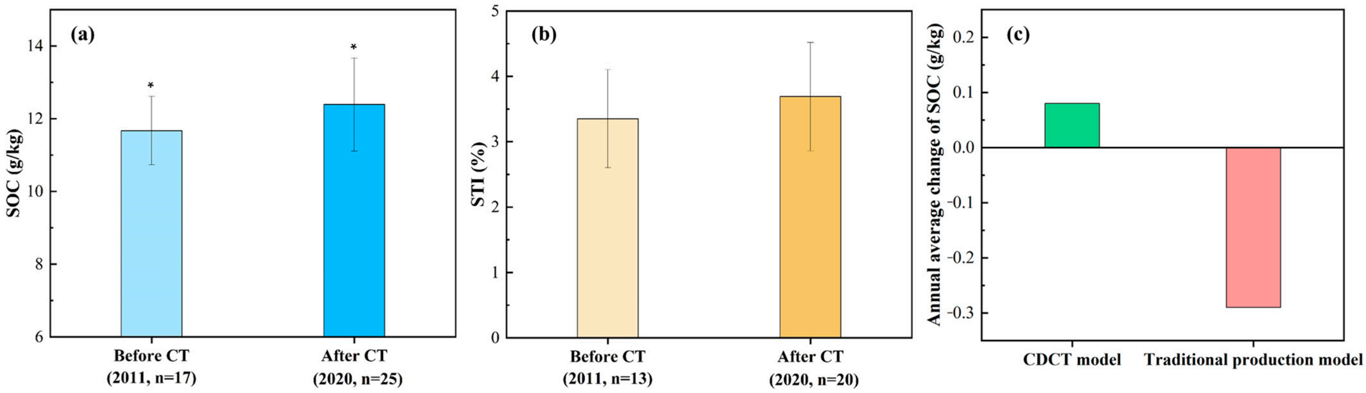

Figure 5. Changes in the soil condition of the cultivated land under the CDCT model. (**a**) Soil organic carbon (SOC) and (**b**) soil structural stability index (STI) of cultivated land in the H Cooperative before and after conservation tillage (CT). Data are the mean ± s.d. * Indicates a significant difference between 2011 and 2020 at $p < 0.05$. (**c**) Comparison of the annual average change in the SOC content under the CDCT model and traditional production model.

3.2.2. Characteristics of Carbon Emissions under the CDCT Model and the Traditional Production Model

The cooperatives that applied CT in maize production significantly reduced their chemical fertilizer inputs and diesel consumption. As shown in Table 2, under the CDCT model, the average use of chemical fertilizer decreased by 10.84% compared to the traditional production model, and diesel consumption decreased from 126.67 L/ha to 105.63 L/ha, a decrease of 16.61%. Meanwhile, herbicide application was reduced from 3.55 kg/ha to 1.54 kg/ha. In general, the carbon footprints per unit area of maize production using CRT and SRTS were 4163.52 kg CO_2-eq ha^{-1} and 3666.26 kg CO_2-eq ha^{-1}, respectively; namely, the carbon footprint per unit area of the CDCT model was 11.94% lower than that of the traditional production model (Figure 6a). Additionally, straw mulching on the farmland surfaces reduced soil water evaporation and enhanced the water storage function of the soil, thus effectively improving the drought resistance ability during crop growth, which stabilized the yields and ensured good harvests. Therefore, compared to the traditional production model, the average maize yield under the CDCT model increased from 11.39 t/ha to 11.89 t/ha (Table 2). When the quality unit (kg) of maize production was used as the functional unit of the carbon footprint evaluation, the carbon footprint of the CDCT model was reduced by 15.65% compared to the traditional production model, from 0.3655 kg CO_2-eq kg^{-1} to 0.3083 kg CO_2-eq kg^{-1} (Figure 6b). This result shows that the standardized application of CT technology in maize production by cooperatives effectively reduced carbon emissions, which can help meet China's carbon neutralization goal.

Table 2. Inputs and yields of maize production under the CDCT model and traditional production model in 2020.

Item	Unit	CRT	SRTS
N fertilizer input	kg/ha	256.42 ± 10.49	226.31 ± 19.87
P fertilizer input	kg/ha	100.33 ± 1.87	89.22 ± 5.29
K fertilizer input	kg/ha	124.84 ± 8.88	112.73 ± 7.15
Herbicide input	kg/ha	3.55 ± 0.49	1.54 ± 0.23
Insecticide input	kg/ha	0.00 ± 0.00	1.75 ± 0.24
Diesel consumption	L/ha	126.67 ± 7.79	105.63 ± 5.30
Maize yield	t/ha	11.39 ± 0.74	11.89 ± 0.63

Note: CRT and SRTS represent conventional ridge tillage and strip rotary tillage with straw mulching, respectively. CRT is the tillage method under the traditional production model; SRTS is the representative tillage method under the CDCT model (the same below). Data presented are the mean ± s.d.

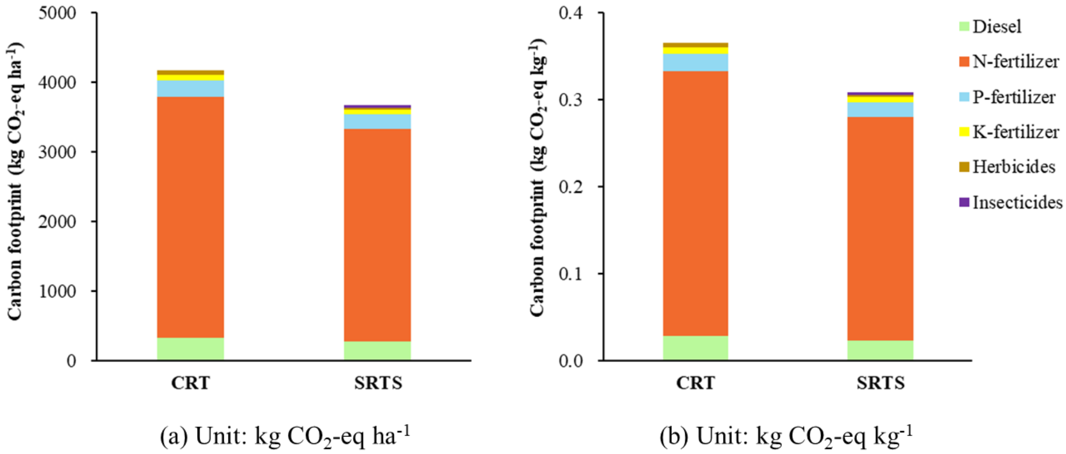

Figure 6. Carbon footprint (CF) of maize production under the CDCT model and traditional production model. (**a**) Unit: kg CO_2-eq ha^{-1}; (**b**) Unit: kg CO_2-eq kg^{-1}.

3.2.3. Changes in Production Efficiency under the CDCT Model

In the traditional production model, there were many operation procedures during maize production, and the cultivated land operated by farmers was relatively fragmented, so the operational efficiency was generally low. As shown in Table 3, the average efficiencies of straw handling, rotary tillage, sowing, and fertilization of CRT were 4.1 ha/d, 4.5 ha/d, and 3.5 ha/d, respectively. While under the CDCT model, the new production units constructed by the cooperatives greatly facilitated mechanical operation, and the use of mechanical equipment, such as no-tillage seeders, strip cultivators, and straw returning machines, realized the whole process of maize production mechanization. Moreover, the operational links, such as ridging, cultivator, and topdressing, were reduced in the mechanical operation process, which saved the operation time in terms of machinery and labor. Therefore, the operational efficiency was significantly enhanced. As the straw did not need to be packed out of the field and only returned after harvest, the efficiency of straw handling increased by 143.90% (Table 3). The rotary tillage operations were changed from conventional rotary tillage to strip rotary tillage, which reduced the tillage times and improved the efficiency by 122.22%, from 4.5 ha/d to 10.0 ha/d. The efficiency of sowing and fertilization also increased by 54.29% due to the use of no-tillage seeders. In addition, the reduction in fertilizer application and the increase in maize yield resulted in a 17.64% increase in fertilizer utilization efficiency (FUE) compared to the traditional production model (Table 3). In general, whole-process mechanized CT technology applied to large-scale production under the CDCT model significantly improved production efficiency.

Table 3. Comparison of production efficiency under the CDCT model and traditional production model.

Efficiency Indicators	CRT	SRTS
FUE (kg kg^{-1})	23.65 ± 1.98	27.83 ± 2.25
Operational efficiency (ha/d)		
Straw handling	4.1 ± 0.6	10.0 ± 1.8
Rotary tillage	4.5 ± 0.5	10.0 ± 1.4
Sowing and fertilization	3.5 ± 0.7	5.4 ± 1.6

Note: Data presented are the mean ± s.d.

3.2.4. Economic Benefits of the CDCT Model

According to the cost–benefit analysis of the whole production process, the production cost of the CDCT model decreased significantly compared to the traditional production model. With the adoption of SRTS, the mechanical operation procedures in the maize production process were reduced, resulting in an average reduction in mechanical operational costs of 668 CNY/ha (Table 4). As the contents of soil organic matter and nutrients such as P and K increased after the maize straw was returned to the field, the cooperatives rationally regulated the application of chemical fertilizers, which reduced the amount of chemical fertilizer inputs. Together with the relatively lower price of unified and centralized procurement of agricultural materials, the total cost of agricultural materials was therefore reduced by an average of 456 CNY/ha. Moreover, the mechanization of the whole process reduced the operating hours of the required labor force, so the labor cost was decreased by 325 CNY/ha. Consequently, the total cost of maize production under the CDCT model was 1449 CNY/ha lower than that under the traditional production model. In terms of benefits, excluding land transfer costs, the profit of maize production under the CDCT model increased by an average of 2599 CNY/ha compared to the traditional production model (Table 4). Therefore, the cooperatives achieved higher economic returns through increased outputs and reduced input costs. Notably, the farmers who were freed from agricultural production activities by transferring their contracted household farmland to the cooperatives could choose to work outside or work in cooperatives nearby, thus obtaining extra employment wages apart from their land transfer income, which helped improve their family living conditions.

Table 4. Comparison of economic indicators of the CDCT model and traditional production model (Unit: CNY/ha).

Item	SRTS	CRT
Cost component		
(A) Mechanical operations		
Harvesting	917 ± 41	1100 ± 141
Straw handling	93 ± 16	-
Eradication of stubble, plowing, ridging, and pressing	-	680 ± 44
Strip rotary tillage	433 ± 52	-
Sowing and fertilizing	418 ± 49	460 ± 55
Cultivator	-	200 ± 14
Spraying pesticides	111 ± 46	200 ± 71
(B) Agricultural materials		
Seeds	450 ± 54	552 ± 51
Fertilizers	2220 ± 161	2666 ± 185
Pesticides	367 ± 31	275 ± 54
(C) Labor cost	375 ± 67	700 ± 112
Total cost	5384 ± 165	6833 ± 131
Maize income	27,347 ± 1938	26,197 ± 1856
Profit	21,963 ± 2031	19,364 ± 1967

Note: Rainfed agriculture is the prevalent practice in maize production in Lishu County, so the irrigation cost was not included in the costs. The land cost was not calculated, and the selling price of maize kernels was 2.3 CNY/kg. Data presented are the mean ± s.d.

4. Discussion

4.1. Strengths and Limitations of the CDCT Model

CT is an important means of sustainable agricultural production and has been widely adopted around the world [58]. However, by the end of 2018, the CT implementation area in China was 8.2 million ha, accounting for only approximately 6% of the total cultivated land, far below the levels in the United States, Canada, Brazil, Australia, and other countries [46,59]. Meanwhile, some studies have found different results related to the effects of CT on crop yield and SOC under different conditions, with both positive and possible negative effects [60–62]. The CDCT model examined in this study overcomes the main constraints of current CT implementation through the synergy of the cooperatives with scientific research institutes, government entities, and enterprises and promotes the standardized application of CT in agricultural production practices according to local conditions, thus ensuring positive application effects and achieving multi-win outcomes for production and ecological goals (Figure 7). In this model, cooperatives reconfigured the land and reconstructed land production units according to the actual production needs. The formation of new production units helped the implementation of CT. Importantly, cooperatives, with their advantages in terms of knowledge, capital, and land size, have addressed the mismatch between CT technologies and the capacity of resource-poor farmers, thereby standardizing the application of site-specific technology integration packages developed and recommended by scientific research institutes into their production practices, namely, avoiding disparities between practices and recommendations (Figure 7). This is the key point for which the CDCT model achieved better results compared to general smallholder farmers who did not use or only used one or two of the CT techniques for agricultural production.

Notably, the CDCT model also has certain limitations. The premise that this model can achieve good results in Lishu County is that the willingness of local farmers to transfer land is strong, providing a basis for the development of new agricultural management agents such as cooperatives and family farms, and there are teachers and students from the Chinese Academy of Sciences, China Agricultural University, and other research institutes in the area that carried out local research and demonstration work related to CT. Therefore, the model is mainly applicable to areas with conditions for promoting large-scale land management and with scientific research institutes taking root. At the same time, the application of this model requires progressive cooperative leaders and relies on the cooperatives' ability to purchase supporting agricultural machinery for CT and the operational level of agricultural mechanics. Although there are teachers and students from scientific research institutes and government agricultural extension personnel to carry out publicity and technical training related to CT, in rural areas, there is still a lack of cooperative directors who have sufficient knowledge and acceptance of CT and agricultural mechanics who are highly skilled in machine operations. We should continue to strengthen technical training on and demonstrations of CT and supporting agronomic technology for cultivated land managers, agricultural mechanics, and township agricultural technicians to promote the outreach and application of this CDCT model in a larger region. Furthermore, agricultural production and operation methods are diverse worldwide; however, there are still 500 to 600 million smallholder farmers dominating food production in developing countries, and most are resource-limited and knowledge-poor [56,63,64]. In this case, how to improve the problem-solving capacity of smallholders and take effective measures to organize the vast smallholder-farming communities to promote moderate-scale operations needs to be further explored in future research on the efficient and sustainable use of cultivated land.

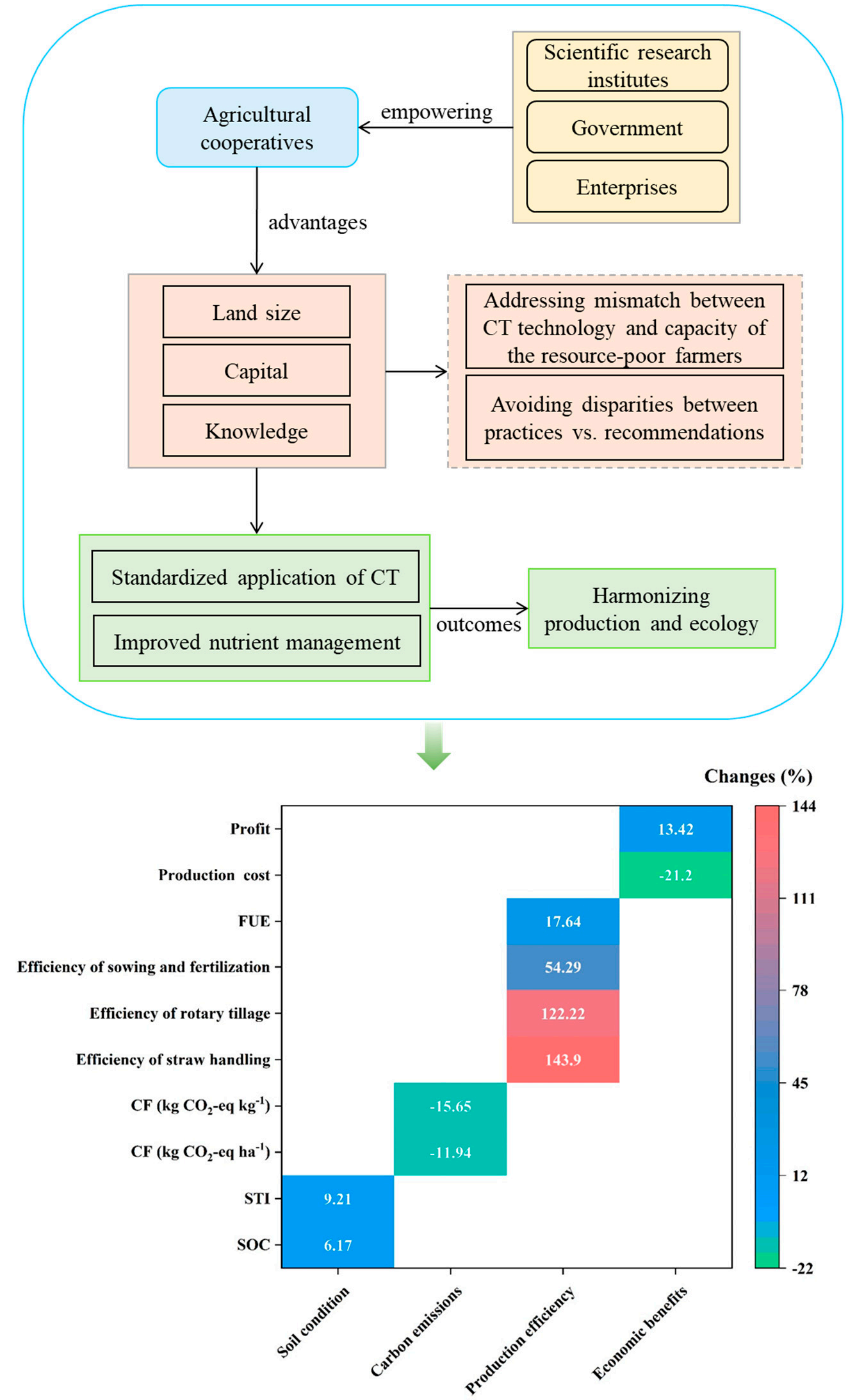

Figure 7. Strengths of the cooperative-dominated conservation tillage model (CDCT model). SOC: soil organic carbon; STI: soil structural stability index; CF: carbon footprint; FUE: fertilizer use efficiency.

4.2. Policy Implications

The CDCT model provides an innovative and successful way to alleviate soil degradation and promote agricultural production with lower environmental costs, and this model can be an effective complement to the currently prevalent government-dominated model of cultivated land governance. Our findings have implications for regions and countries that are dominated by smallholder farming but have the conditions to develop large-scale operations. Several policy implications are presented as follows: (1) In addition to the traditional government-dominated model, governments should encourage the exploration of new approaches to address soil degradation, such as the cooperative-dominated model in this study and the farmer-dominated, company-dominated, or science and technology backyard-dominated models reported in previous studies [65–67]. (2) Consistent government support is critical for the research and implementation of CT. Flexible policies need to be adopted to fully mobilize the initiative of stakeholders in addition to the government, such as research institutes, cooperatives, and farmers. For example, it is important to foster more professional farmer cooperatives to guide and engage smallholder farmers from the same and neighboring villages in sustainable production initiatives and to include more equipment related to CT in the subsidy list. In addition, locally applicable scientific research on CT should be promoted by attracting research institutes to establish local research demonstration bases through financial subsidies or land supply, in addition to general research project funding. Furthermore, it might be necessary to incentivize more farmland managers to adopt environmentally friendly technologies by appropriately rewarding cooperatives and farmers through payments for ecosystem services. (3) It is necessary to establish an organization or platform that can promptly solve problems related to the adoption of new and enhanced management technologies by farmland managers in their production practices. The government can act as an intermediary to build a platform for communication and collaboration among government agricultural departments, scientific research institutes, various enterprises, and farmland managers to facilitate the provision of technical, financial, product, and service support for the efficient and sustainable use of cultivated land by farmland managers, thereby addressing deficiencies in knowledge and resources and improving problem-solving abilities.

5. Conclusions

In the CDCT model, cooperatives, assuming the leading role as the direct managers of cultivated land, implement the construction of new production units and large-scale and mechanized operations and then standardize the application of CT technology in agricultural production. Scientific research institutes, governments, and enterprises act as supporters to empower cooperatives in terms of technology, capital, products, and services. This model mobilizes the participation of all stakeholders and promotes the deep integration of scientific research innovation, policy management, land property rights transfer, key agricultural machinery support, and standardized operation and management, thus overcoming the constraints of applying CT. Through the concerted efforts of multiple agents with the cooperatives as the core, the maize production system is optimized, and the goal of harmonizing production and ecology is ultimately achieved, which provides a paradigm for collaborative resource governance. As the prominent soil degradation problems in Northeast China, the decline in the organic matter content and the soil structural degradation of the cultivated layer have been mitigated. In addition, the CDCT model has also shown good results in terms of decreased carbon emissions, increased production efficiency, and economic benefits. Therefore, the CDCT model in this study is of great value to be extended to other regions and can provide multiple winning situations with great ecological, economic, and social benefits, contributing to sustainable agricultural development and rural revitalization in China and other developing countries.

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