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Assessment of the Coupling Degree between Agricultural Modernization and the Coordinated Development of Black Soil Protection and Utilization: A Case Study of Heilongjiang Province

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Abstract: Agricultural management encompasses various processes, including agricultural modernization and land protection and utilization; however, these aspects are seldom considered simultaneously. This study focuses on Heilongjiang Province, a major grain-producing region in China, in efforts to address this gap. The objective is to facilitate the mutual sustainable development of agricultural modernization as well as the protection and utilization of black soil through research and coordination. Statistical data from a case study conducted in Heilongjiang Province serve as the basis for this investigation, aiming to identify contradictions in the coordinated development of agricultural modernization and black soil protection and utilization in the province, design mechanisms to sustain this development, and ensure the mutually supportive progress of both aspects. This research delves into an infrequently explored dimension of the current policies surrounding black soil imposed by the Chinese authorities, offering significant insights into agricultural modernization.

Keywords: agricultural modernization; black soil protection and utilization; coordinated development; coupling degree evaluation

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1. Introduction

This study focuses on Heilongjiang Province, which is situated in the northeastern plains of China and recognized as one of the world's four major black soil regions. The province receives annual precipitation ranging from 370 to 670 mm and experiences long, cold winters; its frost-free period is limited to only 100–140 days per year. These factors create a single-season agricultural production cycle and an extended dormancy period for arable land [1].

Heilongjiang Province has a total black soil area of approximately 4,824,727 hectares, which can be classified into five soil types: dark brown soil, chernozem (black soil), calcic black soil, meadow soil, and typical black soil [2]. The distinctive characteristics of black soil in this region include a dark and fertile topsoil layer exceeding 20 cm in depth, well-developed granular structure, and organic matter content generally exceeding 15 g/kg. The salt saturation levels often exceed 70%, and pH values range between 5.5 and 7.0, making the area suitable for the production of most crops. The surface soil bulk density is concentrated in the range of 1.0 to 1.3 g/cm^3 [3].

Since the reclamation of the black soil area in 1963, extensive farming management has been implemented. Although relevant departments have begun to attach great importance to its sustainable development in recent years, the average thickness of the black soil layer still shows an astonishing downward trend, decreasing by 1 cm per year. Initially concentrated between 80 and 100 cm, the current thickness mostly falls between 20–40 cm [4]. Climate change and anthropogenic activities, coupled with overdevelopment and unsustainable management, have led to a rapid decrease in both the quantity and quality of black soil [5,6]. This has resulted in soil structure degradation, intensified wind and water erosion in some areas, and the thinning of the black soil layer. Today, these changes pose a significant threat to the sustainable development of regional agriculture and food security.

The data from the second national land erosion remote sensing survey indicate that the erosion of black soil in Heilongjiang Province has reached 11.2 million hectares, accounting for 1/4 of the total area of the province. The total annual soil loss is as high as 200–300 million m^3. At this current rate of soil erosion, the existing black soil layer of Heilongjiang farmlands will be completely eroded within 40–50 years [7]. The effective protection and utilization of black soil will be crucial for ensuring food security and sustainable agricultural development in Heilongjiang Province [8].

Existing studies suggest a lack of coordination between agricultural modernization and black land use, leading to black soil degradation. Scholars supporting this view attribute issues such as shallow black soil layers to long-term singular cultivation methods and excessive mechanization [9]. Issues like soil compaction, pollution, and degradation arise from excessive irrigation, fertilizer application, and pesticide usage [10,11]. The pursuit of economic benefits while neglecting ecological, environmental, and social benefits has manifested as a lengthy history of cultivating only high-yield crops in Heilongjiang Province, where corn, rice, and soybeans accounted for 98.97% of the total grain crop production in 2020 [12]. This singular planting structure exacerbates problems such as soil acidification and land degradation [13]. Research on the coordinated development of agricultural modernization and the conservation and utilization of black soil is urgently needed to address these problems.

Agricultural modernization includes aspects such as agricultural mechanization, the scientization of productive technique, agricultural industrialization, agricultural informatization, and the sustainable development of agriculture [14–16]. Among them, the relationship between agricultural mechanization, the scientization of productive techniques, sustainable agriculture, and land protection and utilization is more direct. The coordinated development of land protection and agricultural modernization is the key to doing a good job in the work of agriculture, rural areas, and farmers in the new era. Only by strictly implementing land protection and accelerating the modernization of agriculture and rural areas can we effectively respond to risks and challenges and achieve sustainable agricultural development [17].

To date, research on this topic has focused predominantly on agricultural modernization, land protection, and land evaluation; however, there is a lack of data and empirical studies regarding the coordinated development of agricultural modernization and black soil protection and utilization. The serious degradation of black soil in Heilongjiang has become a bottleneck hindering the further development of regional agricultural modernization. From the practice in developed regions, it is generally necessary to carry out land feedback strategies in the middle and later stages of regional agricultural modernization development [18]. In the main grain-producing areas with black land as the core development resource, black land is the foundation of agricultural modernization. In theory, there is an inherent coupling and coordination relationship between agricultural modernization and black soil protection (Figure 1). The findings of the present study may bridge this gap. We used a coupled coordination model to estimate the current status of agricultural modernization and black soil conservation and utilization, exploring the protective use of black soil in the process of agricultural modernization to foster coordinated development between the two aspects.

Research on agricultural modernization has yielded valuable findings, which can be roughly divided into five categories. The first centers on agricultural modernization most broadly. For example, Zhao [11] explored the connotation, tasks, and pathways of contemporary ecological agricultural modernization, asserting that Chinese agricultural practices will inevitably modernize. The second category encompasses factors affecting agricultural modernization, including studies on institutional guarantees and new technologies [19]. Qiao [20] suggests that the green transformation of production methods plays a vital role in China's sustainable agricultural development and modernization processes.

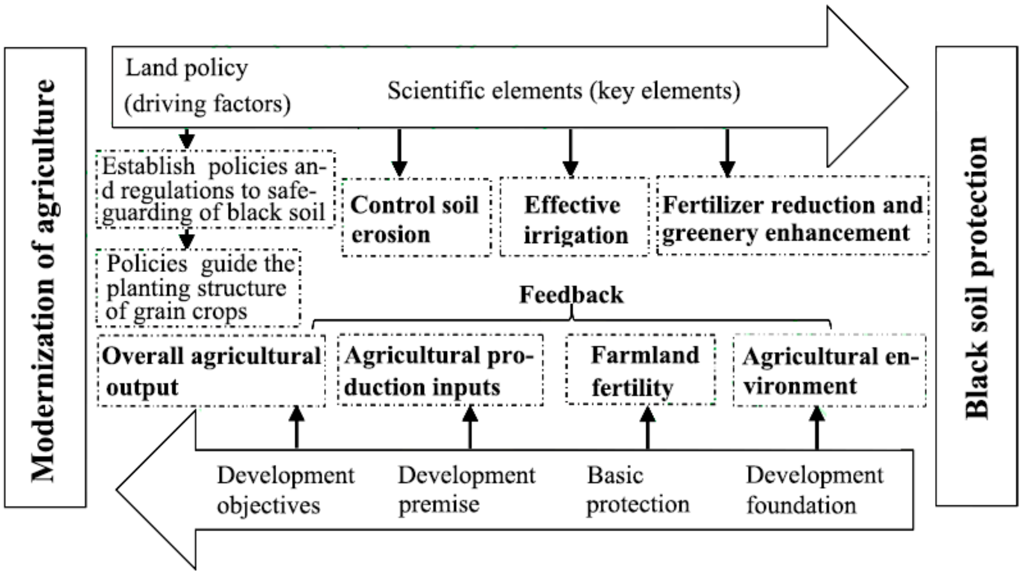


Figure 1. Coupling and coordination relationship between agricultural modernization and the protection and utilization of black soil.

The third category centers on the development paths of agricultural modernization. Ma [21] found that "Internet+" is an innovative path for the modernization of Chinese agriculture. Guo [22] proposes that agricultural modernization can be achieved through the path of rural revitalization. Udall [23] suggests the transition of modern agriculture from subsistence farming to complex and diversified agriculture, and from decentralization to centralization, to move from traditional agriculture to modern commercial agriculture. The fourth category involves agricultural modernization index systems. Agita Gancone [24] explored several developing countries and proposed 11 evaluation criteria for modernization, including per capita GDP, agricultural output value proportions, non-agricultural labor force proportions, service industry output value proportions, university attendance among workers, illiteracy rates, doctors per capita, life expectancy, natural death rates, natural population growth rates, and urbanization rates. The fifth category mainly involves evaluation methods. Zhang [25] investigated an evaluation index system for Chinese agricultural modernization. Liu [26] evaluated the level of agricultural modernization in the reclamation areas of Heilongjiang based on the entropy method.

Concerning research on land protection, firstly, agricultural workers' willingness to participate in land protection efforts has been extensively investigated. Wang [27] explored the impact of different external environments on their willingness to participate. Yang [28] investigated the influence of land fragmentation on farmers' crop rotation behavior. Li [29] found that farmers' awareness of policies positively influences their willingness to participate in land transfers. Niu [30] suggests that factors such as gender, education level, labor force size, land area, migration from traditional agricultural areas, average family income, and understanding of policies significantly affect farmers' behavior. Xiao [31] argues that farmers' satisfaction levels with compensation standards, funding requirements, and government supervision are significantly influenced by factors such as their education level, land area, annual agricultural income, understanding of conservation land protection funds (CLPFs), recognition of CLPF value, and perception of changes in family economic conditions. Yan [32] found that farmers are willing to restore polluted soil, preferably through plant restoration, and that their participation status and perceived benefits are the main factors influencing this willingness.

Other researchers have investigated the impact of ownership on land-protection-related behavior. For instance, Zhou [33] empirically analyzed the impact of farmers' awareness of land ownership security on their behavior regarding the conservation of cultivated land. Ngo [34] explored the effects of forest land rights systems on forest management behavior among Vietnamese households. Li [35] argued that only the rights to ecological products influence farmers' willingness to invest in forestry, while other property rights are negligible.

Concerning the technical aspects of land protection, researchers like Hong [36] have quantitatively studied the distribution of water-stable aggregates (WSAs) in black soil under long-term cultivation in different seasons and their relationship with microbial community structures and diversity. Factors influencing farmer's use of black soil have been explored by scholars like Guo [37], who focused on eco-friendly tillage techniques, and Ai [38], who identified seven significant factors influencing rice farmers' acceptance of agricultural production services. Zhang [39] empirically analyzed the fertility of black soil in the Northeast Black Soil Region and irrigation agricultural areas. Dong [40] comparatively analyzed the grading of black soil farmlands and in terms of fertility.

Scholars have also explored various approaches to evaluating black soil. Feng [41] utilized the Ecological Efficiency of Land Use (ECLU) model to analyze spatiotemporal pattern changes and influencing factors in the Northeast Black Soil Region, innovatively incorporating net carbon sinks and non-point source pollution emissions into the ECLU. Liao [42] established an integrated customized model that can be used to diagnose key issues and leading factors of black soil degradation based on the regional system of human–land relationships, existing management practices, agricultural system theory, and agricultural informatization, guided by comprehensive geographic concepts. Marivel [43] systematically analyzed the resilience of a cropland system, emphasizing its significant importance for the protection of black soil and national food security. Wang [44], based on the resilience theory, constructed a provincial- and urban-level Comprehensive Land Security Review (CLSR) evaluation system for Liaoning Province. Their analysis focused on the key factors that are influential in the CLSR in Liaoning and its 14 cities. Gong [45] applied an improved TOPSIS model to evaluate the multifunctionality of farmlands over a 30-year period.

In addition, coupling research between agricultural modernization and ecological environment, common themes can also be traced. For instance, Weng [46], based on the theory of social–ecological resilience and taking Cambodia as an example, explored the interaction between agriculture, roads, and the agricultural eco-environment using a coupled coordination model and a grey relational analysis model. Deng [47], based on the indicator evaluation system of agricultural ecological environment and agricultural economic development in Anhui Province, studied the coupling and coordination relationship between the two. Mao [48] proposed the current positive situation of the construction of a beautiful countryside and the problems faced by the integrated development of the three rural industries, analyzes the coupling relationship between the two.

In summary, previous research findings offer valuable guidance for advancing both agricultural modernization and the protection and utilization of black soil; however, there are still opportunities for innovation in terms of both research content and methodology. Scholars have delved into various strategies and pathways for the coordinated development of both aspects, yet there have been few analyses performed on the factors influencing this development. Regarding research methodologies, while there have been several quantitative empirical analyses on agricultural modernization and the protection and utilization of black soil, there is a lack of quantitative studies directly observing the endogenous relationship between the two.

Employing a standard economic research paradigm and integrating a coupled coordination model could facilitate exploration into the mechanisms promoting the coordinated development of both aspects. Effective approaches would not only allow agricultural modernization to drive the protection and utilization of black soil but also enable the reciprocal contribution of black soil protection and utilization to agricultural modernization, thereby supporting sustainable development.

2. Materials and Methods

2.1. Theoretical Foundation

Coupling, originally a physics concept, refers to the interaction between two or more systems resulting in their mutual connection. It can also denote the phenomenon of the integration of various systems through interactions driven by intrinsic mechanisms. The study of coupling, coordination, feedback, and development mechanisms among individual entities is widely applied in fields such as society, geography, and law [49,50]. In the present study, we extend the concept of coupling to the coordinated development of agricultural modernization and the protection and utilization of black soil, aiming to explore the coupling-related mechanisms between them.

2.2. Indicator System and Data Sources

Before examining the coupling relationship between two major entities, it is necessary to select indicators and construct an evaluation indicator system. There has been extensive research on the comprehensive evaluation of agricultural modernization, but a unified evaluation indicator system has not yet been established. Most scholars choose to construct evaluation systems based on four dimensions: input, output, social development, and sustainable development [15,51,52]. However, specific indicators vary due to differences in data availability and research spatial scales. Drawing on existing indicators from research on black soil evaluation and agricultural modernization and based on a deep understanding of these two aspects, a comprehensive evaluation indicator system was constructed for 13 prefecture-level cities in Heilongjiang Province, including Harbin, Daqing, Suihua, Jixi, Hegang, Shuangyashan, Jiamusi, Qiqihar, Yichun, Qitaihe, Mudanjiang, Heihe, and Daxing'anling (Table 1). The system aligns with principles such as scientificity, operability, systematicity, independence, comparability, comprehensiveness, foresight, and data availability. Black soil protection and utilization utilizes indicators such as organic matter, total nitrogen, available phosphorus, quick-acting potassium, soil pH, soil layer thickness, and fertilizer usage, which were also utilized to characterize the quality and sustainable development status of black soil in Heilongjiang Province. Agricultural modernization was defined using dimensions such as agricultural production input and comprehensive agricultural output, reflecting its complementary relationship with black soil protection. Twenty secondary indicators corresponding to the characteristics and essence of the primary indicators were selected to complete the evaluation system.

Table 1. Evaluation system and indicator weighting for agricultural modernization and black soil conservation and utilization in the main grain production areas of Heilongjiang Province.

Primary Indicator	Secondary Indicator	Indicator Explanation	Polarity
Farmland fertility	Organic matter	Changes in organic matter content	+
	Total nitrogen	Changes in total nitrogen content	+
	Available phosphorus	Changes in effective phosphorus content	+
	Readily available potassium	Changes in quick-acting potassium content	+
	Soil pH	Fluctuations in soil pH	Appropriate
Agricultural environment	Thickness of the black soil layer	Changes in the thickness of the black soil layer	+
	Fertilizer application rate	Changes in fertilizer application rate	+
Agricultural production inputs	Rural electricity consumption	Changes in rural electricity consumption	+
	Aggregate farm machinery amount	Variations in aggregate farm machinery amount	+
	Main crop sowing area	Changes in sowing area of major crops	+
	Effective irrigated area	Variations in effective irrigation area	+
	Reservoir capacity	Changes in reservoir capacity	+

Table 1. *Cont.*

Primary Indicator	Secondary Indicator	Indicator Explanation	Polarity
Overall agricultural output	Grain yield	Changes in grain yield	+
	Grain yield per unit area	Changes in grain yield per unit area	+
	Vegetable yield	Changes in vegetable yield	+
	Orchard fruit yield	Changes in orchard fruit yield	+
	Main agricultural product output	Changes in yield of major agricultural products	+
	Livestock production	Changes in livestock production	+
	Aquatic product yield	Changes in aquatic product yield	+
	Agricultural gross production value	Variations in agricultural gross production value	+

The data used in this study mainly come from the *China Urban Statistical Yearbook* (2011–2021), the *Heilongjiang Statistical Yearbook* (2011–2021), statistical bulletins on the national economy and social development of various prefecture-level cities in Heilongjiang Province (2011–2021), related Master's and Doctoral theses and journal articles from China National Knowledge Infrastructure (CKNI), and relevant black soil parameters obtained through searches on Baidu, Toutiao, and other mobile applications. Any missing data were filled in using the mean imputation method.

2.3. Weight Determination and Comprehensive Evaluation Index Calculation Method

In general, index weighting methods may be subjective or objective. Subjective weighting methods typically exhibit non-deterministic, error-prone, biased, and unstable characteristics. An objective weighting method was utilized in this study to eliminate these characteristics. Objective weighting methods include entropy weighting, principal component analysis, and factor analysis. The entropy weighting method can be used to directly calculate the weight of an index based on the information it contains, reflecting the difference between the evaluation value of the index and the evaluation unit. This approach was employed in this study to determine the weights of various indicators in the system of agricultural modernization and black soil protection and utilization. To mitigate the impact of differences in the dimensions of indicators, a method of extreme value standardization was applied for dimensionless processing. Subsequently, the weights of indicators were calculated following the steps of the entropy method (Table 1).

To conduct dimensionless processing using the extreme value standardization method, first, let x_{ij} be the original actual value of the j-th indicator in the i-th city, while Z_{ij} is the standardized value of the j-th indicator in the i-th city after range standardization. When the attribute of x_{ij} is positive, the x_{ij} indicator contributes positively to its upper-level criterion domain (where a larger value is preferable).

$$Z_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{1}$$

When the indicator x_{ij} attribute is negative, it has a reverse negative effect on their upper-level criterion domain (where a smaller value is preferable).

$$Z_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{2}$$

When the attribute of indicator x_{ij} is negative, x_{ij} reacts with a negative effect on its superior standard domain (again, where a smaller value is preferable).

$$Z_{ij} = \begin{cases} 1 - \frac{a_j - x_{ij}}{\max(x_{ij} - \min x_{ij}, \max x_{ij} - x_{ij})} & x_{ij} < a_j \\ 1 & a_j \le x_{ij} \le b_j \\ 1 - \frac{x_{ij} - b_j}{\max(x_{ij} - \min x_{ij}, \max x_{ij} - x_{ij})} & x_{ij} > b_j \end{cases} \tag{3}$$

min x_{ij} is the minimum value of the j-th indicator, min x_{ij} is the maximum value of the j-th indicator, and $[a_j, b_j]$ is the optimal interval of the j-th indicator.

After extreme value standardization, the coefficient of variation weighting is calculated in the following steps.

1. Solve the average value of various original indicators.

$$\overline{x}_j = \frac{1}{m}\sum_{i=1}^{m} x_{ij} \tag{4}$$

2. Solve the standard deviation of various indicators.

$$S_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m} (x_{ij} - \overline{x}_j)^2} \tag{5}$$

3. Solve the coefficient of variation for various indicators.

$$CV_j = \frac{S_j}{\overline{x}_j} \tag{6}$$

4. Calculate the weight of the coefficient of variation for each indicator.

$$w_j = \frac{CV_j}{\sum\limits_{j=1}^{n} CV_j} \tag{7}$$

5. Solve the comprehensive development index of agricultural modernization and black soil protection and utilization across Heilongjiang Province.

$$U_i = \sum_{j=1}^{n} w_j \times Z_{ij} \tag{8}$$

2.4. Coupling Coordination Degree Analysis Method

The model used in this study serves to compute the coupling and coordinated development degree of agricultural modernization and black soil protection and utilization in Heilongjiang Province. It is based on the capacity coupling coefficient model, borrowed from physics with some modifications. The final calculation formula is as follows:

$$T = \alpha U_1 + \beta U_2 \tag{9}$$

$$C = \sqrt{\frac{U_1 \times U_2}{(U_1 + U_2)^2}} \tag{10}$$

$$D = \sqrt{C \times T} \tag{11}$$

where U_1 and U_2 are the comprehensive evaluation indices for agricultural modernization and black soil protection and utilization, respectively; T is the comprehensive coordination index of the two systems, which can be used to prevent "false coupling" phenomena and reflect the true coordination level between the two systems; and α and β are the development coefficients of the contributions of the two systems, which should be equally important so that they develop in tandem and while supporting each other. Therefore, $\alpha = \beta = 0.5$. C represents the coupling degree between agricultural modernization and black soil protection and utilization, which indicates a more harmonious development of the two systems when its value is higher. D represents the coupling and coordination of agricultural modernization and black soil protection and utilization, which is stronger when the value is closer to 1.

Drawing on previous research by Hou Hongxing [53], Wang Qiqi [54], and Li Ningning [55], the coupling coordination types of the two systems were divided according to the calculated coupling coordination degree (Table 2).

Table 2. Classification criteria for coupling coordination degree.

Coupling Co-Scheduling Interval	Coordination Level	Coupling Coordination Type
0–0.1	1	Extremely imbalance
0.1–0.2	2	Hyper imbalance
0.2–0.3	3	Moderate imbalance
0.3–0.4	4	Mild imbalance
0.4–0.5	5	On the verge of imbalance
0.5–0.6	6	Barely coordination
0.6–0.7	7	Primary coordination
0.7–0.8	8	Intermediate coordination
0.8–0.9	9	Good coordination
0.9–1.0	10	High-quality coordination

3. Results

3.1. Comprehensive Development Index Analysis of Agricultural Modernization and Black Soil Conservation and Utilization

The comprehensive development index of agricultural modernization and black soil conservation and utilization in Heilongjiang Province was calculated according to Formulas (1)–(8) (Tables 3 and 4). From the perspective of the province's overall development, the level of agricultural modernization in Heilongjiang was generally lower than that of black soil conservation and utilization from 2011 to 2021. This is mainly due to the fact that the comprehensive fertility of black soil in Heilongjiang Province was outstanding among the four provinces in the black soil region of the Northeast Plains prior to reclamation in 1963. Although extensive management and utilization over several decades caused significant damage to the black soil, the pH value, plow layer thickness, organic matter, and the unit content of trace elements in most black soil areas of Heilongjiang remain in relatively favorable ranges. However, agricultural modernization has developed more slowly.

Table 3. Comprehensive development evaluation indicators for agricultural modernization in various regions of Heilongjiang Province.

Region	2011	2013	2015	2017	2019	2021	Average
Harbin	0.656	0.693	0.677	0.680	0.544	0.642	0.649
Qiqihar	0.505	0.543	0.560	0.557	0.545	0.578	0.548
Jixi	0.163	0.180	0.185	0.181	0.171	0.223	0.184
Hegang	0.079	0.073	0.074	0.074	0.081	0.111	0.082
Shuangyashan	0.133	0.140	0.130	0.124	0.128	0.175	0.138
Daqing	0.335	0.350	0.380	0.302	0.299	0.372	0.340
Yichun	0.073	0.078	0.078	0.072	0.071	0.081	0.076
Jiamusi	0.266	0.274	0.281	0.274	0.293	0.359	0.291
Qitaihe	0.067	0.072	0.075	0.098	0.086	0.088	0.081
Mudanjiang	0.292	0.312	0.344	0.371	0.320	0.384	0.337
Heihe	0.177	0.182	0.185	0.186	0.199	0.244	0.196
Suihua	0.461	0.505	0.518	0.522	0.514	0.560	0.513
Daxinganling	0.053	0.053	0.057	0.051	0.041	0.041	0.049
Average	0.251	0.266	0.273	0.269	0.253	0.297	0.268

As shown in Table 3, over time, the overall comprehensive index of agricultural modernization in various regions of Heilongjiang Province has trended upward with some fluctuations. In 2019, the overall mean index dropped significantly; only Hegang, Jiamusi, and Heihe saw an increase instead of a decrease. In most cities where the index decreased in 2019, there was a substantial rebound in 2021, surpassing the pre-2019 indices; however, Harbin experienced the largest decline in 2019 and did fully recovered to the pre-2019 level by 2021. This may be related to the rapid rate of soil acidification and severe soil erosion in Harbin in recent years. In 2019, most production areas in Heilongjiang were significantly affected by factors such as low temperatures, low light, and heavy rainfall during the crop-growing season. The average yield per unit area of soybeans and corn decreased by 20–30%, which was the main reason for the overall decline in the agricultural modernization index of Heilongjiang Province in 2019.

Table 4. Comprehensive development index of black soil protection and utilization in various regions of Heilongjiang Province.

Region	2011	2013	2015	2017	2019	2021	Average
Harbin	0.716	0.707	0.700	0.692	0.683	0.674	0.695
Qiqihar	0.696	0.690	0.685	0.681	0.675	0.674	0.684
Jixi	0.447	0.444	0.439	0.437	0.433	0.433	0.439
Hegang	0.404	0.402	0.399	0.385	0.384	0.386	0.393
Shuangyashan	0.460	0.451	0.444	0.438	0.431	0.426	0.442
Daqing	0.766	0.764	0.756	0.754	0.746	0.740	0.754
Yichun	0.261	0.259	0.257	0.253	0.253	0.252	0.256
Jiamusi	0.414	0.469	0.405	0.400	0.395	0.390	0.412
Qitaihe	0.247	0.247	0.241	0.240	0.236	0.232	0.241
Mudanjiang	0.188	0.185	0.184	0.182	0.179	0.178	0.183
Heihe	0.515	0.512	0.510	0.506	0.504	0.500	0.508
Suihua	0.841	0.834	0.828	0.819	0.811	0.803	0.823
Daxinganling	0.408	0.410	0.406	0.404	0.404	0.403	0.406
Average	0.489	0.490	0.481	0.476	0.472	0.469	0.479

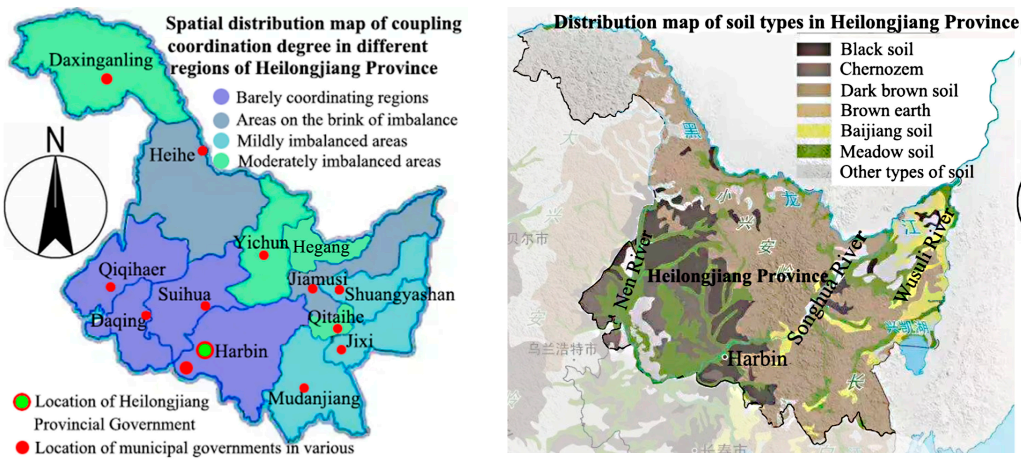
Table 4 displays the overall comprehensive development evaluation index of black soil conservation and utilization in Heilongjiang Province, which declined slowly from 2011 to 2021. This may be related to soil acidification, the thinning of cultivated soil layers, and a continuous decrease in organic matter content in black soil layers. The difference in the magnitude of this decrease led to varying impacts on the protection and utilization of black soil.

From a spatial layout perspective, there were significant differences in the development levels of agricultural modernization and black soil conservation and utilization among prefecture-level cities in Heilongjiang Province from 2011 to 2021. The Heilongjiang region was separated into two parts per its geographical distribution: the southwest and the northeast. The southwest includes Harbin, Suihua, Qiqihar, and Daqing, covering the central and eastern parts of the Songnen Plains and the western part of the province. The northeast includes Jixi, Hegang, Shuangyashan, and Yichun, covering the Sanjiang Plains.

Cities with a high level of agricultural modernization, according to the comprehensive evaluation index for this aspect, are distributed in the southwest of Heilongjiang Province. These are traditional agricultural regions with a solid agricultural foundation. Areas such as Yichun, Shuangyashan, and Qitaihe, conversely, are part of the development zone for the forest-based economy and old industrial bases; they are less cultivated and have lower agricultural modernization development levels than elsewhere in the province.

The spatial layout of the black soil conservation and utilization development level is similar, with an evident trend of polarization across Harbin. The comprehensive development level is significantly lower in cities such as Shuangyashan and Qitaihe than in Harbin, as it is the provincial capital and the center of economic development in the entire province, thus exerting a trickle-down effect on the surrounding cities. From a spatial layout perspective, there are significant differences in the development levels of both agricultural modernization and black soil conservation and utilization among prefecture-level cities in Heilongjiang Province from 2011 to 2021.

The three regions of Qiqihar, Daqing, and Suihua, which exhibit the highest indices for agricultural modernization as well as black soil protection and utilization, are mainly covered with black soil, black calcareous soil, and meadow soil. However, most of the cultivated land in Harbin features dark brown soil, as illustrated in Figure 2. The spatial distribution of these comprehensive evaluation indices can be attributed to Harbin's dominance as the provincial capital city. The distribution of these indices in various regions of Heilongjiang can also be attributed to the soil types in each region (Figure 2).



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

Figure 2. (**a**) Spatial distribution map of black soil types of Heilongjiang Province; (**b**) coupling coordination degree in various regions.

3.2. Analysis of Coupling Coordination Degree between Agricultural Modernization and Black Soil Protection and Utilization

The coupling coordination of agricultural modernization and black soil protection and utilization in various regions of Heilongjiang Province was calculated according to Formulas (9)–(11). The results are shown in Table 5. The coordination degree between agricultural modernization and black land protection and utilization in various parts of the province fluctuated slightly from 2011 to 2021, with an overall upward trend. The degree of coupling between these two systems also appears to be slowly increasing, which is likely attributable to the mutual promotion and interaction between them; their relationship is actively developing under the influence of policy incentives and operational mechanisms.

Table 5. Coupling coordination degree of agricultural modernization and conservation and utilization of black soil in the main grain production areas of Heilongjiang Province.

Region	2011	2013	2015	2017	2019	2021	Comprehensive Value	Coupling Coordination Type
Harbin	0.585	0.592	0.586	0.586	0.552	0.574	0.579	Barely coordination
Qiqihar	0.544	0.553	0.556	0.555	0.551	0.559	0.553	Barely coordination
Jixi	0.366	0.376	0.378	0.375	0.369	0.394	0.376	Mild imbalance
Hegang	0.299	0.293	0.293	0.291	0.297	0.322	0.299	Moderate imbalance
Shuangyashan	0.352	0.355	0.347	0.341	0.343	0.369	0.351	Mild imbalance
Daqing	0.503	0.509	0.517	0.488	0.486	0.512	0.503	Barely coordination
Yichun	0.263	0.266	0.266	0.260	0.258	0.268	0.264	Moderate imbalance
Jiamusi	0.407	0.409	0.411	0.407	0.412	0.433	0.413	On the verge of imbalance
Qitaihe	0.254	0.258	0.260	0.277	0.267	0.267	0.264	Moderate imbalance

Table 5. *Cont.*

Region	2011	2013	2015	2017	2019	2021	Comprehensive Value	Coupling Coordination Type
Mudanjiang	0.342	0.346	0.355	0.360	0.346	0.362	0.352	Mild imbalance
Heihe	0.399	0.391	0.392	0.392	0.398	0.418	0.398	Mild imbalance
Suihua	0.558	0.570	0.572	0.572	0.568	0.579	0.570	Barely coordination
Daxinganling	0.272	0.272	0.276	0.268	0.254	0.254	0.266	Moderate imbalance
Comprehensive value	0.396	0.400	0.400	0.400	0.392	0.409	0.399	Mild imbalance

As shown in Table 5, from 2011 to 2021, the coupling coordination degree of agricultural modernization and black land protection and utilization in Heilongjiang Province has generally trended upward with some slight fluctuations. There were variations in coupling coordination levels across different cities. Harbin, Qiqihar, Daqing, and Suihua demonstrated low coordination levels, and Jiamusi was on the verge of imbalance. Jixi, Shuangyashan, Mudanjiang, and Heihe were mildly imbalanced, while Yichun, Qitaihe, Daxing'anling, and Hegang were moderately imbalanced, as illustrated in Figure 1.

From a spatial layout perspective, the degree of coupling between agricultural modernization and black soil conservation and utilization in various prefecture-level cities fluctuated between 2011 and 2021, mainly increasing over time. Harbin exhibited stable growth from 2011 to 2017, but experienced a significant decline in 2019, followed by a substantial rebound in 2021, as shown in Table 5. These fluctuations can be attributed to Harbin's particular agricultural development strategy. The city increased fiscal expenditures on farmland water affairs with the support of the National Farmland Irrigation Construction Project, which led to expansion of the rice cultivation area and rational planning of farmlands, ultimately raising the level of agricultural modernization. Simultaneously, the establishment of agricultural machinery cooperatives, the creation of green food industrial parks, and the development of high-quality cultivation techniques provided ample support for agricultural modernization, satisfying diverse needs for its development and promoting progress in this regard.

The coupling development between agricultural modernization and black soil conservation and utilization appears to be closely linked to factors such as agricultural input, agricultural development planning, and the dissemination of advanced technology. During the study period, in the southwestern part of Heilongjiang Province, areas such as Harbin, Suihua, Qiqihar, and Daqing exhibited fluctuating upward trends in the coupling degree between the two systems. These areas are located in the Songnen Plains, which is a crucial national grain production area. Bolstered by geographical advantages and a national rural revitalization strategy, these cities have vigorously promoted the construction of high-standard demonstration fields, mechanized production, and innovation in new types of operational entities. Leveraging the funds, talents, and technology brought about by agricultural modernization, they have accelerated the transformation of agricultural management methods and technological innovation.

In terms of black soil conservation and utilization, economic development enhanced farmers' awareness of wealth accumulation, increased their enthusiasm for learning modern agricultural technology and management techniques, expanded the integration space between black soil conservation and utilization, and promoted agricultural modernization development, thereby maintaining a stable coupling degree between the two systems.

The coupling coordination degree between agricultural modernization and black soil protection and utilization in various prefecture-level cities in Heilongjiang Province exhibits differentiated characteristics. From 2011 to 2021, the coupling coordination degree of the Yichun, Qitaihe, Daxing'anling, and Hegang regions was less than 0.300; the two systems were in a moderately imbalanced state. The comprehensive development index suggests that agricultural modernization development lagged significantly behind black soil protection and utilization in these regions, and that agricultural modernization was significantly lower in those regions compared to the rest of the province. This can be attributed to an abundance of mineral resources, particularly coal, in Qitaihe, making it a city centered on coal electricity integration. Yichun and Daxing'anling are renowned as "forest oxygen bars", making them forestry-resource-based areas. Consequently, these three regions have weaker agricultural resources, lower comprehensive agricultural output, and lower agricultural production inputs than the rest of the province, leading to a lack of positive coordination between agricultural modernization and black soil protection and utilization.

Areas like Jixi, Shuangyashan, Mudanjiang, and Heihe also face limitations imposed by local natural resources. These areas have emphasized the revitalization of old industrial bases and forest conservation efforts, placing their coupling coordination levels in mild imbalance. Similarly situated in a coal electricity integration area, Jiamusi has established farmer cooperatives, leveraging the role of new business entities and demonstration bases for "reduce fertilizer, reduce pesticides, and reduce herbicides" policies, enhancing the positive coupling relationship between agricultural modernization and black soil protection and utilization.

3.3. Coordinated Development Model between Agricultural Modernization and Black Soil Protection and Utilization

The coupling degree between agricultural modernization and the development of black soil protection and utilization in Heilongjiang Province is poor based on the comprehensive coupling degree of 0.399, and the two entities are in a state of mild imbalance. Based on the empirical results discussed above and the particular regional characteristics, rural revitalization policies, and agricultural technology levels of the study area, we established a coordinated development model between agricultural modernization and black land protection and utilization, as depicted in Figure 3. This model may assist in promoting the coordinated development of agricultural modernization and black soil protection and utilization in Heilongjiang Province and in furthering rural revitalization across the province.

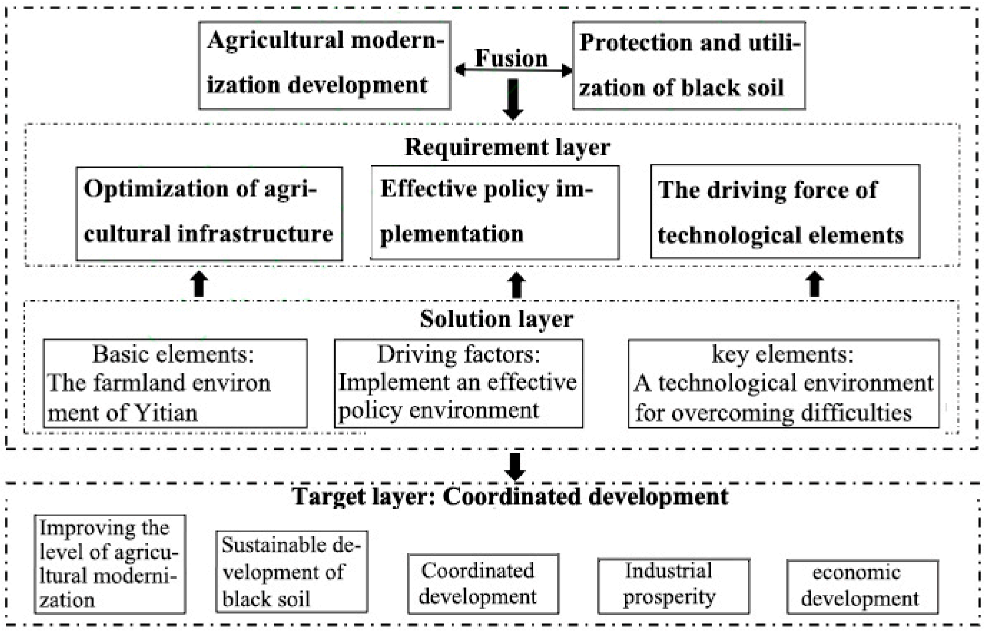


Figure 3. Coordinated development model of agricultural modernization and black soil protection and utilization.

3.3.1. Suitable Farmland Environment as a Basis for Coordinated Development

Considering the unique climatic conditions and topography of Heilongjiang Province, relevant departments may be most effective by focusing on optimizing the farmland cultivation environment across three key levels. Firstly, controlling soil erosion and repairing erosion ditches should be prioritized. Soil erosion in Heilongjiang is dominated by water erosion and wind erosion, with the water erosion area accounting for approximately 80% and wind erosion for about 20%. Both types of erosion will lead to the thinning of the cultivated soil layer and a reduction in black soil organic matter. Water erosion will also cause the siltation of downstream rivers and reservoirs, weakening the region's flood control and drought resistance capabilities. As mentioned above, the total amount of black soil erosion in Heilongjiang Province has reached 200–300 million m^3 per year. At this rate, the black soil layer of existing farmlands will be completely eroded within 40–50 years [8]. It is crucial to promote conservation tillage, non-tillage, reduced tillage, and the mulching of the surface with straw, which can not only mitigate wind erosion and water erosion but also enhance the soil's moisture retention capacity. Straw can also be converted into organic matter after natural decomposition in summer months, yielding environmental benefits.

With 115,500 water-eroded gullies covering a total length of 45,000 km and an area of nearly 93,000 hectares in Heilongjiang Province (Figure 4), addressing erosion ditches promptly is a crucial consideration. This consolidation of land can facilitate improved efficiency in the large-scale operation of agricultural machinery.

(**a**)

(**b**)

Figure 4. (**a**) Erosion ditch processing in Heilongjiang Province; (**b**) processed erosion ditches.

It is also imperative to implement fertilizer reduction and greenery enhancement measures while improving agricultural electricity facilities. The improper usage of chemical fertilizers not only kills the humus in black soil, leading to its degradation, but also leads to soil acidification, disrupting the soil's structure and biological activity. Therefore, adopting a scientific and judicious fertilizer application approach, with a combination of chemical and organic fertilizers, is essential to mitigate soil acidification and hardening. Actively promoting the efficient ecological recycling agriculture model and strengthening the protection and restoration of agricultural ecology are critically important as well. Electricity usage in remote agricultural areas is necessary to power both agricultural production and the daily living needs of farmers while reducing the dependence on coal.

Furthermore, improving irrigation projects and expanding the area of effective irrigation are important measures. Heilongjiang has abundant water resources, but they are unevenly distributed and have substantial seasonal variations. While China's effective irrigated area accounts for about 54% of the country's cultivated land, Heilongjiang Province's effective irrigated area accounts for only 37% of the province's cultivated land. Heilongjiang's provincial government should focus on improving irrigation project facilities and long-term management and protection systems, improving the management of water conservation services at the grassroots level, ensuring the long-term efficient operation of irrigation projects and improving the effective irrigation rate.

Heilongjiang Province should initiate comprehensive farmland environment development policies to establish a fertile soil layer in an ecologically sound and disaster-resistant manner. Constructing high-quality farmlands that are compatible with modern agricultural production and management methods will be essential for ensuring stable incomes during drought and flood periods, thereby forming a well-equipped foundation for the coordinated development of agricultural modernization and the protection and utilization of black soil.

3.3.2. Implementation of Effective Policy Environment: Driving Factor for Coordinated Development

In light of the development status of agricultural modernization and black soil protection and utilization in Heilongjiang Province, the Heilongjiang provincial government should optimize the policy environment through two key aspects. Firstly, policies should be implemented to guide farmers in improving the planting structure of grain crops. The crops currently grown in Heilongjiang Province include rice, wheat, corn, millet, sorghum, soybean, potato, rapeseed, sunflower seed, and white melon seed, covering the sown areas depicted in Figure 5. Rice, corn, and soybeans dominated the planting area in Heilongjiang Province in 2021, creating an effectually singular planting structure; long-term single planting structures lead to frequent occurrences of pests and diseases, decreased soil fertility, and negative effects such as soil acidification. Therefore, it is essential to ensure a reasonable rotation of multiple crops.

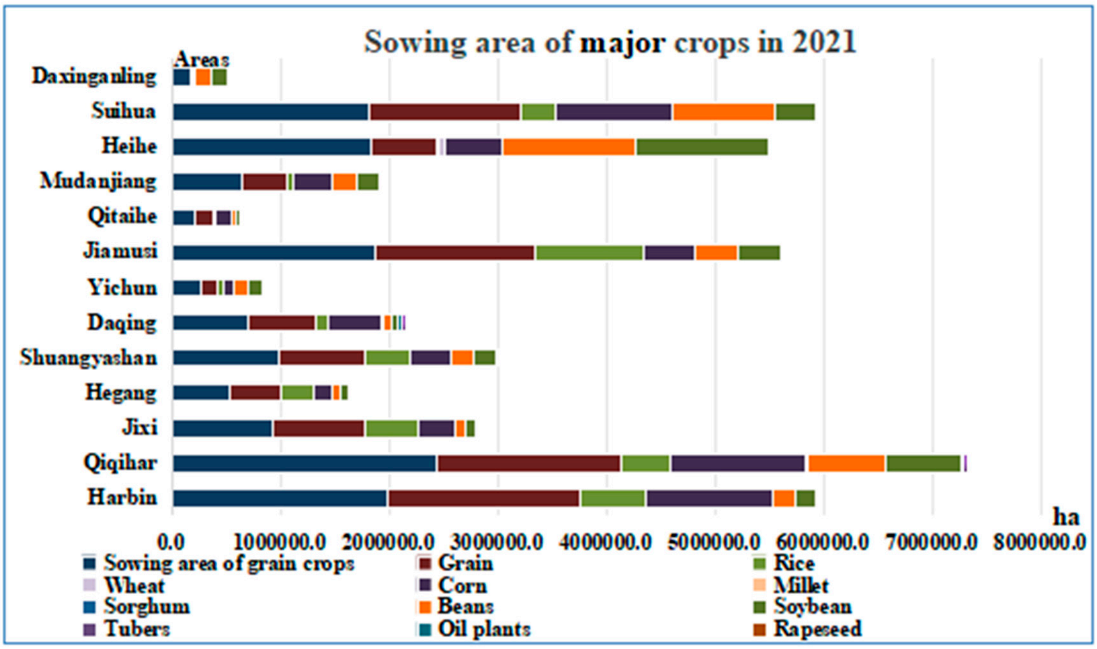


Figure 5. Sowing area of main crops in various regions of Heilongjiang Province in 2021.

Heilongjiang's provincial government would also do well to continue promoting the structural reform of its agricultural supply, increase the differentiated subsidies for crop-planting and crop rotation subsidies, and intervene in the crop-planting categories selected by farmers. Regulating agricultural production and improving agricultural efficiency would promote the coordinated development of agricultural modernization and black soil protection and utilization.

Additionally, it is imperative to establish land policies and regulations dedicated to the safeguarding of black soil in Heilongjiang Province. Given the weak rural economic foundation of the province, there is a substantial impact on the enthusiasm (and incomes) of rural residents in terms of changes to the cultivation and utilization of farmlands. To address this, land policies and regulations to protect farmlands must be formulated. These may include policies related to land contracts, land use planning, cultivated land rotation, and wetland and grassland protection, among others. Simultaneously, the formulation of laws and regulations to strictly supervise and penalize the theft and pollution of black soil is imperative. By implementing scientific planning and the regulation of land use, the agricultural ecological environment in Heilongjiang Province can be effectively preserved.

3.3.3. Technological Environment As a Key Element of Coordinated Development

It is necessary to provide targeted science and technology to conserve Heilongjiang's black soil, considering the unique resources and environmental characteristics of the province. Focused efforts by relevant departments will be essential and should target three key levels. Firstly, addressing challenges in soil erosion is paramount. Soil erosion poses a major problem in regard to the coordinated development of agricultural modernization and black soil protection and utilization. Central and local scientific research departments can collaborate to address specific technological challenges related to controlling soil erosion. Establishing erosion-monitoring stations across various regions would assist in better understanding the province's soil migration and sedimentation patterns so that erosion control technologies can be developed in response.

Secondly, there is a need for research into and the development of high-quality agricultural machinery. The current shortage of effective machinery supply for promoting tillage reform merits careful attention. Beyond the existing non-tillage seeder, there is a lack of machinery to support other operational links and technical models. The agricultural machinery industry should prioritize the development of equipment specific to non-tillage, reduced tillage, strip tillage, ridge cropping, straw mulching, and cover planting tasks. This would include accelerating the production of advanced and practical machinery to facilitate the widespread adoption of corn straw mulching and tillage reduction technologies.

Thirdly, it is important to research, develop, and promote modern water-saving irrigation technologies in Heilongjiang Province. Emphasizing intelligence and informatization, irrigation projects should be constructed based on local conditions. For example, promoting water-saving projects such as a low-pressure pipeline water delivery system and sprinkler irrigation for field crops, along with the usage of drip irrigation and micro-sprinkler irrigation systems, are advisable.

4. Discussion

The protection and utilization of black soil, coupled with the development of agricultural modernization, have been significant events in China's recent agricultural development advancement. This study integrated the comprehensive development indices of agricultural modernization and black soil protection and utilization to identify factors impeding their coordinated development. The goal was to formulate targeted strategies for harmonizing these two systems effectively. By analyzing pertinent data from 13 regions in Heilongjiang Province, the following conclusions were drawn.

Firstly, the comprehensive development index of black land protection and utilization is 0.479, and the comprehensive development index of agricultural modernization is 0.268. However, the agricultural modernization development index shows a fluctuating upward trend, while the comprehensive index of black soil protection and utilization exhibits a slow decline.

Secondly, the average coupling degree of agricultural modernization and black soil protection and utilization in various regions of Heilongjiang is 0.399, indicating a mild imbalance. The overall coordination pattern mirrors the trends in agricultural modernization and black soil protection and utilization, with high-value areas concentrated in the Songnen Plains region and relatively lower coordination in the Sanjiang Plains region.

Thirdly, there are considerable regional disparities in the development of agricultural modernization and black soil protection and utilization across Heilongjiang. Most prefecture-level cities lag significantly behind Harbin, resulting in an overall imbalance across the province.

Considering the complexity between agricultural modernization and the protection and utilization of black soil, policy makers and agricultural practitioners should adopt various intervention strategies to create a conducive farmland environment, effective policy environment, and advanced technological environment, and to promote coordinated development between the two from multiple perspectives.

First, the government and society must vigorously build the agricultural environment and promote the specific forms and requirements needed to protect the agricultural environment because building high-standard farmland that is compatible with modern agricultural production is the foundation for the coordinated development of the two.

Second, the government should effectively promote the supply side of the structural reform of agriculture, intervene in crop-planting categories for farmers, and formulate land policies and regulations to protect black land, which is an effective driving factor for promoting coordinated development between the two.

Third, given the unique agricultural resources and environment of Heilongjiang, technological assistance in protecting black soil is a key element for the coordinated development of the two.

Given these findings, it is recommended that relevant departments undertake long-term monitoring of black soil protection and utilization in each region of Heilongjiang Province. This should involve analyzing imbalances, identifying weaknesses, and leveraging agricultural modernization technologies to elevate the level of black soil protection and utilization, which would contribute to the holistic development of agricultural modernization.

5. Conclusions

Currently, China's agricultural modernization is entering a phase of high-quality development. The black soil region in the Northeast Plains of China, as a representative major grain-producing area, is closely tied to the high-quality development of agricultural modernization and the country's rural revitalization goals. However, these areas face challenges such as soil erosion, soil acidification, declining fertility, and shallower soil layers during the development process, underscoring the need for sustainable utilization of black soil.

Previous research has tended to overlook the comprehensive evaluation of coupling coordination between agricultural modernization and black soil protection and utilization. There is a lack of empirical analyses and strategic discussions on both fronts. To fill this gap, a comprehensive evaluation index calculation and coupling coordination evaluation model for agricultural modernization and black soil protection and utilization was developed in the present study. Based on original data from various regions of Heilongjiang Province, an empirical analysis was conducted to examine the current coupling coordination status of the development of agricultural modernization and black soil protection and utilization. The findings may contribute to a clearer understanding of this status overall. The proposed model for the coordinated development of agricultural modernization and black soil protection and utilization may help in addressing fundamental issues in the comprehensive development of black soil protection and utilization in Heilongjiang Province, which may, in turn, facilitate improvements to the quality and efficiency of agricultural economy and achieving rural revitalization.

Data were gathered from 13 prefecture-level cities in Heilongjiang Province through an empirical case study. The comprehensive development level and coupling coordination degree of agricultural modernization and black soil protection and utilization were measured accordingly. Due to limitations in data acquisition, county-level cities and regions within Heilongjiang Province were not included, resulting in certain limitations. Future research endeavors could involve innovative methods for a more systematic and in-depth exploration of the coordinated development model between agricultural modernization and land protection and utilization. This approach would enrich the literature related to agricultural economies and make valuable contributions to regional agricultural economic development.

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