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Effects of Conservation Tillage on Agricultural Green Total Factor Productivity in Black Soil Region: Evidence from Heilongjiang Province, China

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Abstract: The implementation of conservation tillage is crucial for the preservation and utilization of black soil. This study examined 297 new agricultural management entities in five pilot counties in the black soil region of northeast China. Using the SBM-Undesirable model, this study measured and evaluated the agricultural green total factor productivity (AGTFP) of these entities. We further employed the Tobit model to explore the impact of conservation tillage on the AGTFP. The findings revealed that the average AGTFP value of the sample entities was 0.4364, indicating a generally low degree of AGTFP that exhibited significant variation. Improvement in input indicators (such as machinery) and undesirable output indicators (such as net carbon emissions) was particularly needed. Additionally, conservation tillage had a significant positive impact on AGTFP, with a higher number of applied technologies correlating with increased productivity. Material subsidies for conservation tillage offered greater direct cost relief and had a stronger positive effect on AGTFP in comparison with cash subsidies. Furthermore, apart from policy factors, key production and operation characteristics—such as access to agricultural materials—also significantly influenced AGTFP. The results of this study offer a valuable decision-making framework and scientific reference for countries in black soil regions worldwide, enabling them to enhance the conservation and sustainable utilization of this vital resource.

Keywords: AGTFP; conservation tillage; new agricultural management entities; black soil region

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1. Introduction

Black soils, found predominantly at middle and high latitudes worldwide, are renowned for their exceptional fertility and high organic matter content, making them vital to global agricultural production [1]. Black soils compose 19% of the world's farmland, with the four major black soil regions serving as key areas for agricultural production [2]. Black soils are mineral soils that have a black surface horizon, enriched with organic carbon that is at least 25 cm deep [3]. According to the WRB classification, black soils comprise Chernozems, Kastanozems, and Phaeozems [4]. Particular types of black soil vary from country to country and region to region, but the protection of this valuable resource is a consensus widely held worldwide [5]. The 2015 Paris Agreement emphasizes mitigating the impacts of climate change, prompting countries to set goals related to carbon neutrality and ecological protection [6]. Black soils play a critical role in global carbon regulation and climate adaptation due to their exceptional carbon sequestration capacity [7,8]. According to the Global Soil Organic Carbon Sequestration Potential map, the world's 725 million hectares of black soil hold 8.2% of the global soil organic carbon stock and can sequester up to 10% of global soil organic carbon potential [9]. Therefore, black soil is crucial for ensuring food security and ecological stability and achieving global carbon neutrality [10,11]. Given projected population growth and increasing food consumption, global food demand and the urgency of managing carbon emissions will escalate over the next 40 years [12,13].

Consequently, maximizing the effectiveness of black soil in order to balance agricultural, environmental, and economic needs (while adapting to climate change) remains an urgent and critical research focus [14,15].

The black soil region of northeast China is one of the world's four major black soil regions, encompassing 1.09 million square kilometers and accounting for about one-fifth of the total global black soil area [16]. This region not only is the cornerstone of agricultural development in northeast China but also serves as China's granary, playing a crucial role in ensuring national food security [17]. However, on one hand, extensive exploitation and irrational traditional farming practices over an extended period have led to significant soil degradation and loss of organic carbon in the black soil region [18]. Soil erosion in this zone affects 275,900 square kilometers, representing roughly 27% of the total area. Many black soils have lost half of their organic carbon stocks, weakening their carbon sequestration capacity [19]. Such a decline in soil organic carbon stocks exacerbates soil fertility degradation and reduces land productivity [20]. On the other hand, improper use of heavy machinery has intensified soil compaction in recent years. Issues such as soil hardening, consolidation, and diminished water and moisture retention capacity in the drylands of the black soil zone have also worsened [21]. These challenges have severely limited the sustainable utilization of black soil in northeast China, impacting regional food production, as well as economic and social development [22]. Conventional farming practices threaten the stability of soil ecosystems [23], but conservation tillage represents a progressive farming approach that can enhance the soil's structure. This method integrates no-tillage, minimum-tillage, straw mulching, and crop rotation practices [24–26]. Conservation tillage minimizes soil disturbance by leaving at least 30% of the soil surface covered with residue, thereby reducing soil erosion [27,28]. It represents a significant reformation of conventional tillage methods, offering substantial benefits such as carbon sequestration and a reduction in emissions [29,30]. This practice increases soil organic carbon, reduces the risk of soil erosion [31], and fosters a better soil environment, thereby enhancing crop yields with minimal environmental impact [32,33]. Currently, in China, conservation tillage is a crucial measure being taken to curb soil erosion and promote the restoration of degraded black soil croplands. China has developed a system of policies to support the popularization and application of conservation tillage in its nationwide plan for northeastern black soil. The "Outline of the Northeast Black Soil Conservation Plan (2017–2030)" emphasizes technological innovation and integrated demonstrations of conservation tillage. The "Implementation Program of the National Black Soil Protection Project (2021–2025)" lists the promotion of conservation tillage in black soil regions as a major measure and task. The "Action Plan for Conservation Tillage on Black Soil in Northeast China (2020–2025)" outlines detailed arrangements for the comprehensive promotion and application of conservation tillage in suitable areas. Furthermore, China has enacted the only special legislation dedicated to black soil protection among the world's major black soil countries, with the Black Soil Protection Law emphasizing the promotion of conservation tillage technology tailored to local conditions.

Existing studies have demonstrated that conservation tillage technology can foster agricultural technological progress and generate both economic and ecological benefits by optimizing the efficiency of resources' allocation [34]. On one hand, conservation tillage provides clear economic benefits. Buehren et al. (2019) suggested that conservation tillage techniques can improve farmers' production and crop yields, thereby increasing their income [35]. Contemporary conservation tillage technology encompasses a variety of new methods, such as reduced tillage, no-tillage, and stubble mulching. Ogieriakhi et al. (2022) found that no-tillage technology, which boasts a more streamlined production process than conventional methods, can increase net farm income by reducing labor input and machinery operating costs [36]. On the other hand, conservation tillage can bring about ecological benefits such as soil consolidation and enhanced soil carbon sequestration capacity. Pisani et al. (2020) suggested that strip-tillage can reduce the loss of nutrients like nitrogen, phosphorus, and potassium through surface runoff by improving the soil structure [37]. Field surveys have indicated that conservation tillage can also help to preserve local biodiversity [38,39]. Although most scholars have an optimistic view of the economic and ecological effects of conservation tillage, some controversy remains. For example, Jussi et al. (2006) found that no-till technology, when used for corn cultivation in northern Colorado and oat and wheat cultivation in Finland, resulted in lower yields than conventional methods when under optimal conditions. They noted that even though production costs decreased, these savings did not compensate for the reduced yields, potentially overshadowing associated environmental benefits [40]. Government support is a crucial factor in promoting conservation tillage technology. The USDA's Environmental Quality Incentives Program (EQIP), which provides technical assistance and incentive payments, encourages farmers to protect cropland quality. Evaluations by Claassen (2008) and Wunder (2008) found that the program significantly improved the ecological quality of U.S. plantations [41,42]. Greiner (2009) and Bopp (2019) suggested that compensation policies, which offer both technical assistance and financial support, can offset the costs of adopting new technologies and enhance economic returns. This dual support motivates farmers to protect cropland quality more effectively [43,44]. Johnston (2021) and others also suggested (as early as 2002) that if the promotion of conservation tillage technology is not accompanied by corresponding support subsidies, farmers will reduce their input of other factors in order to control costs. Or in order to ensure their yield, farmers may increase their use of fertilizers and other pollution-producing factors of production, meaning the marginal gains made through the promotion of technologies for increasing production and greening will continue to diminish or even disappear [45]. Other factors may also influence the protection of cropland quality by affecting farmers' behavior. Mishra et al. (2022) proposed that there is a significant positive correlation between planting area (i.e., scale) and the behaviors that farmers exhibit to protect quality [46]. Tey et al. (2012) concluded that farmers with land titles exhibited stronger and more stable conservation behaviors compared with those of farmers who only have land management rights; leased land was shown to be less conducive to high levels of conservation behavior by the farmers leasing such land [47]. Asfaw (2017) and Darkwah (2019) noted that external conditions, such as the availability of technical extension services and the degree of professionalism, also positively influence farmers' conservation behaviors [48,49]. The existing research systematically evaluating the effect of conservation tillage in the black soil region is relatively limited, and the index used for evaluation is singular, failing to reflect the multiple roles played by conservation tillage in the conservation and utilization of black soil. Additionally, regional differences in economic development and environmental conditions affect the adoption of conservation tillage techniques, making it essential that we conduct comprehensive assessments that are tailored to local contexts. Finally, we must improve the integration of research across disciplines and the diversity of indicators used to evaluate the effects of conservation tillage.

This study introduces the concept of agricultural green total factor productivity (AGTFP) as a metric for assessing the effects of conservation tillage on both the economic and the ecological aspects of agricultural production in black soil regions. AGTFP is recognized as an effective measure of the balance between agricultural economic performance and ecological health [50]. Improving AGTFP is essential in addressing the challenge of balancing agricultural economic growth with environmental sustainability [51]. It reflects the environmental costs associated with agricultural production and provides an objective evaluation of the combined economic and ecological impacts of conservation practices in black soil regions. Understanding and measuring AGTFP is crucial for promoting green agriculture [52]. Compared with traditional total factor productivity (TFP), AGTFP offers a more comprehensive and accurate assessment of the efficiency with which production inputs are converted into desirable economic outputs, while also accounting for undesirable outputs such as surface source pollution and carbon emissions [53]. This approach considers both the positive and the potentially negative impacts of agricultural activities on black soil arable land. Furthermore, the slack-based measure (SBM) model, which includes undesirable outputs, allows for the evaluation of input redundancies, undesirable outputs, and output deficiencies. This detailed calculation of AGTFP highlights areas in which improvements can be made, providing valuable insights into sustainable agricultural practices.

This paper is structured as follows. First, we analyze how conservation tillage in the black soil region influences the agricultural green total factor productivity (AGTFP) of new agricultural management entities; we do so through integrating theories of environmental regulation, the effects of substitution, and technological advancements. Second, we provide an empirical overview of the application of conservation tillage in five pilot counties, detailing the input–output dynamics of 297 new agricultural management entities. Third, we construct the SBM-Undesirable model to measure and evaluate AGTFP among these entities. Finally, we use the Tobit model to investigate the impact of conservation tillage technology on AGTFP, verifying our theoretical analysis and providing a basis for optimizing the protection and utilization of black soil.

2. Analysis of Theoretical Mechanisms

2.1. Environmental Regulatory Perspective

Based on the theory of environmental regulation, conservation tillage technology in the black soil region impacts the input–output status and AGTFP of new agricultural management entities in two main ways: "compliance costs" and the "innovation effect." On one hand, adopting conservation tillage technology in response to government mandates increases input costs, creating "compliance costs" that can limit AGTFP under certain conditions [52]. Compared with traditional methods like burning straw or removing it from the field, returning straw to the field is more complex and incurs higher labor and machinery costs. Although organic fertilizers are relatively inexpensive, their large-scale application requires additional labor or rented machinery [53]. Technologies such as no-till and deep plowing necessitate the use of multifunctional large-scale agricultural machinery, thereby increasing the demand for green production services such as aerial pest control and plant protection and leading to additional costs related to purchasing or leasing machinery and services. Under financial constraints, these increased costs may force entities to reduce their input of other production factors, which will affect the resource allocation capacity and efficiency. To cover these higher total production costs and achieve economic goals, entities might increase fertilizer usage to improve production quality and ensure revenue covers expenses; however, this has the potential to exacerbate surface pollution and carbon emissions. On the other hand, the application of conservation tillage technology can create an "innovation compensation" effect, partially offsetting "compliance costs," improving output, and thus increasing AGTFP [54]. The green production factors introduced by conservation tillage technology are more effectively converted into comprehensive outputs. Organic fertilizers improve production and reduce pollution [55], while large-scale no-till seeders and deep-tillers offer higher operational efficiency and have a minimal negative impact on the physicochemical properties of black soil arable land [56]. This leads to increased economic output while controlling surface pollution and carbon emissions [57].

2.2. The Effect of Technology

Conservation tillage technology offers both economic and ecological benefits, increases comprehensive output, and enhances the AGTFP of new agricultural management entities by transforming traditional rough production methods into modern green production methods [58,59]. From a micro perspective, improvements in technical efficiency and the alignment of technological progress with production needs both determine the level of AGTFP [60]. The greening and high efficiency with which production factors are input—both brought about by conservation tillage technology—align well with the research, development, and application of technological progress, thereby enhancing AGTFP [61]. Promoting conservation tillage technology in the black soil region can increase food production, mitigate surface pollution, and reduce carbon emissions without changing the input of other resources. From a macro perspective, the influence of conservation tillage technology needs to be further expanded, and the technological transformation of the entire industry has not yet been achieved. However, business entities can still leverage such positive technological effects to achieve remarkable profits [62].

2.3. The Substitution Effect

Conservation tillage technology can replace expensive, inefficient, and pollution-producing production factors via the substitution effect [63], thereby reducing input costs and controlling surface pollution and carbon emissions and ultimately improving the AGTFP of new agricultural management entities. Compared with traditional farming methods, conservation tillage involves fewer production processes, reducing the demand for and cost of manual labor and mechanical operations. The operational efficiency of large-scale agricultural machinery used in conservation tillage is higher, making it a direct substitute for manual labor, traditional rotary plows, and other expensive and inefficient small-scale machinery. The increased application of organic fertilizers and conservation tillage improves the quality of black soil arable land, reducing the need for chemical fertilizers during crop growth [64]. Organic fertilizers, such as manure compost or biological fertilizer, have a direct substitution effect on nitrogen, phosphorus, and potassium blended fertilizers [65]. Consequently, fertilizer inputs, surface pollution, and carbon emissions are controlled.

2.4. The Technology Agglomeration Effect

The effects of different combinations of conservation tillage techniques on the AGTFP of new agricultural management entities vary. First, the “environmental regulation” and substitution effects of individual technologies are less pronounced than those of combined technologies. A singular technology can only address a specific issue related to black soil cultivation, and at this stage, the marginal utility of conservation tillage technology is still in the early stages of incremental increase. The “innovation compensation” effect created by a single technology has limited ability to cover the “compliance costs” and may even produce a negative “environmental regulation” effect. A single technology can only substitute a certain expensive, inefficient, and highly polluting factor, resulting in a minimal substitution effect. Second, different technologies and their combinations produce varying technological effects. As shown in Table 1, under the premise of not exceeding the economic capacity of the operational entity and based on the actual condition of the cultivated land, combining conservation tillage technologies can optimize their comprehensive effect. The more integrated and numerous the technologies applied, the more they compensate for each other’s shortcomings, promote mutual reinforcement, and produce a synergistic effect, thus optimizing the overall impact.

Table 1. Description of conservation tillage technologies in black soil region.

Conservation Tillage Technologies	Specific Measures	Roles and Effects
Straw-returning	Incorporating harvested straw back into the soil through plowing or mulching.	Boost soil fertility and reduce chemical fertilizer use while maintaining or increasing crop yields [66,67].
Organic fertilizer	Use specialized machinery to apply organic fertilizer made from harmlessly treated livestock and poultry manure or composted with straw.	Increase microbial diversity and population to stabilize the soil ecosystem [68]. Enhance soil organic matter, etc., to restore soil productivity [69]. Reduce chemical fertilizer use to mitigate surface pollution [70].
No-tillage seeding	Planting seeds directly into the soil without prior tilling.	Simplify seeding for efficiency, extend crop growth [71]. Reduce soil disturbance, stabilize soil structure, and minimize nutrient runoff [72].

Table 1. *Cont.*

Conservation Tillage Technologies	Specific Measures	Roles and Effects
Deep plowing	Turning over the soil to a greater depth than conventional plowing to break up compacted layers.	Reduce soil bulk and compaction in the tillage layer to increase water content and holding capacity [73–75]. Improve crop drought resistance [76].
No-tillage seeding + straw-returning	Conservation tillage technology portfolios.	Soil urease, alkaline phosphatase, dehydrogenase, and invertase activities were higher and more effective at increasing soluble nutrients in the soil [77].
Deep plowing + straw-returning		Increase soil alkaline dissolved nitrogen, quick-acting potassium, and other nutrients effectively [78]. Promote root system development [79]. Enhance soil water content, improve crop drought resistance [80].
No-tillage seeding + straw-returning + organic fertilizer		Enhance the levels of quick-acting phosphorus, enzymes, and microorganisms [81].
Deep plowing + straw-returning + organic fertilizer		Enhance soil physical and chemical properties to promote crop root growth [82]. Increase soil organic matter content and yield [83].

Source: Technical Guidelines for the Action Plan for Conservation Tillage of Black Soil in Northeast China 2023.

Figure 1 demonstrates the mechanisms of conservation tillage technology impact on AGTFP in black soil region.

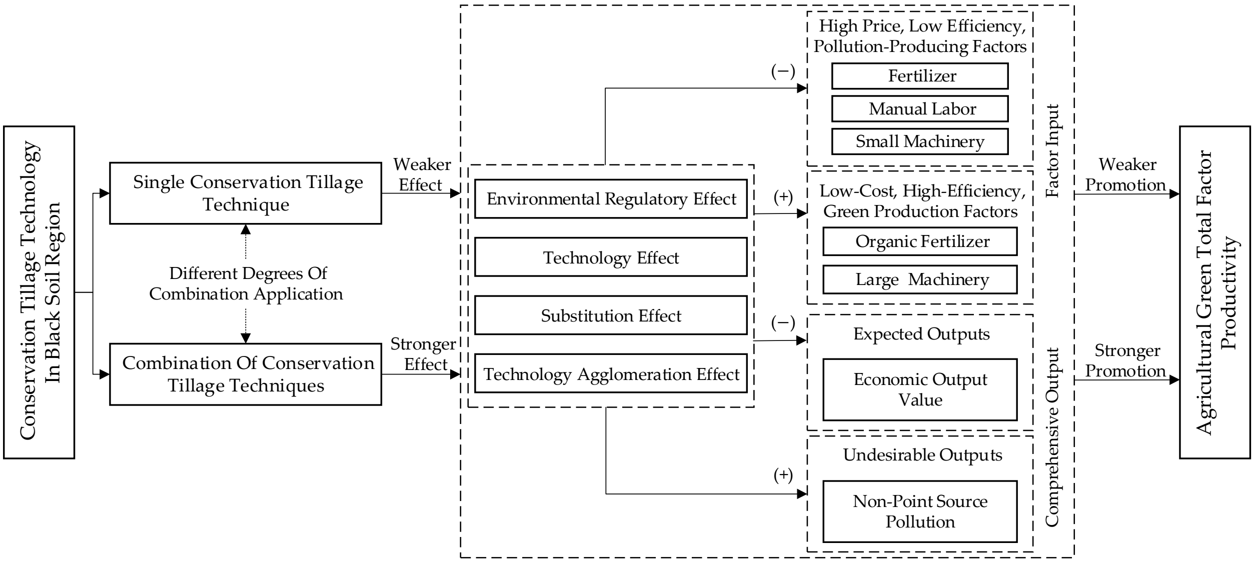

Figure 1. Mechanisms of conservation tillage technology impact on AGTFP in black soil region.

3. Materials and Methods

3.1. Data Sources and Sample Profile

3.1.1. Overview of the Research Area

Heilongjiang Province is renowned for its vast expanse of black soil arable land, named the northeast black soil region. This province plays a crucial role as a strategic grain reserve and the cornerstone of China's grain commodities, thus emphasizing the importance of protecting black soil and ensuring comprehensive grain production. To this end, Heilongjiang Province has focused on pilot projects in counties (cities) with concentrated arable land that is suitable for conservation tillage. These projects aim to promote the protection and utilization of black soil throughout the province, with key areas including

Keshan, Longjiang, and Yi'an counties in Qiqihar City and Beilin and Lanxi counties in Suihua City. The establishment of pilot counties for black soil protection in Heilongjiang involved a meticulous process. This process included county-level declarations, municipal recommendations, and provincial evaluations, taking into account factors such as the extent of black soil arable land, agricultural production conditions, and the professional capacity of agricultural technology and machinery departments. In response to central and provincial government directives on black soil protection, Qiqihar City issued the "Nenjiang River Basin Efficient Eco-agriculture Black Soil Protection and Utilization Project Planning (2020–2025)" directive. This plan provides guidance for the protection and utilization of black soil across counties. Similarly, Suihua City included black soil protection in its 13th Five-Year Plan for Ecological Environmental Protection and has continued to emphasize it in the 14th Five-Year Plan through the Black Soil Strength Enhancement Project. Consequently, Qiqihar City and Suihua City have designated Keshan County, Longjiang County, Yi'an County, Beilin District, and Lanxi County as national-level key protection areas for black soil. Among them, Longjiang and Lanxi are black soil protection whole-establishment promotion counties. At the same time, they are counties in which the eradication of poverty is of great concern, meaning government funding is adequate and timely. The implementation of the pilot policy in these two counties is different in strength and scope from projects in other pilot counties (districts).

This study focuses on the effectiveness of conservation tillage in Keshan County, Longjiang County, Yi'an County, Beilin District, and Lanxi County. These areas were selected based on their shared natural environmental conditions and varied forms of policy implementation. The conclusions and recommendations derived from this study will be both representative and comprehensive.

3.1.2. Data Sources

The "Action Plan for Conservation Tillage in the Black Soil of Northeast China (2020–2025)" prioritizes maize production in the northeast China region (Heilongjiang Province, Jilin Province, Liaoning Province, and the eastern part of the Inner Mongolia Autonomous Region) for the promotion and application of conservation tillage. The data for this study were collected via field research conducted in July and August 2022 in five pilot counties involved in black soil conservation and utilization projects: Keshan, Longjiang, and Yi'an in Qiqihar City and Beilin and Lanxi in Suihua City. Questionnaires were distributed primarily to new agricultural management entities involved in corn cultivation, focusing on their production input and output status as of 2021. A total of 319 questionnaires were distributed, with 297 valid responses retained after screening out 22 invalid ones, resulting in a validity rate of 93%. Among the valid questionnaires, 74 were from Longjiang County, 62 from Yi'an County, 57 from Keshan County, 53 from Beilin District, and 51 from Lanxi County.

Our field research involved discussions with staff from the Agriculture and Rural Affairs Bureau, Agricultural Economics Stations, Agricultural Machinery Stations, and Agricultural Technology Extension Centers of each pilot county. We collected relevant policy documents in order to appraise the current status, effectiveness, and challenges of black soil protection programs. This research also included a questionnaire used to evaluate the new agricultural management entities' level of production and their influence on pilot black soil protection programs. The questionnaire comprised three sections: the first covered the input and output status of production, the second assessed production activities affected by policy (including types of conservation tillage technology and the implementation of compensation policies) and gathered feedback on knowledge of and satisfaction with these policies, and the third focused on the characteristics of the production and management subjects. Before conducting the research, the team confirmed that they thoroughly understood the research content, survey questions, and questionnaire structure. They also received training in interview techniques and efficient record keeping to ensure the authenticity and completeness of each questionnaire.

3.1.3. Overview of Conservation Tillage in Each Sample

The Regulations on the Protection and Utilization of Black Soil in Heilongjiang Province detail the responsibilities of pilot counties to carry out the scientific application of chemical and organic fertilizers, promoting practices such as straw returning, reduced tillage, no-tillage seeding, and deep plowing. These counties have further refined such guidelines on the application of protective tillage technology based on these regulations. For example, the Implementation Plan for the Suihua City Black Soil Protection Project (2021–2025) emphasizes integrating agro-mechanical and agro-technical methods, categorizing the implementation of deep tillage and organic fertilizers, and increasing the return of organic matter like straw and animal manure. The pilot counties (districts) adapted their black soil protection programs to local conditions, considering their specific black soil arable land and basic agricultural production conditions, as well as the professional capabilities of their agronomy and agricultural machinery sectors. Field research observed various combinations of conservation tillage technologies involved in actual production. The application of these technologies in the sample area is summarized in Table 2.

Table 2. Application of conservation tillage technologies in the sample.

Degree of Combination	Technologies	Quantities	Proportion
Not applied	No conservation tillage technology applied	54	18.18%
Single	Only straw-returning	20	6.73%
	Only organic fertilizer	23	7.74%
Combined	No-tillage seeding + straw-returning	69	23.23%
	Deep plowing + straw-returning	77	25.93%
	No-tillage seeding + straw-returning + organic fertilizer	30	10.10%
	Deep plowing + straw-returning + organic fertilizer	24	8.08%
Total	——	297	100%

3.2. Empirical Model Construction

3.2.1. SBM-Undesirable Model Construction

In this study, the SBM-Undesirable model was utilized to measure the AGTFP of new agricultural management entities. This DEA-derived model, which is widely used for assessing green productivity, energy efficiency, and environmental efficiency, addresses technological inefficiency through estimating the frontier surface [40]. First, it resolves the input and output slackness that features in traditional DEA models by eliminating inefficiency due to slack. Second, it evaluates productivity by considering non-expected outputs [84]. Third, its non-angularity avoids bias from differences in angle selection, thereby better reflecting productivity [85]. Last, it retains the DEA model's dimensionless quality, not requiring unified input–output dimensions. The construction of the SBM-Undesirable model proceeds as follows.

Suppose there are n decision-making units (DMUs) in the production system, each with m inputs, s_1 desirable outputs, and s_2 undesirable outputs. These can be represented by the following vectors:

$$x \in R_m, y^g \in R_{s1}, y^b \in R_{s2} \tag{1}$$

We can then define the matrices X, Y^g, Y^b as

$$\begin{aligned} X &= [x_1, x_2, \ldots, x_n] \in R_{m \times n} \\ Y^g &= [y^{g_1}, y^{g_2}, \ldots, y^{g_n}] \in R_{s1 \times n} \\ Y^b &= \left[y^{b_1}, y^{b_2}, \ldots, y^{b_n}\right] \in R_{s2 \times n} \end{aligned} \tag{2}$$

In Equation (2), $X > 0$, $Y^g > 0$, and $Y^b > 0$, which transforms the above set as follows:

$$p = \left\{ \left(x, y^g, y^b\right) \middle| x \geq X\lambda, y^g \leq Y^g\lambda, y^b \geq Y^b\lambda, \lambda \geq 0 \right\} \tag{3}$$

In Equation (3), $\lambda \in R_n$ is a vector of weights, and $\lambda \geq 0$ represents constant returns to scale (CRS), or variable returns to scale (VRS) if the equation also satisfies $\lambda \geq 0$ and $\Sigma\lambda = 1$. $x \geq X\lambda$ means that the actual inputs are greater than the production frontier inputs, $y^g \leq Y^g\lambda$ means that the actual desirable outputs are less than the production frontier desirable outputs, and $y^b \geq Y^b\lambda$ means that the actual undesirable outputs are greater than the production frontier undesirable outputs. The SBM-Undesirable efficiency model for a particular decision unit $\left(x_0, y_0^g, y_0^b\right)$ can be expressed as

$$P^* = min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{S_1} \frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{S_2} \frac{s_r^b}{y_{r0}^b}\right)}$$
$$s.t. \begin{cases} x_0 = X\lambda + S^- \\ y_0^g = Y^g\lambda - S^g \\ y_0^b = Y^b\lambda + S^b \\ s^- \geq 0, s^g \geq 0, s^b \geq 0, \lambda \geq 0 \end{cases} \tag{4}$$

In Equation (4), s^-, s^g, and s^b represent slack variables for inputs, desirable outputs, and undesirable outputs, respectively. The objective function p^* strictly decreases with respect to s^-, s^g, and s^b. When $s^- = s^g = s^b = 0$, there exists an optimal solution of the function, $p^* = 1$, which indicates that the DMU is suitably efficient. If $0 \leq p^* < 1$, the efficiency (i.e., green production inefficiency) has diminished in the DMU. This inefficiency can be improved by adjusting the inputs and outputs, with potential improvement determined by the proportion of slack variables to the respective inputs and outputs.

Green production inefficiency can be decomposed into input inefficiency and output inefficiency, expressed as follows.

Input inefficiency:

$$IE_x = \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{i0}},\ (i = 1, 2, \ldots, m) \tag{5}$$

Expected output inefficiency:

$$IE_g = \frac{1}{s_1}\sum_{r=1}^{s_1} \frac{s_r^g}{y_{r0}^g},\ (r = 1, 2, \ldots, s_1) \tag{6}$$

Undesirable output inefficiency:

$$IE_b = \frac{1}{s_2}\sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b},\ (r = 1, 2, \ldots, s_2) \tag{7}$$

In Equations (5)–(7), $\frac{s^-}{x_{i0}}$ is a non-negative number representing the relative shrinkable proportion of the DMU's item i inputs. Similarly, $\frac{s_r^g}{y_{r0}^g}$ is a non-negative number indicating the relative expandable proportion of the DMU's item r expected outputs, and $\frac{s_r^b}{y_{r0}^b}$ is a non-negative number denoting the relative shrinkable proportion of the DMU's item r undesirable outputs.

3.2.2. Tobit Model Construction

In this study, the Tobit model was chosen to explore the effect of conservation tillage on the AGTFP of new agricultural management entities in the black soil region. The Tobit model is suitable for situations in which explanatory variables are constrained and has broadly been used in studies on green productivity, environmental efficiency, and technological efficiency [86]. The reasons for selecting the Tobit model are twofold: first, the values of AGTFP range between 0 and 1, making it a constrained explanatory variable; second, the explanatory variables are continuous within these constraints, truncated at both ends but continuous in the middle. Tobit model-based estimation uses the latent variable Y^* and must meet the basic assumptions of the classical linear model, with the error term following a normal homoskedastic distribution. To address normality issues, this study followed the method of Jiang et al. (2023) by standardizing the dependent variable using the Z-value [87]. To handle potential heteroskedasticity, heteroskedasticity-robust standard errors were used, per the method of White (1980) [88]. The Tobit model was constructed as follows:

$$Y_i^* = \alpha + \beta x_i + \mu_i, \mu_i \sim N\left(0, \sigma^2\right)$$
$$Y_i = \begin{cases} Y_i^*,\ 0 \le Y_i^* \le 1 \\ 0, Y_i^* < 0 \\ 1, Y_i^* > 1 \end{cases} \tag{8}$$

In Equation (8), Y_i^* denotes the latent variable, α is the constant term, β is the coefficient to be estimated, x_i denotes the independent variable, μ_i is the random disturbance term, and Y_i denotes the dependent variable.

3.3. Variable Selection and Descriptive Statistics

3.3.1. Variable Selection and Descriptive Statistics for the SBM-Undesirable Model

In line with China's "Peak Carbon and Carbon Neutral Strategy", scholars have included carbon emissions as undesirable outputs in the AGTFP accounting system [40]. Conservation tillage technology can increase carbon sinks while reducing carbon emissions [89]. Therefore, this study used net carbon emissions (carbon emissions minus carbon sinks) and surface pollution as indicators of undesirable outputs. The explanation and descriptive statistics of the input–output index system are presented in Table 3. Surface pollution from maize cultivation is primarily a result of fertilizer and pesticide runoff, agricultural film residue, and straw returned to the field [90]. Since the use of agricultural film in the samples was minimal (less than 5% of samples featured it in small amounts), this study focused on the total nitrogen and phosphorus emissions from fertilizer and pesticide runoff and returned straw in order to characterize agricultural surface pollution.

$$E_{ij} = \sum EU_i * \rho_{ij} * \left(1 - \mu_j\right) * C_{ij}\left(EU_{ij}, S\right) \tag{9}$$

In Equation (9), E_{ij} is the emission of agricultural pollutant, including total nitrogen (TN) and total phosphorus (TP). EU_i is the corresponding fertilizer use of unit i, and ρ_{ij} is the pollution intensity coefficient of pollutant j produced by unit i, varying with different fertilizer types. μ_j represents the fertilizer utilization efficiency, influenced by soil properties, fertilizer characteristics, organic fertilizer application, and conservation tillage techniques. C_{ij} is the discharge coefficient of pollutant j produced by unit i, which is affected by unit and spatial characteristics (environment, climate, management measures, etc.).

In this study, carbon emissions are accounted for from sources such as fertilizers, pesticides, irrigation, tillage, straw return, and diesel machinery. The increase in carbon sinks is attributed to soil and biological carbon sequestration resulting from no-tillage, straw return, and other conservation tillage techniques.

$$NCE_i = \sum CE_i - \sum CF_i = \sum_j E_{ij}\theta_{ij} - \left[(1-\alpha)\sum_k S_{ik}\vartheta_{ik} + (1-\beta)\sum_k S_{ik}\rho_{ik}\right] \tag{10}$$

Table 3. AGTFP input–output index system and descriptive statistics.

Type of Variable	Variable	Description	Mean	Standard Deviation
Input variable	Land	Corn planting area (hm^2)	97.3691	133.8124
	Labor	Total own and hired labor hours (h)	2839.3833	4170.9578
	Seed	Total cost of purchased seeds (10,000 yuan)	8.0334	9.9889
	Pesticide	Total cost of purchased pesticides (10,000 yuan)	2.3910	3.2281
	Machinery	Total cost of own and hired machinery (10,000 yuan)	12.2263	20.1863
	Fertilizer	Total input of base fertilizer, seed fertilizer, and top dressing (t)	66.2578	88.7720
Expected output variable	Total agricultural production	Total income from corn production (10,000 yuan)	191.1290	265.6771
Undesired output variables	Non-point source pollution	Total nitrogen and phosphorus emissions (t)	26.3924	37.9033
	Net carbon emission	Carbon emissions minus carbon sequestration (t)	142.4054	195.7664

In Equation (10), NCE_i is the net carbon emission of unit iii, E_{ij} is the total amount of carbon source j for unit i, and θ_{ij} is the carbon emission coefficient for unit i. α is the coefficient for the inverse synergistic effect of no-tillage and straw return on soil carbon sequestration, and β is the coefficient for the effect of these practices on slowing biological carbon sequestration. S_{ik} is the area in which conservation tillage technology k is applied, and ϑ_{ik} and ρ_{ik} are the annual rates of soil carbon sequestration and biological carbon sequestration for conservation tillage technology k, respectively.

3.3.2. Variable Selection and Descriptive Statistics for the Tobit Model

Based on the specific metrics of black soil conservation tillage implemented in the five pilot counties studied (Keshan County, Longjiang County, Yi'an County, Beilin District, and Lanxi County), this study combined the production and operation characteristics of each sample subject and their impact on AGTFP levels. Considering the comprehensibility of the questionnaires and the availability of data, the selected variables and descriptive statistics are presented in Table 4.

Table 4. Tobit model variable description and descriptive statistics.

Type of Variable	Variable	Description	Effect Direction	Mean	Standard Deviation
Dependent variable	AGTFP	Range of values [0,1]	/	0.4364	0.2214
Independent variable	Application of conservation tillage techniques	Not applied = 1, only straw-returning = 2, only organic fertilizer = 3, no-tillage seeding + straw-returning = 4, deep plowing + straw-returning = 5, no-tillage seeding + straw-returning + organic fertilizer = 6, deep plowing + straw-returning + organic fertilizer = 7	+	4.0565	1.7820

Table 4. *Cont.*

Type of Variable	Variable	Description	Effect Direction	Mean	Standard Deviation
Control variable	Subsidies for conservation tillage	No compensation = 1, cash subsidy = 2, material subsidy = 3	+	1.9919	0.6564
	Access to agricultural materials	Purchase by oneself = 1, purchase by cooperatives and village departments = 2, shipment from fixed agricultural company = 3	+	1.8226	0.8839
	Adoption of agricultural socialized services	Not adopted = 0, adopted = 1	+	0.5323	0.5010
	Degree of farmland fragmentation	Very decentralized = 1, more decentralized = 2, concentrated = 3	+	1.3634	0.8873
	Quality of farmland	Below average = 1, medium = 2, above average = 3	+	2.1613	0.6790
	Suitability of farmland for mechanized operations	More than half unsuitable = 1, More than half suitable = 2, all suitable = 3	+	1.7182	0.7500
	Age of person in charge	Actual age of the person in charge (years)	−	46.2581	8.4680
	Education level of person in charge	Elementary school and below = 1, secondary school or middle school = 2, college and above = 3	+	1.7892	0.8021
	Proportion of managers	Range of values (0.00%,100.00%]	+	0.8082	0.2551
	Presence of village cadres among members	None = 0, yes = 1	+	0.4516	0.4997

4. Results

4.1. Analysis of AGTFP Measurement Results

As shown in Table 5, the results indicated that the degrees of improvement in each input factor, surface pollution, and net carbon emissions were all negative, signifying a need for reduction. On average, the improvement required in each input factor was less than 50%, highlighting the strong contribution of each factor to overall output. This statistic indicated that most new agricultural management entities in the sample were able to source high-quality agricultural resources and demonstrate modernized production and operation capabilities, exhibiting strong decision making and resource allocation skills. The standard deviation in the degree of improvement in factors revealed significant variations among the entities. This disparity was influenced by factors such as differences in resource allocation capacities, varying levels of technological maturity in black soil protection methods, and the varying impacts of policy among the entities.

Table 5. Degree of improvement needed in input–output indicators for the total sample.

Descriptive Statistics	Land	Labor	Seed	Pesticide	Machinery	Fertilizer	Non-Point Source Pollution	Net Carbon Emission
Mean	−14.23%	−14.17%	−28.28%	−35.29%	−45.29%	−11.07%	−6.73%	−18.18%
Maximum	−34.09%	−55.16%	−83.77%	−77.03%	−93.00%	−53.00%	−51.87%	−59.33%
Standard deviation	0.1064	0.1525	0.2563	0.2713	0.3242	0.1289	0.1189	0.2189

Analyzing the input factors further, machinery inputs showed the highest mean need for improvement at 45.29%; this was likely due to recent increases in oil prices. The need for improvement in labor input was lesser, with a mean of 14.17% but a maximum value of 55.16%, suggesting a need to enhance the use of machinery in some production processes. Improvement in both fertilizer input and surface pollution emissions was relatively limited, with means of 11.07% and 6.73%, respectively, indicating positive pollution control behaviors among the entities. However, some entities still exhibited a great need for improvement, up to 53.00% for fertilizer input and 51.87% for surface pollution, highlighting the importance of enhancing conservation tillage technology. The mean requirement for improvement in net carbon emissions was 18.18%, but some entities showed values as high as 59.33%, indicating substantial potential for carbon sequestration and the reduction in emissions through improved conservation tillage practices in the black soil region.

The results of slack input and output indicators for new agricultural management entities, taking into account differing applications of conservation tillage technology, are presented in Table 6. As the degree of application progressed from “not applied” to “deep plowing + straw returning + organic fertilizer”, labor, pesticide, machinery, fertilizer, non-point source pollution, and net carbon emissions all showed a decreasing trend. However, in the “traditional rotary tillage with straw” group, both machinery and fertilizer use increased. This increase was attributed to the additional production processes and machinery costs associated with rotary plowing, which also failed to achieve adequate straw decomposition. The levels of improvement for land and seed inputs were affected by factors beyond technology, thus not strictly correlating with the extent to which technology was adopted.

Table 6. Average degree of improvement needed in input–output indicators under different technology portfolios.

Descriptive Statistics	Land	Labor	Seed	Pesticide	Machinery	Fertilizer	Non-Point Source Pollution	Net Carbon Emission
Not applied	−22.10%	−27.09%	−29.75%	−71.16%	−69.15%	−22.00%	−28.37%	−35.58%
Only straw-returning	−27.75%	−24.24%	−46.67%	−58.06%	−74.86%	−28.38%	−45.57%	−41.62%
Only organic fertilizer	−17.86%	−21.64%	−47.71%	−43.59%	−61.30%	0.00%	−18.06%	−22.65%
No-tillage seeding + straw-returning	−12.91%	−11.72%	−21.55%	−34.69%	−53.32%	−7.86%	−11.15%	−20.59%
Deep plowing + straw-returning	−11.72%	−9.37%	−31.16%	−26.76%	−42.28%	−7.37%	−7.16%	−14.83%
No-tillage seeding + straw-returning + organic fertilizer	−15.57%	−5.60%	−32.45%	−26.23%	−41.63%	−0.79%	−3.87%	−11.21%
Deep plowing + straw-returning + organic fertilizer	−6.99%	−3.54%	−21.86%	−18.97%	−34.11%	−0.37%	−1.36%	−7.24%

4.2. Analysis of the Effect of Conservation Tillage on AGTFP

In this study, we employed the Tobit model and used Stata15.1 software to estimate the impact of conservation tillage technology and other influencing factors on the AGTFP levels of the new agricultural management entities in the selected research areas. In Table 7, the first column contains the names of variables, the second column contains descriptions of these variables, and the third column shows the regression coefficient and standard deviation of these variables in the Tobit model.

Table 7. Tobit model results: impact of conservation tillage on AGTFP.

Variables	Description	Coefficient
Ln tech	Application of conservation tillage techniques	0.0100 ** (0.0044)
Ln subs	Subsidies for conservation tillage	0.0913 ** (0.0348)
Ln mate	Access to agricultural materials	0.0093 ** (0.0041)
Ln serv	Adoption of agricultural socialized services	0.0438 * (0.0170)
Ln frag	Degree of farmland fragmentation	0.0462 ** (0.0174)
Ln qual	Quality of farmland	0.0036 (0.0020)
Ln mech	Suitability of farmland for mechanized operations	0.0578 ** (0.0262)
Ln age	Age of person in charge	−0.0019 (0.0009)
Ln educ	Education level of person in charge	0.0154 ** (0.0075)
Ln mana	Proportion of managers	0.0578 * (0.0318)
Ln cadr	Presence of village cadres among members	0.0587 (0.0363)
_cons	constant term	0.5561 *** (0.1376)

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively, with standard deviations in parentheses. Table 8 is the same.

According to the regression results in Table 7, conservation tillage technology had a significant positive impact on the AGTFP levels of new agricultural management entities. The greater the application and combination of this technology, the more pronounced the enhancement of AGTFP. The estimated coefficients of each control variable's effect on AGTFP aligned with our theoretical expectations. Specifically, subsidies for conservation tillage, access to agricultural materials, adoption of agricultural socialized services, degree of farmland fragmentation, suitability of farmland for mechanized operations, education level of persons in charge, and the proportion of managers all positively and significantly affected AGTFP levels. The quality of cultivated land did not pass the significance test, likely because all cultivated land in the sample area was high-fertility black soil, making differences in quality insufficient to impact AGTFP. The age of the person in charge also did not pass the significance test; this may be because land transfer, land trusteeship, and socialized services mitigated the influence of the characteristics of the person in charge on AGTFP. Additionally, whether or not there were village cadres among members did not pass the significance test; this was likely because current policies were more transparent and new agricultural management entities had greater social capital and information resources than ordinary farmers, which reduced the influence of village cadre membership.

To further ensure the reliability of the Tobit model's regression results, this study conducted robustness tests using model substitution, explanatory variable substitution, and reduced-tail regression. Model (I) replaced the Tobit model with the CLAD model, relaxing the normal homoskedasticity assumption. Model (II) reported the regression results of the test by substituting explanatory variables. The application of organic fertilizer, which can represent green production [91], was substituted into the model using normalized data on the organic fertilizer used by new agricultural management entities. Model (III) employed reduced-tail regression, trimming 2.5% of outliers before and after analysis to minimize their impact on conclusions. The results in Table 8 consistently demonstrate a significant positive impact of conservation tillage technology on AGTFP across all test variations, affirming the robustness of this study's findings.

Table 8. Robustness test results: evaluating the impact of conservation tillage on AGTFP using various models and methods.

Variables	Model (I) AGTFP	Model (II) Organic Fertilizer Application	Model (III) AGTFP
Ln tech	0.1206 *** (0.0256)	0.1090 *** (0.0551)	0.0906 ** (0.0028)
Ln subs	0.0001 ** (0.0269)	0.0002 ** (0.0463)	0.0797 *** (0.0071)
Ln mate	0.0194 * (0.0104)	0.0040 ** (0.0015)	0.0108 ** (0.0030)
Ln serv	0.0693 ** (0.0335)	0.0411 ** (0.0157)	0.0613 ** (0.0138)
Ln frag	0.0712 ** (0.0350)	0.0450 * (0.0245)	0.0638 ** (0.0144)
Ln qual	0.0034 (0.0010)	0.0013 (0.0006)	0.0069 (0.0001)
Ln mech	0.0548 ** (0.0269)	0.0559 ** (0.0277)	0.0661 ** (0.0132)
Ln age	−0.0026 (0.0019)	−0.0318 (0.0011)	−0.0108 (0.0001)
Ln educ	0.0131 * (0.0074)	0.0178 * (0.0094)	0.0166 ** (0.0038)
Ln mana	0.0349 ** (0.0158)	0.0609 ** (0.0308)	0.0502 (0.0137)
Ln cadr	0.0534 (0.0372)	0.0629 (0.0460)	0.0678 (0.0177)
_cons	0.6163 *** (0.1393)	0.5563 *** (0.1380)	0.6331 *** (0.1006)

5. Discussion

Against the backdrop of escalating environmental pollution and resource depletion induced by the development of the traditional agricultural industry, black soil is deteriorating, and agriculturally efficient and ecologically friendly practices have become crucial in the pursuit of global agricultural sustainability [92]. Considered the "breadbasket of the world" [93], black soil plays a crucial role in global food production [94]. According to the International Food Policy Research Institute (IFPRI), 30% of global wheat production, 26% of soybean, and 16% of corn come from black soil cropland [95]. These soils, rich in organic matter and fertility, not only support food production but also have a high capacity for organic carbon sequestration, making them vital for adapting to and mitigating climate change [96]. Despite covering only 5.6% of the global soil area, black soils hold 8.2% of the world's soil organic carbon (SOC) reserves and contribute 10% of total global SOC sequestration potential [15]. However, many black soils have lost over half of their carbon stocks, thus negatively impacting regional ecological stability and food security [97]. The Status of the World's Soil Resources Report has identified increasing soil erosion, organic carbon loss, nutrient imbalances, acidification, and pollution in black soils globally [98]. Intensive human development and exploitation have further degraded these soils' natural fertility, reducing the depth of the tillage layer and compromising soil properties and ecological functions [99]. Scholars are increasingly advocating for conservation tillage and better protection of black soil as solutions to these issues [100].

This study built on the existing research by introducing agricultural green total factor productivity (AGTFP) as a key indicator used to assess the combined economic and ecological impacts of conservation tillage in black soil regions in order to investigate the significant effect of conservation tillage on agricultural green total factor productivity (AGTFP) in the black soil zone, thereby filling the research gap left by existing studies. The AGTFP clarifies the mechanisms through which conservation tillage enhances the sustainable production capacity of black soil, supplementing existing theories on black soil conservation and utilization. Subsequently, in this study, we constructed an analytical framework within which to examine the impact of conservation tillage on AGTFP for new agricultural management entities in black soil regions, based on the "Longjiang model" in Heilongjiang Province. Our theoretical analysis was grounded in theories of environmental regulation, the substitution effect, and the technology effect; it examined the economic and ecological impacts of conservation tillage using factor inputs, desirable outputs, and undesirable outputs. Empirically, this study used the SBM-Undesirable model to measure and evaluate AGTFP, analyzing the need for improvement in different input and output elements. The Tobit model was employed to quantify the effect of conservation tillage on AGTFP, providing a basis for evaluating its effectiveness in the black soil region. Additionally, China's unique national-level legislation on black soil protection, featuring clear legal and institutional frameworks at both central and local levels, provided a context for this analysis. The study's findings offered empirical insights and decision-making references for global black soil conservation efforts and the development of conservation tillage programs tailored to black soil environments worldwide.

In order to promote black soil conservation and utilization and to enhance the application of conservation tillage in the black soil region, we provide the following policy recommendations.

1. Comprehensive strategies for integrated black soil protection:

Several pilot counties and districts in Heilongjiang Province have integrated black soil protection into their national economic and social development plans [7]. However, some areas lack specialized projects for black soil protection, focusing instead on conservation tillage, planting, and recycling projects. These areas need to improve their allocation of financial resources and the efficiency of their project management [101]. Regional governments at or above the county level should develop specialized policies and projects for black soil protection and utilization, strengthening leadership, organizational structures, coordination mechanisms, and supervision to continually expand their overall impact.

2. Enhancing the role of new agricultural management entities in black soil protection:

New agricultural management entities should play a leading role in black soil protection, leveraging their production efficiency and radiation-driven capabilities. They should capitalize on opportunities presented by land trusteeship and agricultural socialization services by efficiently conducting conservation activities on their own transferred arable land [102]. Additionally, this study proposed that these entities should provide technical conservation tillage services to small-scale farmers, expanding protected areas through government-funded purchases and publicly promoting black soil protection [103]. The government should support new agricultural management entities by optimizing production operations (thereby enhancing their ability to apply conservation tillage techniques) and providing necessary production services. Forms of support may include subsidies for no-tillage planters, large-scale tilling machines, and agricultural materials like organic fertilizers. Maintaining the feasibility of conservation tillage technology and the provision of external services (along with centralized purchasing channels for quality-controlled agricultural materials) is essential to ensure that production inputs are of acceptable price and quality.

3. Promotion of integrated conservation tillage techniques

Heilongjiang Province emphasizes the promotion and implementation of conservation tillage technology, exploring the "Longjiang model" for black soil protection in drylands [104]. However, challenges include fragmented conservation tillage methods across programs and insufficient promotion of integrated approaches. The results of this study showed that the rate of adoption of the three integrated conservation tillage technologies was low, indicating a lack of systematization. To address this, the authors propose further advancements in scale, standardization, and science in order to achieve a transformation of black soil management. The pilot counties' governments and agricultural technology departments should implement the most suitable combinations of technology for the restoration and enhancement of local black soil fertility by considering actual conditions. Numerous studies have compared the effects of physical processes on soil physicochemical properties using both conventional and conservation tillage methods [105,106]. They have also emphasized the importance of soil organic cover and nutrient management in improving soil quality and crop yields, but they have overlooked the opportunity to mix technologies within conservation tillage [107,108]. To improve the overall quality of soils' structures, agricultural extension and policy-making bodies must thoroughly understand regional black soil quality and its challenges, promoting and combining different technologies to address specific issues and optimization goals. Gathering and addressing feedback from users of this technology on the positive impact of conservation tillage is crucial for refining promotion strategies. Training new agricultural management entities in conservation tillage techniques will increase their awareness of, willingness to adopt, and ability to apply these technologies, thus facilitating integrated application and combination of different techniques.

4. Expanding material subsidies for black soil conservation

Heilongjiang Province has established subsidies in the form of cash subsidies for conservation tillage operations, material and chemical subsidies for organic fertilizer and spreading services, and government-funded conservation tillage services [109]. However, few new agricultural management entities benefit from these subsidies and services. To improve this, the integration of planting and feeding cycle projects and black soil conservation projects should be furthered, that we might increase the input of organic fertilizers to expand their coverage. Combining subsidies for organic fertilizer with support for producers who do not receive free fertilizer and seeding services may enhance this effect. Cooperation between agronomy and soil fertilizer departments and local organic fertilizer manufacturers may improve the bargaining position of business entities. Agricultural machinery departments should designate new agricultural management entities with large-scale and robust service capacities and high proficiency in conservation tillage technology as primary providers of conservation tillage services in the region. This approach aims to systematize government procurement services effectively. Some scholars have also suggested the establishment of a mechanism that accounts for black soil resources within existing systems that account for natural resources [110]. Additionally, cash subsidies for conservation tillage operations should be adjusted based on actual disbursement and recipient satisfaction levels.

5. Enhancing and refining supporting policies for black soil protection

Integrated management and comprehensive policies for typical black soil protection and utilization areas should be implemented in order to improve the construction of policies. Establishing a robust mechanism for policy coherence and reinforcing supportive systems are crucial to ensure the comprehensiveness and alignment of policies [92]. Previous studies have focused on standardizing evaluation criteria [111,112]; however, the results of this study suggest that real-time monitoring and measures for preventing and restoring sustainable management should also be included. Governments in pilot areas should establish systematic and regular monitoring mechanisms, including key indicators such as soil properties, black soil layer thickness, erosion, organic matter content, and quality grading. A dynamic database tracking black soil quality changes should be developed and continually improved, integrating existing monitoring data into a nationally unified database. Implementing a robust early warning system for black soil quality, featuring clear standards and alert levels, is essential for timely intervention. Increasing special funds for black soil protection and utilization, along with enhancing technical and management capacities, is necessary. The establishment of a wide-coverage, rapid-response exchange and cooperation platform for black soil protection and utilization is also recommended.

6. Conclusions

This study initially analyzed the mechanisms through which conservation tillage affected the AGTFP of new agricultural management entities in the black soil region, drawing on theories of environmental regulation effect, substitution effect, and technology effect. It provided an overview of the application of conservation tillage technology in the black soil region and assessed the input–output status of these new agricultural management entities in pilot counties based on empirical research. Furthermore, the SBM-Undesirable model and Tobit model were constructed to measure and evaluate the AGTFP of these entities, analyzing the impact of conservation tillage technology on AGTFP. This empirical analysis substantiated our theoretical framework and presented a basis upon which to optimize the conservation and utilization of black soil. Our specific conclusions were as follows.

AGTFP levels and their variations: The AGTFP of new agricultural management entities in the research region showed significant imbalance and fluctuation. The average AGTFP value was 0.4364, indicating a generally low and greatly varying level. This suggested a need for substantial improvements in the efficiency of resources' allocation, input–output conversion, and the application of green production technology. The disparities in AGTFP levels among different enterprises highlighted the significant impact of production and management characteristics and black soil conservation practices. Improvement was needed in all input–output indicators, ranked as follows by the mean value of the degree of improvement required: machinery > pesticides > seeds > net carbon emissions > land > labor > fertilizers > non-point source pollution.

Impact of conservation tillage: Conservation tillage had a significantly positive impact on AGTFP, with the impact increasing with the number of technical measures applied. Different technology combinations yielded varying effects on AGTFP. When only one technology was used, the AGTFP from straw returning was lower than that from organic fertilizer. Combining two technologies, the AGTFP from no-tillage seeding + straw returning was lower than that from deep plowing + straw returning. When all three technologies were combined, the AGTFP from no-tillage seeding + straw returning + organic fertilizer is lower than that from deep plowing + straw returning + organic fertilizer. Overall, conservation tillage technology enhanced AGTFP, with stronger effects as more technologies and complex combinations were applied.

Influence of government subsidies and other factors: Government subsidies for black soil protection significantly increased AGTFP. Subsidies for organic fertilizer and its supporting services and government-funded conservation tillage services provided more direct financial relief and a stronger impact on AGTFP than cash subsidies. Apart from policy factors, production and operational characteristics also affected AGTFP. Factors such as access to agricultural materials, adoption of agricultural socialized services, the degree of farmland fragmentation, the suitability of farmland for mechanized operations, the education level of the person in charge, and the proportion of managers all had significantly positive effects on AGTFP.

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