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Spatiotemporal Patterns in and Key Influences on Cultivated-Land Multi-Functionality in Northeast China's Black-Soil Region

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Abstract: Cultivated-land multi-functionality has become an important way to achieve sustainable cultivated-land protection, and it has become a hot spot in the field of land-management policy. Taking the cultivated black soils in the grain-producing area of Jilin Province, Northeast China, as a case study, this paper assessed the multi-functions of cultivated land over the past 30 years by applying the improved TOPSIS model. Furthermore, the key limiting factors and influencing factors of the multi-functions of cultivated land were identified through the obstacle-degree model and the Geo-detector. The results show that the level of multi-functionality rose from 1990 to 2020, but an increase in both economic and social functions hindered improvements in the ecological function of cultivated land. There were obvious spatial differences in the functions of cultivated land in different counties, with ecological functions showing the highest degree of differentiation, followed by social and economic functions. The per capita agricultural output, the degree of agricultural mechanization, the average output from cultivated land, and the agricultural-labor productivity had the most restrictive effects on the functions of cultivated land, with barrier-degree values of 15.90, 13.90, 11.76, and 10.30, respectively. Coupling–coordination in the multi-functions and sub-functions of cultivated land showed an upward trend, from "low coupling coordination–antagonistic coupling coordination" to "high coupling coordination-optimal coupling coordination". The government should include the level of multi-functional utilization in future policies for the management and utilization of cultivated land and take measures to reduce the differences in the functions of cultivated land among regions. Quantifying the multi-functional value of cultivated land and subsidizing land cultivation should encourage farmers to protect the land and help to strengthen multi-functional planning and functional design, improve ecological utilization, and promote the sustainable use of cultivated land.

Keywords: multi-functionality of cultivated land; breadbasket; spatiotemporal variation; coupling–coordination degree; influencing factors

Citation: Gong, H.; Zhao, Z.; Chang, L.; Li, G.; Li, Y.; Li, Y. Spatiotemporal Patterns in and Key Influences on Cultivated-Land Multi-Functionality in Northeast China's Black-Soil Region. *Land* **2022**, *11*, 1101. https://doi.org/10.3390/land11071101

Academic Editors: Li Ma, Yingnan Zhang, Muye Gan and Zhengying Shan

Received: 8 June 2022
Accepted: 14 July 2022
Published: 19 July 2022

1. Introduction

As a scarce and non-renewable resource, cultivated land provides many essential products and services for human society [1–3]. With the development of more urbanized societies and economies, cultivated land is not just limited to the traditional function of supplying food products but also carries many other non-productive functions, such as an economic-return function, a social-security function, an ecological function, and a landscape function [4–6]. However, the different functions of cultivated land have not been paid enough attention to in the utilization and management of cultivated land, which makes the contradiction between the supply and demand of cultivated-land functions and eventually leads to the occurrence of unsustainable conditions such as cultivated-land degradation, non-grain cultivation, and abandonment [7–9]. The future expansion of cultivated-land production is likely to encounter a complex situation of competing demands and trade-offs [10]. Effective measures must be taken to balance the supply and demand of multi-functional cultivated land [11,12]. This requires in-depth knowledge of the level and changing characteristics of cultivated-land functionality and the factors influencing them to provide scientific support for the sustainable utilization and protection of cultivated land.

Multi-functional research originates from studies of agricultural multi-functionality [13], referring to the fact that, in addition to food production, agriculture also has a role in ecological services, landscape maintenance, employment security, and cultural heritage [14,15]. However, because of the differences in the types of crops grown and the responsibilities between cultivated land and agriculture, the multi-functionality of cultivated land expands the implications of economic, social, and ecological functions based on agricultural multi-functionality [16]. Particularly in the context of family-based agricultural production in China (a household-responsibility system), cultivated land has many participants who need to produce food to ensure food security, and the connotations of multi-functional cultivated land are rich and complex [17,18].

Quantitative evaluation is key to the study of multi-functional cultivated land and has been applied since the implementation of the Land Use and Land Cover Change (LUCC) program [19]. Currently, research is centered on two main aspects: evaluating a single function of cultivated land and a more comprehensive evaluation of the multi-functionality of cultivated land. The former includes the social value of cultivated land [20], and ecological [21] and monetary compensation [22]. The latter includes spatiotemporal analyses and understanding the driving factors behind the multiple functions of cultivated land [23–26]. However, the emphasis is often on the imbalance of a single function or a specific time point, and it is difficult to effectively trace temporal and spatial variations in the characteristics of cultivated land and its functions. As a result, our understanding of the multi-functionality of cultivated land is still poor. Long-term studies can be used to examine the rates of change over time and test the effectiveness of policies [27], yet there is a lack of long-term research on the multi-functionality of cultivated land. Equally, in terms of research application, the majority of studies focus on analyzing and evaluating the results, and rarely propose measures and policies to improve the function of cultivated land. Currently, the research outputs do not provide any guidance on the actual management of cultivated land, and the focus is usually on developed urbanized areas, where the conflict with cultivated land is more pronounced. Less attention has been paid to the multi-functionality of cultivated land in important grain-producing areas. To improve the shortcomings of existing research, a clear understanding of the historical change in cultivated-land functionality in major grain-producing regions is needed, and the obstacles and driving factors behind the changes in cultivated-land functions need to be identified, so that effective policies can be adopted for the future. The multi-functional utilization of cultivated land should, therefore, become the focus for the protection of cultivated land and the goal of sustainable utilization.

One of the world's major black-soil regions is found in northeast China. This fertile soil represents a key grain-producing area in China, and northeast China is an important exporter of commercial grains. The agricultural functional areas identified in "National Main Functional Area Plan" are also important in maintaining China's food security [28]. However, this region faces serious cropland degradation, including soil-nutrient loss [29], the thinning of the cultivated layer [30], and the loss of soil physicochemical properties. Simultaneously, unfavorable conditions for land cultivation, such as population outflow, low food prices, and reduced agricultural production efficiency, have begun to emerge [25], directly threatening the future sustainable use of cultivated land and the development of the region's economy and society. While these problems have existed across China for some time, they are particularly prominent in the main grain-producing areas. Cultivated land has various functions, but no one is investing in them. The government has not prioritized the issue of multi-functionality and currently lacks effective control measures, which is eroding farmers' rights and interests and reducing their enthusiasm for cultivated-land protection.

Counties represent the smallest unit with complete administrative power in China and are the basic unit for policy formulation and implementation. Carrying out research at the county level could yield direct and targeted suggestions for formulating practical and effective cultivated-land-use policies. Breadbaskets are the core unit for grain production in China's major grain-producing areas and are also important county-level units for cultivated-land management, making the black-soil region ideal for multi-functional research. Considering the research gaps highlighted above, this study used the breadbaskets in Jilin Province, in the hinterland of Northeast China, as a research area to evaluate the multi-functionality of cultivated land, analyze the obstacles to and driving factors behind the multi-functionality, and ultimately put forward suggestions for improving the multi-functionality of cultivated land. An improved Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) model was used to evaluate the multi-functionality of cultivated land in the breadbaskets in 1990, 2000, 2010, and 2020. An obstacle-degree model was then used to determine the key obstacles limiting the functionality of the cultivated land. Geographic detectors were used to analyze the main factors changing cultivated-land functions. Finally, based on the analyses, effective measures to improve the multi-functional utilization of cultivated land in this area are proposed as a reference point for future developments.

2. Materials and Methods

2.1. Study Area

The study area was located in the geographic geometric center of Northeast Asia, spanning from 121°38′ to 131°19 ′ E and from 40°50′ to 46°19 ′ N, and is known as "Hometown of Black Soil", representing one of the world's three major black-soil belts. The soil in this region is fertile, with a high organic matter content (the average organic matter content being > 27 g/kg) and abundant cultivated-land resources.

The breadbaskets of China are the top-ranked counties based on the proportion of commercial grain output, overall grain production, and area sown for grain, accounting for 50%, 25%, and 25% by weight of all grain produced. In 2009, China's State Council promulgated "National Plan for Newly Increased Grain Production Capacity of 100 Billion catties (2009–2020)", and a total of 800 breadbaskets were identified as the core areas for grain production across the country. The breadbaskets chosen for this study were located in Jilin Province, northeast China (Figure 1); in total, 28 research units were represented and nine prefecture-level cities, including Changchun, Jilin, and Siping, for a total land area of 118,259.42 km^2. Together, the breadbaskets account for 78.25% of the cultivated land in Jilin Province and contribute 89.7% of the province's grain output. However, while this area has made significant contributions to national and regional food security, its economic and social development faces serious challenges. It is the most important grain-production base in China, but over the last 10 years the population of the study area fell by an astonishing 25.08%, twice the overall rate for Jilin Province. Over the last 10 years, the gross domestic product (GDP) decreased by 10.54%, and the per capita income decreased by 3%. In contrast, over the same time period China's GDP and per capita income considerably grew, by 146.53% and 133.05%, respectively. The problems highlighted in this region are prevalent in many major grain-producing regions in the country; this study, therefore, can provide a reference point for similar regions.

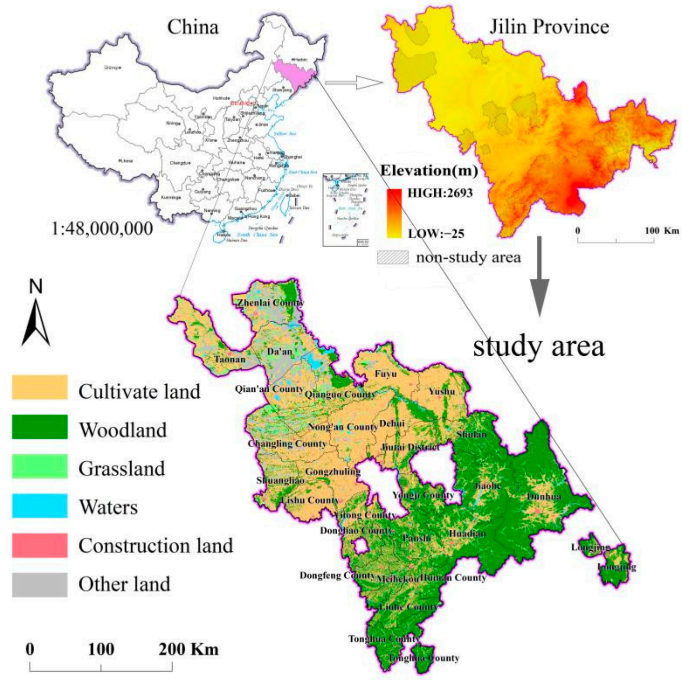

Figure 1. The location and main land types in the black-soil breadbaskets in Jilin Province, Northeast China (The map of China in the figure is produced under the supervision of the Ministry of Natural Resources of the People's Republic of China, drawing number: GS (2019) No. 1673).

2.2. Data Collection and Pre-Processing

The details of the data used for the study are presented in Table 1. The Gauss–Kruger projection and 2000 National Geodetic Coordinate System (CGCS2000) were used, and the scale was unified to counties.

Table 1. Descriptions of the data sources.

Data Type	Data Source	Time Series	Resolution
Land use/land cover	Resource and Environment Science Data Center, Chinese Academy of Sciences	1990, 2000, 2010, 2020	30 m × 30 m
River and road data	Extracted from land-use and -cover data from Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences	1990, 2000, 2010, 2020	Same as land-use/land-cover data
Digital elevation model (DEM)	Geospatial Data Cloud (http://www.gscloud.cn/, accessed on 21 December 2021)	2009	30 m × 30 m
Slope	Calculated from DEM data	2009	30 m × 30 m
Meteorological	Meteorological Data Center, China Meteorological Administration	1990, 2000, 2010, 2020	Site
Socioeconomic	Jilin and counties (cities) statistical yearbooks	1990, 2000, 2010, 2020	County level
Agricultural	Jilin rural statistical yearbooks	1990, 2000, 2010, 2020	County level
Cultivated-land quality	Agricultural-land grading and projections	2009, 2019	1:100,000

2.3. Methods

2.3.1. Classification and Quantification of the Multi-Functional Value of Cultivated Land

The varied classification criteria used for cultivated-land functions can be grouped into three main categories: economic, social, and ecological (Figure 2).

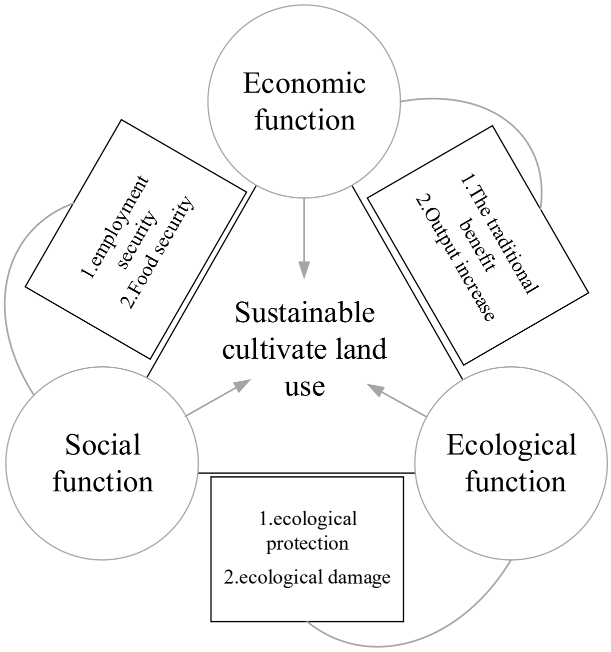

Figure 2. A classification framework for the functions of cultivated land.

However, because of the differential development of human societies and different research areas, the functions of cultivated land and the strength of each function vary significantly, and the selection of indicators for a particular project must adhere to the principles of correlation and availability [31]. Table 2 presents a summary of the indicators chosen for this study.

Table 2. Indices for assessing cultivated-land functions. The overall per capita grain demand was determined as 400 kg per person per year [32]; the safety standard for chemical-fertilizer application followed the international chemical fertilizer application safety standard of 225 kg per hectare [33]; the degree of fragmentation of cultivated land was represented by the ratio of the number of cultivated-land patches to defined area, which was calculated based on an ArcGIS platform; the ecological value of cultivated land was calculated by referring to the ecological service value coefficient table compiled by Xie et al. [34].

Function	Indicator	Calculation Method	Unit	Trend	Weight
Economic	Average grain output	Grain production/Cultivated-land area	kg/hm^2	Positive	0.0422
	Average output of cultivated land	Output value of primary industry/Cultivated-land area	Ten thousand CNY/hm^2	Positive	0.1034
	Percentage of cultivated-land value	Gross plantation output/Gross regional product	Dimensionless	Positive	0.0701
	Agricultural-labor productivity	Output value of primary industry/Employees of primary industry	CNY/person	Positive	0.1003
	Per capita agricultural output	Gross agricultural output/Total population	CNY/person	Positive	0.1208

Table 2. *Cont.*

Function	Indicator	Calculation Method	Unit	Trend	Weight
Social	Per capita cultivated land	Cultivated-land area/Total population	hm^2/person	Positive	0.0394
	Grain commodification index	Grain production/(Per capita grain demand × Population)	Dimensionless	Positive	0.078
	Per capita grain production	Total grain production/Total population	kg/person	Positive	0.078
	Degree of agricultural mechanization	Total power of agricultural machinery/Cultivated-land area	kW/hm^2	Negative	0.0976
	Labor-transfer index	Non-agricultural population/Total population	Dimensionless	Positive	0.0284
Ecological	Fertilizer-use-intensity index	The total amount of fertilizer applied on the ground/Safety standard for fertilizer use	Dimensionless	Negative	0.013
	Production-value energy consumption	Agricultural electricity consumption/Gross agricultural output value	kW/CNY 10,000	Negative	0.007
	Effective-irrigation index	Effective irrigated cultivated-land area/Cultivated-land area	Dimensionless	Positive	0.0689
	Fragmentation of cultivated land	Parameter calculation	Dimensionless	Negative	0.0306
	Proportional ecological value of cultivated land	Ecological service value of cultivated-land area/Ecological service value of total land area	Dimensionless	Positive	0.0737
	Land-reclamation coefficient	Cultivated-land area/Total land area	Dimensionless	Positive	0.0486

The grain output of an area of land represents the traditional grain yield of cultivated land. As well as this, the economic function should also consider the increase in output value generated by cultivating the land, based on the average rate of rural-labor output and the value of the per capita agricultural output. The social function includes employment security for the local farmers and food security. The function of food security can be further divided into two types: intra-regional and extra-regional guarantees, which are expressed as per capita grain output and the grain-commercialization index, respectively. The per capita cultivated-land area, the degree of agricultural mechanization, and the labor-transfer index represent the employment-security function of cultivated land.

Cultivated land is also a part of an ecosystem and has an ecological function. Cultivated land has a positive effect on the ecological needs of human beings and supports biodiversity but can also have a negative impact on the environment if used unsympathetically. Positive effects can be quantified by the proportional ecological value of cultivated land, the effective-irrigation index, and the coefficient of land reclamation. The proportional land ecological value is calculated from the ecological-service-value coefficient [34], which reflects the ecological contribution of cultivated-land systems in all ecosystems and is an important indicator reflecting the basic ecological attributes of cultivated land. Negative effects mainly include the overuse of pesticides, an increase in agricultural energy consumption, and the fragmentation of cultivated land as a result of overuse. These are quantified using the fertilizer-use-intensity index, energy consumption per CNY ten thousand of output value, and the degree of fragmentation of cultivated land, respectively. The specific calculations used for each index are shown in Table 2.

2.3.2. Calculating the Multi-Functional Utilization of Cultivated Land and Determining any Obstacles

An improved TOPSIS ("the distance method between superior and inferior solution") model was used to evaluate the functional value of cultivated land [35]. The TOPSIS model is a commonly used multi-objective decision-making method that considers the advantages and disadvantages of a scheme by determining the distance between the index, and the "positive ideal solution" and "negative ideal solution". If the scheme is close to the "positive ideal solution" and far from the "negative ideal solution", it is superior; the converse means it is inferior. This method not only overcomes the lack of objectivity of, for example, the AHP and Delphi methods, but also the information-loss problem in factor analyses and mutation analyses [36]. TOPSIS models are widely used for decision analyses, environmental assessments, and land evaluations. However, the traditional TOPSIS model does not consider the weights of the indicators, as the weight of each indicator is the same by default. This is inconsistent with real-life situations and widens the difference between the model results and empirical data. In this study, the weight determined with information entropy was used to modify the decision matrix, making the TOPSIS calculations more objective [35]. The specific steps applied were as detailed below.

Step 1: Build a decision matrix. First, the data were normalized, and indicator weights calculated. The range-standardization method was used to eliminate the differences between the dimensions and data levels for each indicator, and the entropy-weight method was used to determine the weight of each indicator (see Table 2 for the calculated weights). Both the range-standardization method and the entropy-weight method are objective and are widely used in statistics, geography, and elsewhere [26,36,37]. When applying the range-standardization method, data translation must be performed to eliminate the interference of extreme values and make the results as accurate as possible. The value of each item of standardized matrix P is then multiplied by its weight vector matrix W to obtain improved decision matrix G:

$$G = P \times W = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1j} \\ p_{21} & p_{22} & \cdots & p_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ p_{i1} & p_{i2} & \cdots & p_{ij} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_i \end{bmatrix} = \begin{bmatrix} p_{11} \times w_1 & p_{12} \times w_1 & \cdots & p_{1j} \times w_1 \\ p_{21} \times w_2 & p_{22} \times w_2 & \cdots & p_{2j} \times w_2 \\ \vdots & \vdots & \ddots & \vdots \\ p_{i1} \times w_i & p_{i2} \times w_i & \cdots & p_{ij} \times w_i \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1j} \\ g_{21} & g_{22} & \cdots & g_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ g_{i1} & g_{i2} & \cdots & g_{ij} \end{bmatrix} \quad (1)$$

where p_{ij} refers to the standardized value of index i in research unit j; w_i refers to the weight of index i; and g_{ij} refers to the improved value of index i in research unit j.

Step 2: Calculate the ideal solution and the ideal value distance. The "positive ideal solution", V_i^+, and "negative ideal solution", V_i^-, of index i in the improved decision matrix were determined, and distances D_j^+ and D_j^- from research unit j to V_i^+ and V_i^- were measured. The closeness of the ideal solution to research unit j, Degree T_j, was calculated as:

$$\begin{aligned} V_i^+ &= \{max g_{ij} | i = 1, 2, \cdots m\} = \{g_1^+, g_2^+, \cdots g_m^+\} \\ V_i^- &= \{min g_{ij} | i = 1, 2, \cdots m\} = \{g_1^-, g_2^-, \cdots g_m^-\} \end{aligned} \quad (2)$$

$$\begin{aligned} D_j^+ &= \sqrt{\sum_{i=1}^{m} (g_{ij} - g_i^+)^2} (i = 1, 2, \cdots m) \\ D_j^- &= \sqrt{\sum_{i=1}^{m} (g_{ij} - g_i^-)^2} (i = 1, 2, \cdots m) \end{aligned} \quad (3)$$

$$T_j = \frac{D^-}{D^- + D^+} (1 \le j \le n) \quad (4)$$

where T_j is the closeness of index j. With $0 \le T_j \le 1$, the larger the value for T_j is, the better the overall effect of the multi-functional evaluation of cultivated land in the region is; conversely, the smaller the value is, the worse the effect is. When T_j is closer to 1, the index is closer to the "positive ideal solution", indicating that the multi-functionality of the cultivated land is optimal, and the multi-functional use of the cultivated land has reached the expected goal. When T_j is closer to 0, the index is closer to the "negative ideal solution", indicating that the multi-functionality of the cultivated land is poor, and the full potential multi-functionality of the cultivated land has not been reached.

Step 3: Determine any obstacles. Based on the multi-functional evaluation, an obstacle-degree model was used to identify any obstacles affecting the multi-functionality of the cultivated land. This can be used as a baseline for the scientific and practical utilization of cultivated land and can improve the feasibility and effectiveness of cultivated-land protection policies and utilization. The obstacle degree was calculated as:

$$O_j = R_{ij} w_j / \left(\sum_{i=1}^{m} R_{ij} w_j \right), R_{ij} = 1 - b_j \quad (5)$$

where O_j is the obstacle degree of cultivated-land function i and index j.

2.3.3. Analysis of the Coupling and Coordination Relationships among Various Sub-Functions of Cultivated Land

A coupling–coordination-degree model was introduced to quantitatively analyze the interactions among various functions of cultivated land and the degree of coupling and coordination among them. Coupling is a physical concept that can describe the strength of an interaction between two or more systems or motions, but it cannot characterize the level of cooperation among systems. The coordination degree makes up for this deficiency by measuring the level of coordinated development among the systems. It is widely used in studies of system relationships among land, economy, and society [37]. The specific steps used were as detailed below.

Step 1: Measure the coupling degree. After standardizing the data, the coupling–coordination degree was measured as:

$$C_t = \sqrt[n]{\prod_{i=1}^{n} Y_m / \left(\sum_{i=1}^{n} Y_m \right)^n} \tag{6}$$

where C_t is the coupling degree in year t. With $0 \leq C_t \leq 1$, the closer the value is to 1, the stronger the interaction between systems is, while the converse is true. Y_m is the comprehensive score of system m, and n is the number of subsystems. When the relationship among three systems is measured, n = 3, and when the relationship between two subsystems is measured, n = 2.

Step 2: Measure the coordination index:

$$T = \sum_{i=1}^{n} \alpha_i Y_m, \sum_{i=1}^{n} \alpha_i = 1 \tag{7}$$

where T is the coordination index and α_i is the weight of subsystem i. When measuring the coupling–coordination degree of each subsystem, the entropy-weight method was used to calculate the weight of each index, and the weight was then calculated [36].

Step 3: Measure the coupling–coordination degree:

$$D = \sqrt{C \times T} \tag{8}$$

where D is the coupling–coordination degree. The higher the coupling–coordination score is, the better the coupling–coordination relationship between the two systems is.

2.3.4. Analysis of the Key Drivers of Multi-Functionality of Cultivated Land

A change in the functionality of cultivated land represents a part of a large, complex system, and the factors influencing cultivated-land evolution during different developmental stages and different regions vary. Development processes, urban construction, and policies are jointly affected, and each factor has a variable degree of influence. To examine the breadbasket regions in Jilin Province, 18 influencing factors were chosen, as shown in Table 3.

Based on the multi-functional evaluation of cultivated land, the key factors affecting change in multi-functionality were identified using Geodetector, a statistical method that detects spatial heterogeneity and reveals the drivers behind it [38]. The strengths of the driving factors were determined following the method by Wang and Xu [39].

Table 3. Definition of factors influencing the multi-functionality of cultivated land. The per capita construction-land standard in rural areas was 150 m^2/person, and the urban per capita construction-land standard was 120 m^2/person. The average weighting method was used to measure the overall pressure; the management and control levels of permanent basic farmland, prohibited construction areas, restricted construction areas, conditional construction areas, and permitted construction areas in the agricultural-policy zoning decreased in order, and were assigned values of 5, 4, 3, 2, and 1, respectively, in the calculations. Because of data limitations in 1990 and 2000, Jilin Province did not produced agricultural-land-grading data; the average grain yield was used to correct the cultivated-land utilization to obtain graded data for the corresponding years.

Factor	Indicator	Abbreviation	Calculation
Physical geography	Elevation	Elevation	Elevation values from DEM
	Slope	slope	The actual slope of the cultivated land
	Annual precipitation	annual precipitation	Regional averages from weather-station data
	Distance from major rivers	DFMR	Euclidean distance based on the distribution of the water system
	Cultivated-land quality	cultivated-land quality	Agricultural-land grading
	Distance from provincial capital	DFPC	Distance from the main city of Changchun
	Distance from central city	DFCC	Distance from the main city of the prefecture-level city
Economic development	Per capita GDP	GDP per capita	Total GDP/Total population
	Per capita agricultural output of farmers	PCAOVF	Output value of primary industry/Rural population
	Proportion of secondary and tertiary industries	PSTI	Output value of secondary and tertiary industries/Total GDP
	Fixed asset investment per land	FAIPL	Total fixed asset investment/Regional land area
Urban construction	Urbanization rate	urbanization rate	Urban population/Total population
	Population density	Population density	Total population/Regional land area
	Percentage of built-up area	PBA	Built-up area/Total land area
	Road-network density	road network density	Proportion of road-network length to total area
Policy	Agricultural policy division	APD	Permanent basic farmland, prohibited construction areas, restricted construction areas, conditional construction areas, permitted construction areas
	Construction-land-index pressure	CLIP	Rural per capita construction land/Rural construction land standard + Urban per capita construction land/Urban per capita land standard
	Proportion of financial support to agriculture	PFFSA	Proportion of expenditure on agriculture, forestry, and water affairs in public finance

3. Results

3.1. Spatiotemporal Variation in and Main Obstacles to the Multi-Functionality of Cultivated Land

3.1.1. Temporal Variation in the Multi-Functionality of Cultivated Land

The evaluation, degree of change, and coefficient of variation of each function of cultivated land during different periods in the breadbasket regions are shown in Table 4. The average multi-functional scores for cultivated land for the four research time nodes were 0.222 (1990), 0.227 (2000), 0.361 (2010), and 0.451 (2020), representing an increase of 102.92% during the 30 years from 1990 to 2020. Although the overall multi-functional level of cultivated land was not high, the increase was large with clearly differentiated phases, showing a trend from basically unchanged to rapid improvement to steady increase. The economic sub-function increased the most, from 0.148 in 1990 to 0.484 in 2020, an increase of 227.51%. The social function was second, with an increase of 152.69%, from 0.159 in 1990 to 0.401 in 2020. The ecological function was almost stagnant, with current levels comparable to those of 30 years ago, only rising from 0.441 in 1990 to 0.456 in 2020. The rapid improvement in the economic and social functions of cultivated land in the breadbaskets led to an increase in the level of multi-functionality, to which the ecological function did not contribute.

Table 4. Trends in multi-functional changes in cultivated land in the black-soil breadbaskets of Jilin Province, Northeast China, from 1990 to 2020.

Function	Score				Change (%)				CV			
	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020	1990–2020	1990	2000	2010	2020
Economic	0.148	0.148	0.359	0.484	0.24%	142.51%	34.73%	227.51%	0.267	0.265	0.310	0.252
Social	0.159	0.165	0.289	0.401	3.75%	75.27%	38.96%	152.69%	0.338	0.309	0.343	0.332
Ecological	0.441	0.451	0.459	0.456	2.16%	1.76%	−0.52%	3.41%	0.368	0.393	0.430	0.450
Multi	0.222	0.227	0.361	0.451	1.97%	59.08%	24.97%	102.72%	0.300	0.212	0.290	0.283

3.1.2. Spatial Variation and Differentiation in the Multi-Functionality of Cultivated Land

There were obvious and significant spatial differences in the multi-functionality and sub-functions of cultivated land in the 28 breadbaskets. The coefficient of variation of the ecological functions was the largest, showing a continuous increase over the past 30 years, from 0.368 in 1990 to 0.450 in 2020 (Table 4), indicating that the ecological functions of cultivated land varied among different breadbaskets. the differences in time-progressed ecological functions were more pronounced than those in other functions.

The spatial differences in the social function of cultivated land were also obvious but to a lesser extent than the ecological function. The coefficient of variation dropped from 0.338 in 1990 to 0.332 in 2020, indicating little overall change, although there were some differences. The differences in the economic function of cultivated land were the smallest compared with the other functions, with the average coefficient of variation decreasing from 0.267 in 1990 to 0.252 in 2020, indicating that the economic attributes of cultivated land were well balanced among the breadbaskets.

Based on the current multi-functionality of cultivated land and the changes recorded over the last 30 years, although the multi-functionality increased, it showed an unbalanced development of the Matthew effect, i.e., higher levels of multi-functionality led to higher levels, while lower levels led to yet lower levels. The range of the multi-functionality and sub-functions of cultivated land among the breadbaskets significantly increased, showing an overall increase of 220%, with the range in economic and social functions increasing by more than 300%. Even the much weaker ecological function also expanded by 12%. Overall, the use of cultivated land over the last 30 years increased the spatial differences in multi-functional utilization to an exaggerated degree. This directly reflects the lack of the consideration of cultivated-land functions in cultivated-land protection (Figures 3 and 4). In addition, the changes in the ecological functions of cultivated land were polarized (Figure 3c) between the east and the west (Figure 4c). On average, the former (with a sum score of about 9.108) had a value about three times that of the latter (sum score of about 3.674) (Figure 3c).

3.1.3. The Main Obstacles to Multi-Functionality of Cultivated Land

The obstacle degree was calculated with the evaluation index for the four time nodes for each breadbasket to determine what factors were limiting the functions of cultivated land. Over the last 30 years, the economic function of cultivated land restricted the multi-functionality of cultivated land the most, followed by the social function and then the ecological function (Table 5). However, the dominant restrictive effect of the economic function weakened (from 13.46 in 1990 to 11.56 in 2020), while the restrictive effect of the ecological function increased (from 4.78 in 1990 to 6.56 in 2020, a rise of 37.24%). This suggests that how the ecological function is managed in the future could be the key to improving the functions of cultivated land. After sorting the index obstacle scores for the breadbaskets, the per capita agricultural output, the degree of agricultural mechanization, the average output of cultivated land, and the agricultural-labor productivity had the strongest restrictive effects on the functions of cultivated land. However, based on the changes in the index values, the per capita agricultural output showed a decreasing trend (from 4.29 in 1990 to 3.63 in 2020), and the degree of agricultural mechanization may soon become the biggest obstacle. Barriers to national contribution and effective irrigation are rising, highlighting the fact that attention must be paid to the multi-functional utilization of cultivated land in the future.

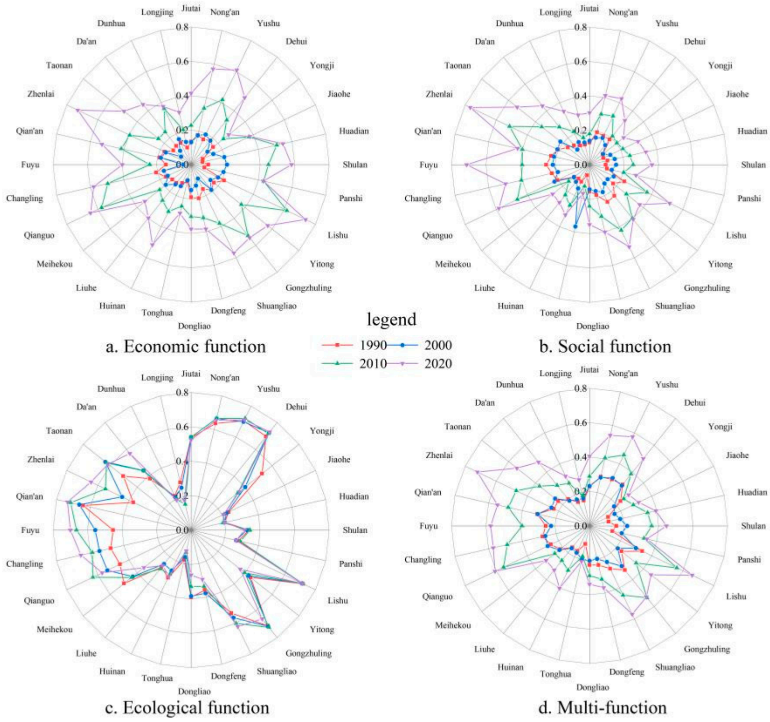

Figure 3. Multi-functional composition of cultivated land in 28 black-soil breadbaskets, Jilin Province, Northeast China, from 1990 to 2020. (**a**) Economic function. (**b**) Social function. (**c**) Ecological function. (**d**) Multi-function.

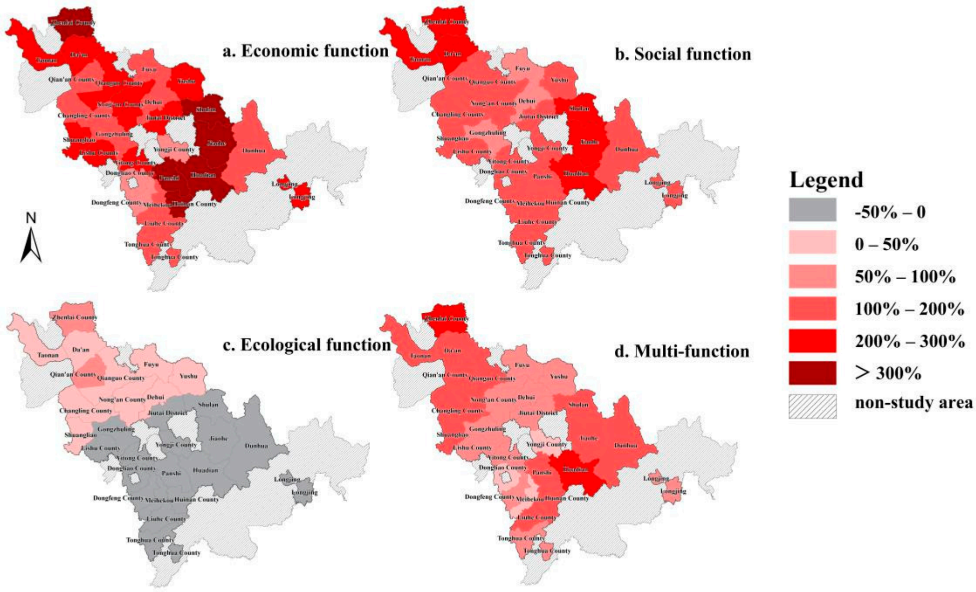

Figure 4. Changes in function of cultivated land in the black-soil breadbaskets of Jilin Province, Northeast China, from 1990 to 2020. (**a**) Economic function. (**b**) Social function. (**c**) Ecological function. (**d**) Multi-function.

Table 5. Calculated obstacle degrees for factors influencing cultivated-land functions in the black-soil breadbaskets of Jilin Province, Northeast China, from 1990 to 2020.

Year	Item	Function Order			Index Order				
		1	2	3	1	2	3	4	5
1990	Barrier indicator	Economic function	Social function	Ecological function	PCAO	AOV	ALP	DAM	FCI
	Handicap	13.46	9.76	4.78	4.29	3.64	3.55	3.42	2.36
2000	Barrier indicator	Economic function	Social function	Ecological function	PCAO	AOV	DAM	ALP	FCI
	Handicap	13.51	9.75	4.74	4.11	3.22	3.21	3.00	2.53
2010	Barrier indicator	Economic function	Social function	Ecological function	PCAO	DAM	PCLV	AOV	FCI
	Handicap	12.31	10.09	5.60	3.87	3.67	2.77	2.60	2.29
2020	Barrier indicator	Economic function	Social function	Ecological function	PCAO	DAM	PCLV	EII	AOV
	Handicap	11.56	9.88	6.56	3.63	3.60	3.02	2.50	2.30
Whole period	Barrier indicator	Economic function	Social function	Ecological function	PCAO	DAM	AOV	ALP	FCI
	Handicap	50.84	39.49	21.68	15.90	13.90	11.76	10.30	9.35

3.2. Coupling and Coordination Relationships among Various Sub-Functions of Cultivated Land

A coupling–coordination degree model was used to compare the sub-functions of cultivated land in the breadbaskets from 1990 to 2020 and was divided into 10 levels (Figure 5). The degree of coupling–coordination among various functions of cultivated land showed an overall upward trend, from "low coupling coordination–antagonistic coupling coordination" to "high coupling coordination–optimal coupling coordination". Nine breadbaskets in eastern Jilin with low levels of coupling–coordination all improved over time, reaching antagonistic coupling–coordination or even high coupling–coordination. Nineteen breadbaskets in central and western Jilin Province all attained a high degree and optimal level of coupling and coordination. Among them, Lishu County and Zhenlai County achieved good coupling–coordination, but no breadbasket reached high-quality coupling–coordination. From 1990 to 2000, overall, the coupling–coordination degree of the multi-functional value of cultivated land remained at a low level, and in fact, the coupling–coordination degree for Gongzhuling City, Yongji County, Qian'an County, Changling County, and Da'an City all declined. During the 20-year period between 2000 and 2020, the coupling and coordination degree of the multi-functional value of cultivated land did improve, although the increase was generally faster in the western region than the eastern region.

3.3. Key Factors Influencing the Multi-Functionality of Cultivated Land

Figure 6 and Table 6 rank the driving factors affecting the multi-functionality of cultivated land in the 28 breadbaskets at the four time nodes. In general, physical and geographical factors were the main factors influencing the multi-functional changes in cultivated land, while the influence of economic factors showed a sharp downward trend over the 30 years (the total q-value decreased from 1.55 in 1990 to 0.92 in 2020). However, urban construction and policy factors had very limited effects on the changes in multi-functionality. The factors that had a greater impact in 1990 were the quality of cultivated land and the proportion of secondary and tertiary industries. In 2000, the pressure of construction land, annual precipitation, and proportion of built-up area began to have a greater impact on the multi-functionality of cultivated land. From 2010, the quality of cultivated land and proportion of secondary and tertiary industries once again dominated the changes in multi-functionality. Annual precipitation and elevation in 2020 were particularly important for cultivated-land multi-functionality.

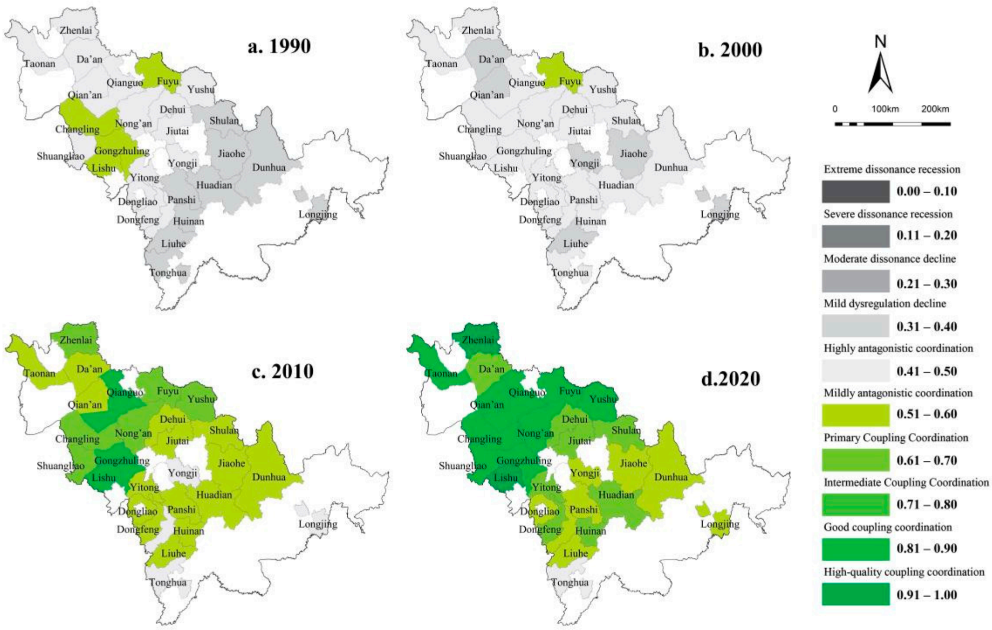

Figure 5. Coupling–coordination among sub-functions of cultivated land in the black-soil breadbaskets of Jilin Province, Northeast China, from 1990 to 2020. Data from Wang et al. [40] were used to divide the coupling–coordination degree into 10 types.

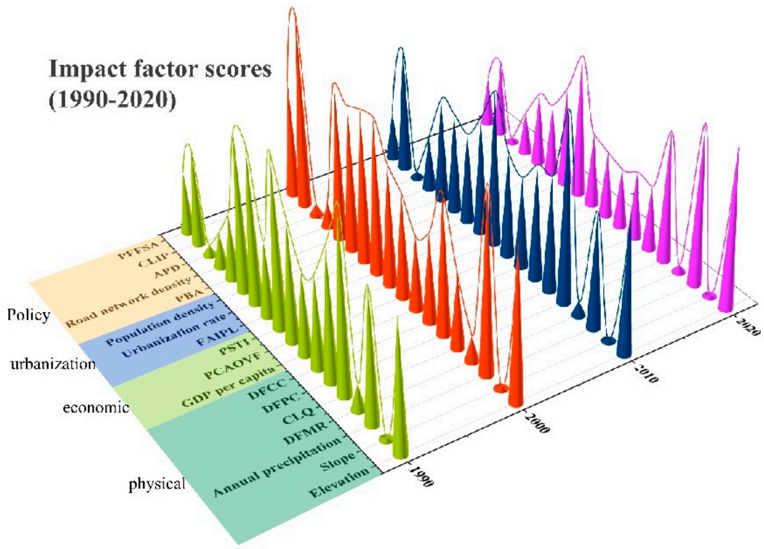

Figure 6. Impact scores for multi-functional factors affecting cultivated land in the black-soil breadbaskets of Jilin Province, Northeast China, from 1990 to 2020. The meanings of the abbreviations used in the figures are shown in Table 3.

Table 6. Indicator values for factors influencing the multi-functionality of cultivated land in the black-soil breadbaskets of Jilin Province, Northeast China, from 1990 to 2020.

Factor	Indicator	1990	2000	2010	2020	Average
Physical geography	Elevation	0.54	0.62	0.56	0.65	0.59
	Slope	0.01	0.01	0.01	0.00	0.01
	Annual precipitation	0.55	0.75	0.48	0.66	0.61
	Distance from major rivers	0.11	0.11	0.06	0.03	0.08
	Cultivated-land quality	0.76	0.31	0.78	0.54	0.59
	Distance from provincial capital	0.54	0.57	0.47	0.26	0.46
	Distance from central city	0.38	0.37	0.47	0.28	0.37
	Subtotal	2.88	2.73	2.81	2.42	2.71
Economic development	Per capita GDP	0.34	0.31	0.37	0.24	0.32
	Per capita agricultural output of farmers	0.50	0.43	0.43	0.27	0.41
	Proportion of secondary and tertiary industries	0.71	0.50	0.63	0.30	0.53
	Subtotal	1.55	1.23	1.44	0.81	1.26
Urban construction	Fixed asset investment per land	0.31	0.64	0.48	0.59	0.50
	Urbanization rate	0.64	0.63	0.37	0.41	0.51
	Population density	0.65	0.60	0.41	0.29	0.49
	Subtotal	1.60	1.86	1.26	1.29	1.50
Policy	Percentage of built-up area	0.27	0.65	0.43	0.30	0.41
	Road-network density	0.14	0.10	0.22	0.17	0.16
	Agricultural-policy division	0.04	0.05	0.03	0.02	0.03
	Construction-land-pressure index	0.40	0.79	0.51	0.31	0.50
	Proportion of financial support to agriculture	0.26	0.48	0.20	0.20	0.28
	Subtotal	1.11	2.07	1.39	1.00	1.39

4. Discussion

4.1. Policy Suggestions for Multi-Functional Management of Cultivated Land

For the mismatch between the supply and demand of multi-functional cultivated land, proper interference and regulation are needed [41]. Implementing smaller-scale land-use management or land-use planning is often more efficient in solving the problem and at a low cost [42]. This research study deepened our understanding of the function of cultivated land and can inform policies for the long-term protection of cultivated land. The results of this study are applicable not only to Northeast China but also to other major grain-producing areas that are under pressure to protect cultivated land.

Incorporating multi-functional utilization into policy considerations for cultivated-land management can help balance differences in cultivated-land functions among regions. Research on cultivated-land protection has a long history and has received special attention in recent years [43], especially in the context of prominent global land-use contradictions and serious threats to food security [44]. However, the protection of cultivated-land quantity, quality, productivity, etc., has perhaps been overemphasized [45], while the sustainability of cultivated-land use has received less attention, although it has started to come into focus [46,47], and the relatively hidden multi-functional attributes of cultivated land have rarely been considered. Differences in the use of cultivated land often lead to differences in management policies, which ultimately affect the future sustainability of land use. The multi-functional imbalance of cultivated land in the 28 breadbaskets studied here highlights the need to address this issue. A regional imbalance results in a lack of drive for cultivated-land protection. The direction and perception of cultivated-land protection need to change towards using the sustainable protection and utilization of cultivated land as a starting point for cultivated-land management, and to integrate multi-functionality into the formulation of cultivated-land-management policies and planning.

The multi-functional value of cultivated land needs to be demonstrated, and sufficient compensation offered, to encourage cultivated-land protection. The economic benefits of growing grain on cultivated land are relatively low, and the comparative benefits of growing grain are likely to continue to decrease with the development of economy and society. When the income of agricultural production is unbalanced, the government can improve and protect farmers through subsidy programs [48]. However, without reasonable compensation for multi-functional land use, there is no incentive for farmers to protect the land [49]. Obstacles to multi-functionality compound the problem. Among the four main obstacles to multi-functionality of cultivated land in the studied breadbaskets, the per capita agricultural output and the average output of cultivated land were directly related to the income level generated by cultivating land, while the other two barriers, agricultural-labor productivity and agricultural mechanization, were highly correlated with the level of economic income from cultivated land. These indicators can only improve if income levels are high enough. Currently, farmers are presented with a stark choice between protecting the land and remaining on lower incomes or giving up the land and moving to cities to achieve higher incomes. The government needs to take effective measures to recalibrate the value of cultivated-land resources, highlighting the multi-functional value of cultivated land, and give farmers proper compensation for land protection.

The ecological utilization of cultivated land in breadbaskets needs to be improved and the long-term sustainable utilization of cultivated land needs to be promoted. Ecological issues with cultivated land are closely related to the presence of people, compared with other natural resources, because of the long history of human settlement around areas of cultivation [50]. People benefit directly from the positive effects of cultivation, such as environmental improvement and biodiversity, but there are also negative effects, such as water pollution and straw-burning pollution [51]. The ecological function of breadbaskets has not been improved for many years, and this has increasingly restricted the multi-functionality of cultivated land. At a time when global ecological security is under threat, effective measures should be taken to curb negative trends, and the future ecological utilization of cultivated land is necessary. When considering the cultivated-land output, recycling and reducing the use of pesticides, fertilizers, herbicides, etc., should be promoted to save production costs and improve agro-ecological benefits.

4.2. Limitations and Future Research

Based on long-term research, we analyzed the unbalanced state of the multi-functionality of cultivated land and gave a feasible solution to balance the multi-functionality of cultivated land. However, with the continuous emergence of global ecological threats and the rapid urbanization of agricultural areas, the multi-functional utilization of cultivated land still requires further attention and more in-depth research, and our study still has two important limitations that need to be addressed [52].

The evaluation criteria used to assess the multi-functionality of cultivated land at different research scales are different, and policy formulation needs to be adjusted accordingly. The multi-functional mismatch of cultivated land is multi-scaled, and the analysis of different scales is an important method to determine the reasons for this mismatch between supply and demand [53]. Based on the scales being considered, relevant indicators for evaluation need to be selected [31]. As a county-level study, this research study addresses problems in county-level farmland protection policies, and can suggest countermeasures, but it is difficult to extrapolate the results to larger or smaller study areas. For example, understanding the imbalance of cultivated-land functions among regions and taking corresponding measures require the evaluation of the functions of cultivated land at a national level. Conversely, engineering and utilization measures to improve the function of cultivated land need to be considered at a plot scale. Evaluation forms the basis for policy-making, and the choice of indicators forms the basis for evaluation [54]. Therefore, in future research at different scales, different evaluation-index systems should be selected according to local conditions, to make the results more robust.

The functions of cultivated land represent a large, complex system, and it is difficult to describe all the relevant aspects of cultivated land with the existing macro data. The functions of cultivated land are intertwined with economic, social, and ecological systems, and macro-statistical data and geographic data can only reflect the overall functions of cultivated land to a certain extent. The different scales and standards of the statistical data used are also likely to cause discrepancies between evaluation results and empirical data. To eliminate such errors, data encompassing as many perspectives as possible need to be collated [55]. For example, regarding the ecological function of cultivated land, the level of farmland pollution may be affected by factors such as straw burning, agricultural non-point source pollution, and plastic pollution [56]. These indicators may require additional investigation and research at a micro level. Equally, extrapolating policy recommendations from cultivated-land utilization through research on multi-functionality and facilitating farmers in recognizing the multi-functionality of cultivated land are topics worthy of long-term research.

5. Conclusions

Multi-functionality is an objective attribute of cultivated land that influences the sustainability of cultivated-land utilization and the long-term protection of cultivated land. To date, the importance of black-soil cultivation and protection has not received sufficient attention because of an overemphasis on grain output. An effective way of addressing this situation is to understand the changes in the multi-functionality of cultivated land and identify the key driving and limiting factors behind any changes. We used an improved TOPSIS model to measure the temporal and spatial variation in the cultivated-land functions over 30 years, from 1990 to 2020, in 28 breadbaskets in Jilin Province, Northeast China. The key driving factors behind and major obstacles to cultivated-land functions were determined using an obstacle degree model and a geographic detector model. The coupling and coordination relationships among the various functions of cultivated land were also analyzed. Suggestions are made to help improve future land-management policies. This study provides a baseline for the multi-functional utilization of cultivated land and the long-term protection of cultivated land in China and even in the world's major grain-producing regions and expands the perspective of cultivated-land protection.

The multi-functionality of cultivated land in the breadbaskets increased significantly in the 30 years from 1990 to 2020 (by 102.92%). Whether a function is used to its full potential is an important limiting factor for cultivated-land utilization, and the ecological function of cultivated land is likely to be more important in the future. There was an obvious spatial differentiation in cultivated-land functions across the breadbaskets; this difference was the largest for the ecological function, followed by the social function, and was the smallest for the economic function. The coupling–coordination degree for each sub-function generally showed an upward trend, but there was again an obvious spatial differentiation. The multi-functionality of cultivated land in the breadbaskets presented an unbalanced growth trend. In addition, the sub-functions of cultivated land were not well coordinated, leading to an imbalance in promoting cultivated-land protection. Cultivated-land protection in this region over the last 30 years also exacerbated social inequality. The government must intervene with effective measures, especially in the processes of cultivated-land utilization and management, and the multi-functionality of cultivated land should be taken as a starting point for formulating policies. The multi-functional value of cultivated land needs to be evaluated, and farmers should be offered reasonable compensation to reduce the imbalance and differences in cultivated-land functions among regions and improve farmers' enthusiasm for cultivated-land protection. The ecological utilization of cultivated land in breadbaskets should be improved and sustainable utilization should be promoted.

Author Contributions: H.G., Conceptualization, Methodology, Software, Formal analysis, Visualization, Investigation, and Writing—original draft; L.C. and Y.L. (Ying Li), Methodology and Writing—review and editing; G.L., Formal analysis and Data curation; Z.Z., Visualization and Validation. Y.L. (Yuefen Li), Conceptualization, Supervision, Funding acquisition, and Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by National Natural Science Foundation of China (grant No. 42177447) and Science and Technology Development Plan Project of Jilin Province (grant No. 20210203010SF).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the article.

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

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