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Cultivated Land Use Layout Adjustment Based on Crop Planting Suitability: A Case Study of Typical Counties in Northeast China

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Abstract: Cultivated land use layout adjustment (CLULA) based on crop planting suitability is the refinement and deepening of land use transformation, which is of great significance for optimizing the allocation of cultivated land resources and ensuring food security. At present, people rarely consider the land suitability of crops when using cultivated land, resulting in an imbalance between crop distribution and resource conditions such as water, heat, and soil, and adversely affects the ecological security and utilization efficiency of cultivated land. To alleviate China's grain planting structural imbalance and efficiency loss, this paper based on the planting suitability of main food crops (rice, soybean, and maize) to adjust and optimize the cultivated land use layout (CLUL) in the typical counties of the main grain production area in Northeast China, using the agent-based model for optimal land allocation (AgentLA) and GIS technology. Findings from the study show that: (1) The planting suitability of rice, soybean, and maize in the region is obviously different. Among them, the suitability level of soybean and maize is high, and that of rice is low. The current CLUL of the food crops needs to be further optimized and adjusted. (2) By optimizing the layout of rice, soybean, and maize, the planting suitability level of the food crops and the concentration level of the CLUL spatial pattern have been improved. (3) The plan for CLULA is formulated: The study area is divided into rice stable production area, maize-soybean rotation area, maize dominant area, and soybean dominant area, and town or village is identified as the implementation unit of CLULA. The plan for CLULA will be conducive to the concentrated farming of food crops according to the suitable natural conditions and management level. The research realized the optimization of spatial structure and cultivated land use patterns of different food crops integrating farming with protecting land. The significance of the study is that it provides a scientific basis and guidance for adjusting the regional planting structure and solving the problem of food structural imbalance.

Keywords: land use transition; cultivated land use layout adjustment (CLULA); suitability; food crops; planting structure; Northeast China

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1. Introduction

Land use transition is the result of the comprehensive effect of regional own conditions and external environmental factors in the process of economic and social development, and it also brings direct socio-economic and environmental impacts on regional sustainability [1]. As a new approach to the comprehensive study of national/regional land use/cover change [2], land use transition refers to the changes in regional land use morphology corresponding to the transition of the socio-economic development stage over a certain period of time, including the dominant morphological transition and the recessive morphological transition [3]. The dominant morphology is presented through the land use features of quantity, structure, and spatial pattern, and the recessive morphology is presented through the land use features of quality, property rights, management mode, input, output, and function [4]. Cultivated land resources are an important part of land resources, and the core element contributing to food security and socio-economic development [5], and cultivated land use transition is an important manifestation of land use transition. The research on cultivated land use transition not only includes the exploration of regional cultivated land use morphology, transition pattern, and transition mechanism at different stages, but also needs to answer the question of what kind of cultivated land use transition should be adopted, and what measures should be taken to ensure its implementation [6]. Cultivated land use layout adjustment (CLULA) is an important part of cultivated land use transition. Based on grasping the regional cultivated land spatial distribution, planting structure characteristics (cultivated land use dominant morphology), and the spatial distribution of cultivated land use natural and socio-economic elements (cultivated land use recessive morphology) under a certain socio-economic development stage, CLULA is to reasonably match various cultivated land use spatial elements guided by certain goals and practical needs, so as to realize cultivated land use layout optimization and clear direction of cultivated land use transition. CLULA enriches the elements and connotation of cultivated land use transition, and further answers the questions of "what kind of transition" and "how to transform".

In 2019, China's urbanization reaching above 60%, which means that China has entered the mid-late stage of urbanization, and it is an important stage for digesting the accumulated contradictions during the rapid expansion of urbanization [7]. Accelerated urbanization and the subsequent increase in human activities are triggering land use transitions in China [4]. China Statistical Yearbook data shows that from 2006 to 2015, China's corn area continued to increase, with an average annual increase of over 1 million hectares, while soybean area decreased by more than 400,000 hectares annually, resulting in an imbalance in crop planting structure. From 2004 to 2015, despite the twelfth consecutive increase in China's total grain volume, the grain market showed a simultaneous increase in imports, production, and stocks. The phased supply of corn exceeds demand, while the gap between supply and demand of soybeans has expanded year by year, which has intensified the urgency of grain planting structure adjustment and cultivated land use transition. In China, the food security problem has changed from insufficient quantity to structural contradiction, which has created new food security problems. From 2015 to 2018, the Chinese government successively issued policies to take advantage of the main grain-producing area and adjust the planting structure.

In recent years, the quantitative structure of food crops in China has been appropriately adjusted under policy guidance, but the spatial distribution of regional food crops lacks scientific basis. Under the current rural land system in China, cultivated land use layout (CLUL) is increasingly affected by factors such as agricultural market price, farmers' planting preferences, and agricultural techniques, while the climate, terrain, soil conditions [8], and spatial suitability for crop cultivating are not considered adequately. The current CLUL, especially the food crops layout, has a problem of unbalanced allocation of land, water, and heat resources [9], resulting in loss of efficiency and land degradation [10], threatening the sustainable use of cultivated land [11,12]. The spatial planting structure of regional food crops needs to be further optimized and adjusted. Land suitability analysis for crops is a prerequisite to achieve optimum utilization of cultivated land resources [13,14]. It is necessary to comprehensively consider the spatial matching relationship between the natural conditions, human factors of cultivated land utilization, and actual requirements of crops to explore the planting suitability and production potential of different crops [15,16]. Cultivated land use layout adjustment (CLULA) based on crop planting suitability has become the essential path to guarantee food supply without degradation of cultivated land.

There are abundant research results on the adjustment and optimization of land use layout, which have gone through a research process from qualitative analysis to quantitative calculation, and quantitative structural configuration to spatial distribution. Most of the research is based on the consideration of land quality, ecology, function, food production, and economic benefit to optimize the land use layout [17–21], which can be divided into two aspects: Quantity optimization and space optimization of land use.

Socio-economic factors are important factors considered in land use quantity optimization, which are mainly reflected in the guiding role of regional grain production [22], input–output [23], and net income [24] in the optimization. Land evaluation is often used as one of the key processes for land use space optimization [25], including land suitability evaluation, land quality evaluation, land ecological evaluation [26], etc. Factors such as climate, topography, soil, hydrology, land management conditions, as well as socio-economic aspects, are often selected [27,28], and a wide range of methods have been developed, including Multi-criterion evaluation (MCE) [29–31], analytic hierarchy process (AHP) [32,33], Storie index (SI) [34], rule-based classification method [35,36], etc., for land evaluation. In terms of research methods, the related research has used multi-objective programming model (MOP) [37], cellular automata (CA) [38], comparative advantage index [39], agent-based model (ABM) [40], and multiple optimization algorithms [41–43] to optimize land use layout in terms of quantitative structure, spatial pattern, and benefit optimization. However, the planting suitability of food crops and the spatial structure relationship between crops, as well as the reasonable matching of natural and human factors of cultivated land use for different food crops have not received sufficient attention. CLULA based on the planting suitability of food crops is an extension and refinement of the research on cultivated land use and protection issues, taking the research deep into the essence of cultivated land use, which needs to be further explored. Thus, this paper takes the typical area of the main grain production area in Northeast China as the study area, based on the planting suitability of the main grain crops: Rice, soybean, and maize in the region, comprehensively considering the environmental conditions and requirements of crop planting such as climate, terrain, soil, and management, using AgentLA model and GIS methods to match various cultivated land use factors in space, and achieve the layout optimization and spatial relationship coordination of food crops. This research will provide a scientific basis for guiding the regional planting structure adjustment, alleviating the problem of food structural contradictions, at the same time clearing the way for the practice of regional cultivated land use transition.

2. Materials and Methods

2.1. Description of the Study Area

Keshan County, Yi'an County, and Baiquan County are the three adjacent counties situated in Heilongjiang Province, the main grain production area in Northeast China, and it is an important commodity grain base and soybean production base. It is also located in the black soil belt in the northern part of the Songnen Plain of China (Figure 1), in which the planting system is bringing in one harvest a year. The region has a temperate continental monsoon climate and receives annual precipitation of approximately 500 mm. Plains and hills are the main geomorphic types of the region. The soil types are mainly black soil and chernozem.

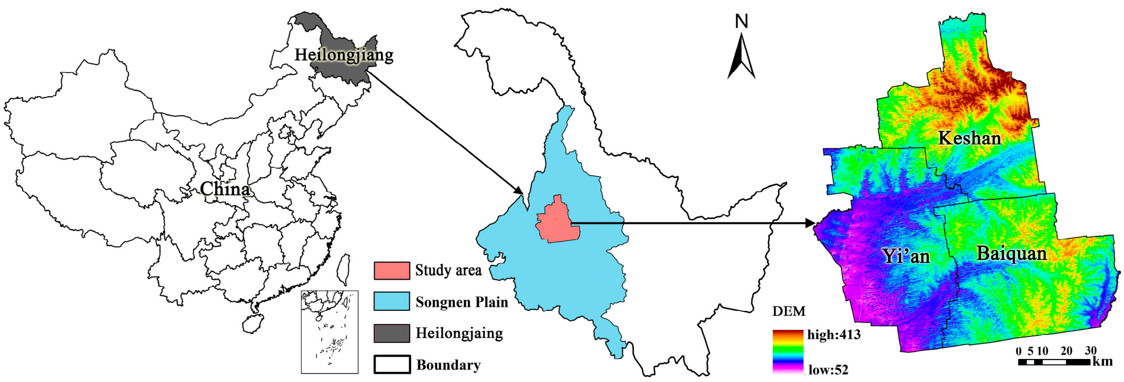


Figure 1. Location of the study area.

According to the remote sensing images interpretation results in the study, the total area of the study area is about 10,460 km^2, in which 8307.43 km^2 (79.42%) is covered by cultivated land in 2018. The main crops are maize, soybean, and rice, which have a total area of 8000.70 km^2, accounting for 96.31% of the cultivated land in the region. The ratio of the planted area of rice, soybean, and maize is about 1:8.71:8.64. The rice is concentrated in the north of central Yi'an County and northern Keshan County, the maize is mainly distributed in Yi'an County and southern Baiquan County, and the soybean is mostly distributed in the north and east of Keshan County and Baiquan County. According to the Qiqihar Economic Statistical Yearbook (1989−2019), from 2000 to 2015, the maize area increased by 308,152 hectares in the region, an increase rate of 353.17%, while the area of soybeans decreased significantly, especially from 2009 to 2015, when its area decreased by 175,363 hectares. In order to alleviate the imbalance of crop planting structure, in 2016, the Chinese government released the policies of "Guiding Opinions on the Adjustment of Maize Structure in the 'Sickle Bend' Region" and "Pilot Scheme on Exploring the Implementation of Cultivated Land Fallow and Rotation System". Keshan County, Yi'an County, and Baiquan County in the study area were listed as key pilots for cultivated land fallow and rotation in 2017 and 2018, which is very typical.

2.2. Data Sources and Processing

In this paper, meteorology, topography, soil, land use data, and remote sensing image data are available for consideration. (1) Meteorological data are obtained from the monthly data set of China's ground cumulative value (1981–2010) of National Meteorological Administration of China (http://data.cma.cn) and the Chinese meteorological background data set of the Resource and Environmental Science Data Center of Chinese Academy of Sciences (http://www.resdc.cn), including accumulated temperature, monthly average temperature, and precipitation during the crop growth period. The meteorological data are the cumulative annual averages of meteorological stations in the study area from 1981 to 2010. ArcGIS was used to make universal Kriging interpolation analysis on the temperature, precipitation, and accumulated temperature of the meteorological stations, and the spherical function was selected to obtain meteorological spatial raster data in the region, with a spatial resolution of 100 m. (2) Topographic data includes Digital Elevation Model (DEM), slope, and landform type. DEM and slope are the 30 m resolution data in 2009, obtained from the ASTER Global Digital Elevation Model (ASTER GDEM) provided by Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). The landform types data comes from the 2009 Atlas of Landforms of the People's Republic of China (1: 1 million), which is raster data with a resolution of 1 km. (3) Soil data comes from the 1:1 million soil type vector map and the dataset of main traits of cultivated land quality in Heilongjiang Province, China in 2010, including soil texture, soil thickness, organic matter, available potassium, available phosphorus, and soil pH. (4) Land use data were spatial vector data extracted from the 2018 China land change survey database, including farmland ditches, water surfaces, shelter forests, residential areas, and farmland plots, etc. By calculating the Euclidean distances from each farmland plot to farmland ditches, water surfaces, and residential areas with ArcGIS, the spatial raster data of the drainage capacity, irrigation potential, and farming convenience were obtained. Besides, the kernel density analysis tool in ArcGIS was used to calculate the spatial density of the shelter forests, obtain the spatial raster data of the farmland shelterbelt density, and the calculation geometry tools were used to obtain the perimeter and area of each farmland plot. The field shape regularity of farmland plots was calculated by the formula of "4*(area/perimeter) ˆ1/2". (5) Landsat8 (OLI) satellite remote sensing image data are obtained from the USGS EROS Data Center. Combined with the characteristics of crop phenology, remote sensing image quality, and cloudiness in the region, multi-period remote sensing images were selected. Through remote sensing image processing such as radiometric calibration, atmospheric correction, geometric correction, and band fusion (6, 5, 2 bands), obtained the raster image map for crop interpretation, with a spatial resolution of 30 m. Combining the remote sensing image map and the 2018 cultivated land vector diagram in the study area extracted from the annual change database of the second national land survey in China, the spatial distribution vector map of the main crops was got through manual visual interpretation based on the image characteristics of different crops such as color and texture. To calculate and analyze various types of spatial data uniformly, ArcGIS was used to convert all raster data into vector data.

2.3. Land Suitability Evaluation of Crops

Land suitability evaluation is the process of estimating the land performance for alternative kinds of use [15,44,45], and its basic features are the comparison of the requirements of land use with the resources offered by the land [46]. Land suitability analysis for crops is a function of crop requirement and land characteristics reflected in final decisions [15], which can be identified as a multi-criteria evaluation (MCE) approach [35]. Drawing on the Food and Agricultural Organization (FAO) framework for land suitability [47–50], agricultural land suitability evaluation (ALSE) process [28], and other research results [5,34], land suitability evaluation for crops could mainly include (1) structuring the MCE model by identification of the environmental requirements of crops; (2) selecting standardization functions and determining the quantitative relationship between each considered environmental factor and the requirement of the target crop; (3) calculating the suitability score for a single factor for each evaluation unit; and (4) combining of the scores from all the considered factors [51,52]. Given this, the specific evaluation methods of this research are as follows:

2.3.1. Evaluation Indicators and Criteria

Sixteen indicators from the aspects of climate, topography, soil, and land use management were selected in the evaluation (Table 1). Climate, topography, and soil indicators characterize the natural conditions of crop planting, which are the prerequisite factors affecting crop suitability. Management indicators reflect the utilization conditions of crop planting, adding human factors based on natural conditions. The irrigation potential means the distance from the land to canals and dams. The drainage capacity represents the distance from the land to the ditches, and the farming convenience indicates the distance from the land to the settlement. The closer the distance, the greater the irrigation potential, drainage capacity, and farming convenience of the land. The field shape regularity reflects the difficulty of mechanized farming, and the shelterbelt density reflects the wind-proof and sand-fixing conditions of the land. Land management factors are also important factors affecting crop planting suitability and can be improved through engineering measures.

The indicators including restrictive, and non-restrictive indicators. The restrictive indicators have specific criteria for different crops with the most suitable range, maximum threshold, and minimum threshold, while the non-restrictive indicators have no specific suitability standards, which need to be further defined. The FAO guidelines [47,53], regional land evaluation materials [54,55], and relevant research results of the study area [56] were referenced in determining the evaluation criteria. For restrictive indicators, such as accumulated temperature, precipitation, slope, soil thickness, etc., the crop growth model [57,58] and membership function method were used to quantify the relationship between environmental conditions and crop requirements, and then calculate the crop planting suitability for each restrictive indicator. For non-restrictive indicators, such as available potassium, available phosphorus, farming convenience, shelterbelt density, etc., combined with the expert scoring of the relevant land evaluation results in the study area [54,55], the statistics-based classification method was used to define the evaluation criteria, and the scores of non-restrictive indicators were obtained. The quantified suitability results of each indicator are converted to 0–100 points, which is used to calculate the comprehensive score of suitability for the next step.

2.3.2. Evaluation Indicators Weight

The analytic hierarchy process (AHP) is an important tool for system analysis developed after mechanism analysis and statistical analysis. In this study, the AHP was used to determine the weight of the indicators. The specific steps mainly include (1) build a hierarchical structure model: The decision goals, decision criteria, and decision objects are layered according to their mutual relationship, and a hierarchical structure diagram is drawn, which is divided into the target layer, the middle layer, and the lowest layer. The target layer is the problem to be solved. In this study, it refers to the land suitability evaluation of crops. The middle layer refers to the criteria for decision-making, including climate suitability, topography suitability, soil suitability, and management suitability. The lowest layer refers to alternatives in decision-making, that is, evaluation indicators; (2) construct a judgment matrix: Based on the hierarchical structure model, the judgment matrix is determined by comparing the importance of indicators to the target. The 1–9 scale method was used to compare the importance of indicators in pairs and rank them according to their importance; (3) hierarchical sorting and consistency check: Hierarchical sorting is to calculate the weight of factors (indicators) at the same level based on their importance. The sum-product method is used to calculate the maximum eigenvalue λ_{max} of the judgment matrix and the corresponding eigenvector W_i. The random consistency index RI and the consistency index CI are introduced to check the consistency of the hierarchical sorting results, and the random consistency index can be obtained in the table of RI standard value.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

$$CR = \frac{CI}{RI} \tag{2}$$

where λ_{max} is the maximum eigenvalue, n is the order of the judgment matrix. CI is the consistency index, and the smaller the index value, the more consistent it is. CR is the consistency ratio, and the larger the value, the more inconsistent it is. When $CR < 0.1$, the consistency test is passed.

The consistency test results show that the target layer and factor layer of the land suitability evaluation for the three main crops all pass the consistency test (Table 2).

2.3.3. Comprehensive Score of Land Suitability

On the basis of determining evaluation indicators, criteria, and weights, the multi-index comprehensive score calculation method was used to assess the land suitability score of the crops. Based on the Cannikin Law, when a score of a certain indicator is "0", it will become a "shortboard" factor for suitability results, and the suitability scores of other indicators will have no effect on the comprehensive score. Therefore, when the score of an indicator of the evaluated unit is "0", the comprehensive suitability score of the unit is "0", regardless of the suitability of other indicators. When none of the indicator scores of the evaluated unit is "0", the comprehensive score will be calculated by weighting and summing the scores of all indicators. It can be expressed as the following formula:

$$S = 0, \text{(When the score of a restrictive indicator of a unit is "0")} \tag{3}$$

$$S = \sum_{i=1}^{n} s_i * w_i, \text{ (When none of the restrictive indicator scores of a unit is "0")} \tag{4}$$

where S is the comprehensive score of the evaluated unit, n is the number of evaluation indicators, s_i and w_i are the score and weight of the i-th evaluation indicator, respectively.

Table 1. Land suitability evaluation index system and quantitative standard for crops.

Factors	Indicators	Soybean	Maize	Rice
		Criteria and Weights (*a-b*, *c*, *d*, *w*)		
Climatic factors	Daily mean temperature during the growth period* (°C)	20–23, 15, 25, 0.0941	20–23, 16, 28, 0.0797	22–24, 16, 28, 0.0678
	Precipitation during the growth period* (mm)	450–500, 270, 680, 0.1078	450–500, 220, 630, 0.1448	-, -, -, 0.1231
	≥10 °C accumulated temperature* (°C)	>2500, 2000, -, 0.2467	>2800, 2300, -, 0.2630	>2600, 2300, -, 0.2237
Terrain factors	Slope* (%)	0-8, -, 30, 0.0419	0-8, -, 30, 0.0295	0-2, -, 8, 0.1827
	landform type*	-, -, -, 0.0839	-, -, -, 0.0886	-, -, -, 0.0609
Soil factors	Soil texture*	-, -, -, 0.0613	-, -, -, 0.0727	-, -, -, 0.0121
	Soil thickness * (cm)	>50, -, -, 0.0568	> 50, -, -, 0.0340	>100, -, -, 0.0383
	Organic matter (g/kg)	-, -, -, 0.0305	-, -, -, 0.0340	-, -, -, 0.0121
	Available potassium (mg/kg)	-, -, -, 0.0146	-, -, -, 0.0139	-, -, -, 0.0050
	Available phosphorus (mg/kg)	-, -, -, 0.0146	-, -, -, 0.0139	-, -, -, 0.0050
	pH*	6.0–6.5, 5.2, 7.5, 0.1101	5.0–7.0, 5.2, 8.0, 0.1076	5.5–6.0, 5.2, 8.2, 0.0258
Management factors	Irrigation potential	-, -, -, 0.0386	-, -, -, 0.0259	-, -, -, 0.0841
	Drainage capacity	-, -, -, 0.0551	-, -, -, 0.0445	-, -, -, 0.0841
	Farming convenience	-, -, -, 0.0092	-, -, -, 0.0075	-, -, -, 0.0146
	Field shape regularity	-, -, -, 0.0183	-, -, -, 0.0201	-, -, -, 0.0319
	Shelterbelt density	-, -, -, 0.0165	-, -, -, 0.0201	-, -, -, 0.0290

Note: The suitability reference values of the indicators are listed in the order of *a-b*, *c*, *d*, and *w*, where *a-b* is the most suitable range of the indicator, *c* and *d* are the lowest and highest thresholds of the indicator, and *w* is the indicator weight. Indicators with "*" are restrictive indicators, and those without "*" are non-restrictive indicators. "-" means that the indicator has no suitable range or thresholds.

Table 2. Consistency test result of evaluation indicators weight.

Target Layer	Consistency Ratio	Factor Layer	Consistency Ratio
Planting Suitability of Rice	0.0304	Climatic factors	0.0088
		Terrain factors	0.0000
		Soil factors	0.0299
		Management factors	0.0214
Planting Suitability of Maize	0.0579	Climatic factors	0.0088
		Terrain factors	0.0000
		Soil factors	0.0348
		Management factors	0.0308
Planting Suitability of Soybean	0.0172	Climatic factors	0.0176
		Terrain factors	0.0000
		Soil factors	0.0594
		Management factors	0.0292

2.4. Cultivated Land Use Layout Adjustment Model

CLULA in this paper includes crop layout optimization and spatial relationship coordination. The crop planting suitability is the main basis for this study to optimize the crop layout. To facilitate the large-scale management of cultivated land, the cultivated land concentration is also an important factor to be considered. The agent-based model for optimal land allocation (AgentLA) can well take into account the land suitability and space compactness [59], which can be used for crop layout optimization. Based on the optimized crop layout, the planting characteristics, farming system, food needs, and planning orientation are take into consideration to clarify the priority order of crops occupying the same space. ArcGIS spatial analysis tools are used to achieve spatial relationship coordination between crops, and then the plan for cultivated land use layout adjustment is determined (Figure 2).

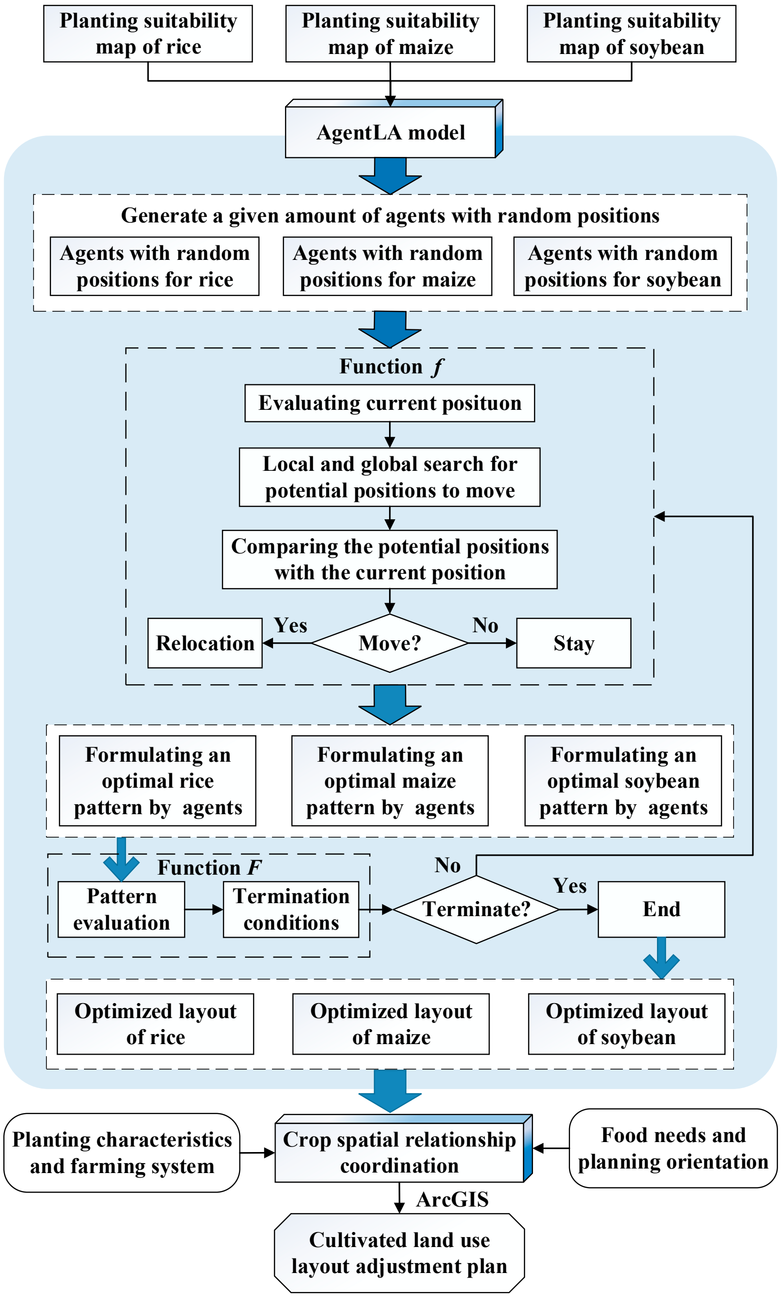


Figure 2. Procedure of cultivated land use layout adjustment.

In the AgentLA model, an agent is used to identify a single unit of the given crop type to be allocated, and each agent occupies a spatial grid. In this study, the scale of each spatial grid is set to 100 m $\times$ 100 m, which can distinguish the spatial distribution of different crop types. All the agents are different, but have the same criteria for determining a move to a better location. Initially, the model generates a spatial agent group with random positions according to the spatial scale of the study area. The population size of agents is equal to the given amount of land use to be located. Each agent will use a fitness function f to assess a potential site for relocation. An agent will move to a better location based on the assessment of the site by collecting local and global information. After all agents complete the decision, another function F is used to evaluate the optimization degree and feasibility of the whole simulated pattern [60]. By repeatedly iterating until the value change of function F tends to be stable and less than the preset threshold, the model stops iterating and outputs the final optimization result.

A fitness function f is defined to measure whether a position is worth occupying by an agent, and it includes two objectives: Suitability and space compactness. The two objectives have different weights, which directly affect the fitness function value and the final optimized layout. The formulas are as following:

$$f = w_v v + w_c c \tag{5}$$

$$c = \frac{\sum\limits_{i \in \Omega} x_i \exp(-d_i/\gamma)}{\sum\limits_{i \in \Omega} \exp(-d_i/\gamma)} \tag{6}$$

where f is the fitness function, v is the crop suitability value, c is the spatial compactness, and w_v and w_c are their weights, respectively ($w_v + w_c = 1$), x_i is a binary variable which equals 1 if cell i is occupied and 0 otherwise. Ω represents the Moore neighborhood of the central agent. d_i is the Euclidean distance from cell i to the focal agent. γ is a compensation parameter that ranges from 1 to 10.

A function F is equivalent to the evaluation function of the optimization result. It considers both suitability and spatial efficiency and considers the two factors to be equally important. The F value is between 0 and 1. The higher the F value, the better the optimization effect. F function is defined as follows:

$$F = SV - SL \tag{7}$$

$$SV = \sum_{i=1}^{n} v_i / V_{MaxSum} \tag{8}$$

$$SL = \frac{L_{Sum} - L_{MinSum}}{L_{ManSum} - L_{MinSum}} \tag{9}$$

where n is the number of agents, v_i is the suitability value of the i-th cell, V_{MaxSum} is the suitability value of the most suitable cell, SV is used to measure how well the objective of suitability is achieved, SL is a spatial morphological feature, which measures the dispersion of the simulated pattern, L_{Sum} represents the sum of the perimeter of the current pattern, L_{MinSum} is the sum of the perimeter when the pattern is assumed to be the most compact, L_{MaxSum} is the sum of the perimeter when the assumption is that all agents exist in isolation and are not adjacent to each other. The wellness of the resulted pattern increases when SV is higher and SL is smaller.

3. Results and Discussion

3.1. Planting Suitability of Food Crops

There are obvious differences in the planting suitability of rice, maize, and soybean in the study area. The natural breaks (syn. Jenks) method is used to classify the suitability, and to facilitate the comparison of suitability between crops, the classification results of the three crops are integrated into five classes: Highly suitable (S1), suitable (S2), moderately suitable (S3), marginally suitable (S4), and unsuitable (N). The results of crop planting suitability classification and distribution are shown in Table 3 and Figure 3.

3.1.1. Planting Suitability of Rice

The suitability level of rice is the lowest among the three main corps. It is indicated that 52.66 km^2, 286.37 km^2, 475.09 km^2, and 694.89 km^2 of cultivated land are located in S1, S2, S3, and S4 suitability classes respectively, accounting for only 18.16% of the cultivated land in the region. Nearly 6798.41 km^2 (81.84%) of cultivated land are not suitable (N) for rice, which covers most parts of the study area (Table 3). The main constraint for rice planting is the slope and geomorphological types in the region. Low slope and plain areas are suitable for cultivating rice. Rice cultivation has high requirements for terrain factors. The best slope is 0–2°, once the slope is more than 8°, it is not suitable for rice cultivation.

The average slope of most cultivated land in the study area is greater than 8°, and the landform type is mainly low elevation platform, which is not conducive to planting rice. Considering the suitability map (Figure 3a), the highly suitable and suitable (S1-S2) areas for cultivating rice are concentrated in the north of central Yi'an County and the south of Keshan County. The moderately suitable and marginally suitable (S3-S4) areas are mainly located in the southwest of Yi'an County and north of Keshan County. Baiquan County is less suitable for rice cultivation among the three counties, and the area suitable for rice cultivation is small and scattered.

3.1.2. Planting Suitability of Maize

The suitability results for maize showed that almost all cultivated land in the study area is suitable for cultivating maize. The suitable (S2) and moderately suitable (S3) areas for cultivating rice is 6636.15 km^2 (79.88%), which accounts for the highest proportion of cultivated land area in the region. Only 1.19% (99.10 km^2) of the cultivated land were classified as highly suitable (S1), and the marginally suitable (S4) area is 1572.16 km^2, accounting for 18.93% of the cultivated land area in the region (Table 3). The land suitability map for maize (Figure 3b) showed that the best areas for cultivating maize (S1-S2) are concentrated in the north of Yi'an County and southwest of Keshan County, and scattered in the south of Yi'an County and Baiquan County. Areas that are moderately suitable (S3) are mainly distributed around the suitable (S2) area, and the two occupy a similar proportion of cultivated land. The marginally suitable (S4) area is mainly located in the northern of Keshan County, south of central Yi'an County, and southwest of Baiquan County. Keshan County is less suitable for maize cultivation among the three counties, and nearly half of the area is marginally suitable (S4) area. According to the distribution characteristics of land suitability of maize, the main limiting factors for maize planting are climate and soil. Compared with rice and soybeans, maize cultivation has higher requirements for mean daily temperature and accumulated temperature.

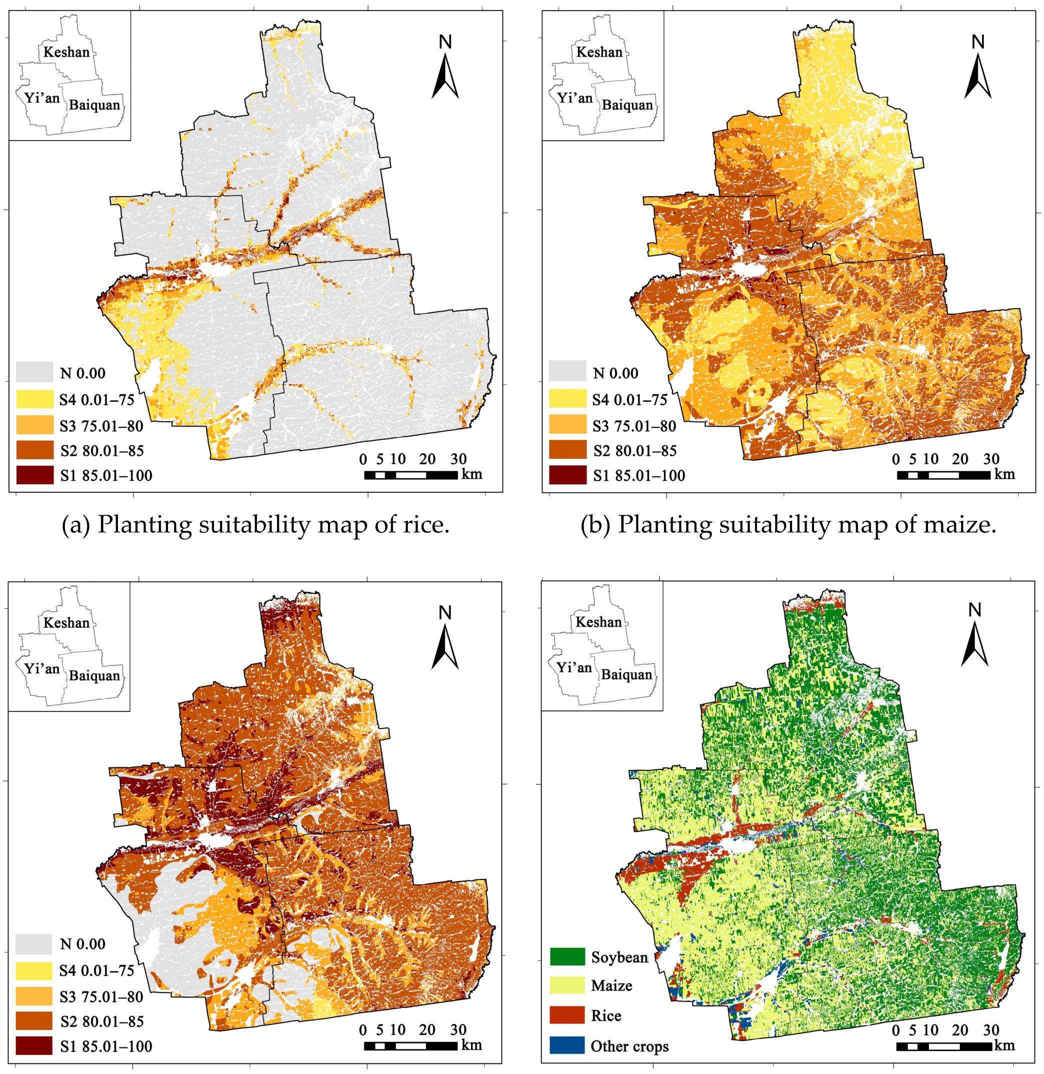
3.1.3. Planting Suitability of Soybean

The suitability level of soybean is the highest among the three main corps. It was shown that, while 1051.28 km^2 (12.65%) of the cultivated land is unsuitable (N) for soybean cultivation, 1146.73 km^2 and 4671.95 km^2 of cultivated land are located in S1 and S2 suitability classes respectively, which covered 70.04% of the cultivated land. S3 and S4 suitability classes consisted of a 62.13 km^2 and a 1375.34 km^2 area, respectively, which only covered about 0.75% and 16.56% of the cultivated land area in the region (Table 3). As can be seen from Figure 3c, the unsuitable (N) area is concentrated in the southwest of the study area, which is mainly affected by the limiting factor of soil pH. Compared with rice and maize, soybean has higher requirements for soil pH. When the pH is greater than 7.5, it is not conducive to soybean cultivation. The moderately suitable (S3) and marginally suitable (S4) areas are located mainly in the northeast and south of the region, and most of them are adjacent to the unsuitable area. The highly suitable (S1) and suitable (S2) areas are located over large areas of the study area such as the north, northwest, southeast, and central parts.

Comparing the current distribution and the planting suitability maps of crops in the study area (Figure 3), it is found that the rice is mainly concentrated in the central area of Yi'an County, while the planting suitability of rice in some areas of central Yi'an County is low. The southern area of Keshan County is very suitable for rice cultivation, but it is not used effectively. The current area of maize in the study area is very large, accounting for a relatively high proportion in three counties. However, the planting suitability level of maize in Keshan County is low, indicating that the area of maize in this area needs to be reduced. Furthermore, it can be seen that the current soybean distribution has not fully covered the high suitability area. For example, the planting suitability of soybean is high in the north and northeast of Yi'an County, but fewer soybeans are planted in this area. The above analysis shows that the current crop layout needs to be further optimized. The results show that the current distribution of crops in the study area needs to be further optimized and adjusted.

Table 3. Results of planting suitability classification of rice, maize, and soybean.

Suitability	Classification	N	S4	S3	S2	S1
	score	0	(0,75]	(75,80]	(80,85]	(85,100]
Rice	Area (km^2)	6798.41	694.89	475.09	286.37	52.66
	Proportion (%)	81.84	8.36	5.72	3.45	0.63
Soybean	Area (km^2)	1051.28	62.13	1375.34	4671.95	1146.73
	Proportion (%)	12.65	0.75	16.56	56.24	13.80
Maize	Area (km^2)	0.02	1572.16	3317.53	3318.62	99.10
	Proportion (%)	0.00	18.93	39.93	39.95	1.19



(a) Planting suitability map of rice.

(b) Planting suitability map of maize.

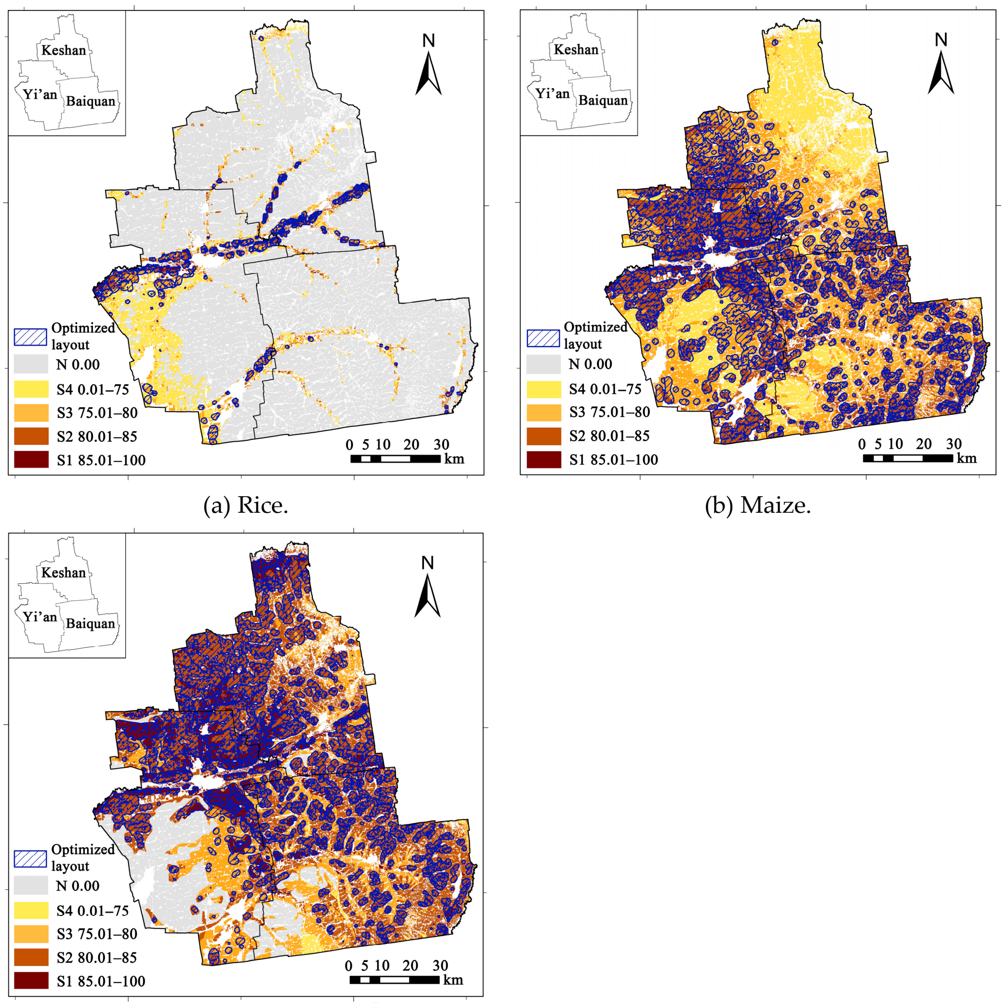
(c) Planting suitability map of soybean.

(d) Current distribution of main food crops.

Figure 3. The current distribution (**a**) and the planting suitability maps (**b**–**d**) of main food crops in the study area.

3.2. Optimized Layout of Food Crops

To improve the suitability level of crops and facilitate the large-scale management of cultivated land use, this study takes into account the planting suitability of crops and the concentration of cultivated land to optimize the layout of the main food crops in the study area. Before the AgentLA model runs, the agent number to be optimized for the target crop needs to be set. Under the influence of agricultural policies in recent years, the food crop quantitative structure in the study area has been adjusted to some degree, so this research only optimizes the spatial structure of the food crops. It is assumed that the quantity structure of the three main food crops is the same as the current year, in 2018. According to the results of the remote sensing interpretation of the current crop distribution in this study, taking 100 m × 100 m grids as the cell, the agent number to be optimized for rice, maize, and soybean are set to 43,650, 379,668, and 376,897, respectively. Through multiple experiments, it is found that when the weight w_v value is 0.7, the fitness function value F of the three crops are the largest. F values of these three outcomes are 0.87, 0.92, and 0.92, respectively, which is a relatively optimal result. Therefore, the suitability weight and the space efficiency weight are set to 0.7 and 0.3, respectively. Rice, soybean, and maize went through 134, 125, and 127 iterations, respectively, and the fitness function values tended to be stable. The iterations were stopped, and the results of cultivated land layout optimization for food crops were output. The optimized layout of rice is mainly distributed in the north of central Yi'an County and the south of Keshan County. The optimized layout of soybean is concentrated in Keshan County and the north of Yi'an County, and the optimized layout of maize is mainly distributed in Yi'an County and the west of Keshan County. For Baiquan county, the proportion of maize and soybean optimized layout is also large, but the distribution is relatively scattered (Figure 4).



(a) Rice. (b) Maize. (c) Soybean.

Figure 4. Optimized layout of rice (**a**), maize (**b**), and soybean (**c**) in the study area.

To further verify the feasibility of the optimization results, the current layout of the three crops were evaluated using the F function to compare with the optimization results. Through calculation, the evaluation values F of the current layout of rice, soybean, and maize were 0.59, 0.89, and 0.87, respectively, which were lower than the optimized value. The results show that the land suitability level of the three food crops and the concentration level of the spatial pattern of CLUL have been improved. The optimization results effectively take into account the space suitability and space efficiency of the crops and realize the optimal allocation of the cultivated land use space of food crops. Among them, the optimization effect of rice was the best, indicating that the current rice distribution is not reasonable, and the land production potential can be further tapped. This is mainly because the planting suitability level of the current rice layout is low, and the improvement space is large.

3.3. Adjustment Plan of CLUL

Food crops and cultivated land have a unique correspondence in space. The spatial combination of multiple crops forms the CLUL. On the same land space, there are both competition and cooperation between crops. How to coordinate the spatial relationship between crops is a key issue to be considered in CLULA. This study combines the planting characteristics, farming system, and policy orientation of the food crops in the region, and considers factors such as food demand, cultivated land management, and cultivated land ecological security to coordinate the spatial layout relationship of crops, and then to delineate the adjustment areas of CLUL and determine the adjustment unit.

3.3.1. Distribution of CLULA Areas

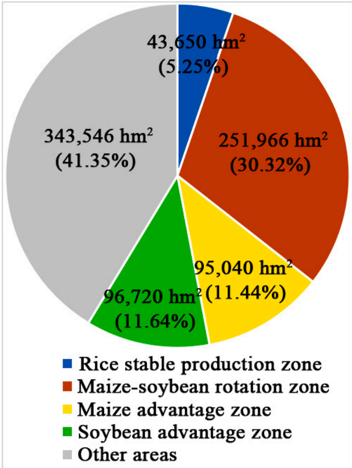
The remote sensing interpretation results of the current crop distribution in this study show that, in 2018, the planting ratio of rice, soybean, and maize in the region was about 1:8.71:8.64. In 2016, the Ministry of Agriculture of China issued the "National Plant Restructuring Plan (2016−2020)" and put forward requirements for the crop planting structure in Northeast China, that is, by stabilizing the rice area, reducing the maize area, expanding soybeans, miscellaneous grains, potatoes, and forage crops, and constructing a reasonable rotation system to adjust the crop planting structure. To protect paddy field resources in the study area and stabilize rice production, the first step is to determine a rice stable production area based on the agricultural policy guidance and the optimized layout of food crops. In this study, the rice optimized layout (Figure 4a) was directly identified as the rice stable production area. To further adjust the cultivated land layout of other crops, we used the toolbox of ArcGIS to subtract the stable rice production area from the optimized layout of maize (Figure 4b) and soybeans (Figure 4c), and extract the optimized layout of maize and soybeans that do not overlap with the stable rice production area, which can be defined as area M and area N. The continuous cultivation of the same crop for many years will cause problems such as soil environmental damage and the decline of cultivated land fertility [61]. To ensure the ecological security and the sustainable use of cultivated land, priority should be given to determine the crop rotation area to reduce the ecological cost of continuous farming. Among the major crops in the region, maize and soybeans have similar climate, humidity, and temperature requirements. Soybean can absorb and fix nitrogen in the air, which can effectively improve soil fertility. Maize is a nitrogen-loving crop. Soybean and maize rotation planting will have a good effect on the storage of soil nutrients. Therefore, the second step was to determine the maize–soybean rotation area. The ArcGIS toolbox was used to take the intersection of area M and area N, and get the maize–soybean rotation area. The final step was to determine maize and soybean layout adjustment areas. The ArcGIS toolbox was used to subtract the maize–soybean rotation area from the area M and area N respectively, to obtain the maize dominant area and the soybean dominant area, which can guide the maize and soybean planting decisions such as reduction and expansion.

According to the statistics of the research result (Figure 5a), the total area of the stable rice production area is about 436.50 km^2, accounting for 5.25% of the total cultivated land area of the region, which is mainly distributed in Keshan County and Yi'an County. The overall shape of the stable rice production area is like a stripe running through the east–west direction, concentrated in the central region and scattered in the southern part of the study area. The maize–soybean rotation area accounts for 30.32% of the total cultivated land in the region, with a total area of about 2519.65 km^2, concentrated in the west of Keshan County and the north of Yi'an County, and scattered in the south of Yi'an County and Baiquan County. The area of the maize dominant area and the soybean dominant area are similar, about 950.40 km^2 and 967.20 km^2, respectively, accounting for 11.44% and 11.64% of the total area of cultivated land in the region, but the spatial distributions of the two areas are quite different. The soybean dominant area is mainly distributed in the northern part of the region, and Keshan County occupies a relatively high proportion. The maize dominant area is scattered in the southern part of the region, and Yi'an County and Baiquan County have a relatively high proportion (Figure 5b).

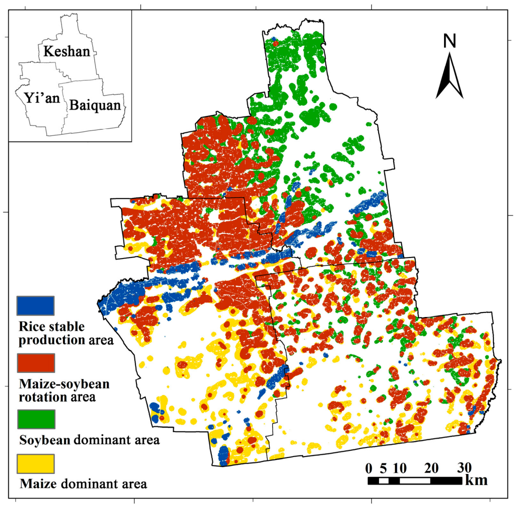
The results of CLULA show that the planting suitability and spatial agglomeration of the three main crops have been improved, which can be verified by the F value mentioned above. It can be estimated that after adjustment, the F value of corn and soybeans has increased by about 5%, and that of rice has increased by 47%. The improvement of planting suitability can effectively increase the potential for food production, and the centralized crop layout can increase the scale benefits of farmland. Besides, corn and soybean rotation can effectively improve the fertility of farmland and ensure sustainable land use.

3.3.2. Implementation Unit of CLULA

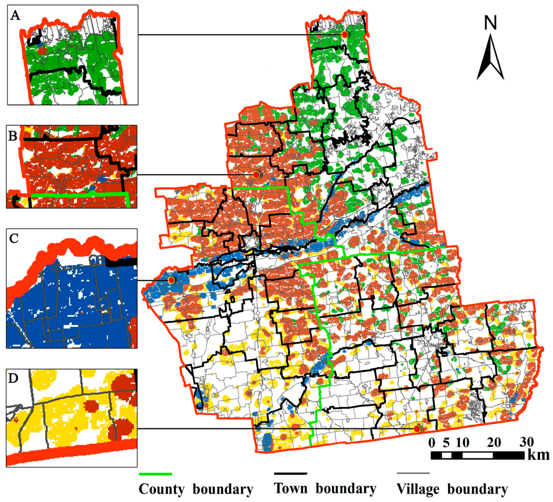
Based on the adjustment area for the utilization of cultivated land, this study determined the adjustment unit according to the distribution characteristics of the adjustment areas. There are obvious differences in the distribution of different adjustment areas. Among them, the soybean dominant area, and maize–soybean rotation area in the north and west of Keshan County are concentrated, while the soybean dominant area, rice stable production area, and maize–soybean rotation area in the east and south of the county are scattered. In the northern, central, and eastern parts of Yi'an County, the distribution of maize–soybean rotation area and rice stable production area are concentrated, while the distribution of maize dominant area and maize-soybean rotation area in the southeast of the county are scattered. In contrast, the distribution of the four adjustment areas in Baiquan County is scattered. To ensure the efficiency and effectiveness of the implementation of CLULA, considering the distribution characteristics of the adjustment areas and the scale of the internal administrative units of each county, the adjustment units are divided into towns and villages. The areas where the adjustment areas are concentrated are adjusted in units of towns. For example, town A in the north of Keshan County is identified as an adjustment unit of soybean dominant area, and town B in the west of Keshan County is identified as an adjustment unit of maize–soybean rotation area. The areas where the adjustment areas are scattered are adjusted in units of villages. For example, village C in the west of Yi'an County is identified as an adjustment unit of rice stable production area, and village D in the south of Baiquan County is identified as an adjustment unit of maize dominant area (Figure 5c). Town or village should be selected as the implementation unit for CLULA according to local conditions to effectively implement the adjustment plan.



(a) Statistics of cultivated land use layout adjustment (CLULA) areas.



(b) Distribution of CLULA areas.



(c) Implementation unit of CLULA.

Figure 5. Statistics (**a**), distribution (**b**), and implementation unit (**c**) of CLULA.

The study effectively coordinated the spatial relationship between different food crops, and obtained an adjustment plan for CLUL integrating farming with protecting land, which provides a scientific basis for the spatial implementation of CLULA, and enables the adjustment plan within the scope of town or village to be carried out quickly. The research results also provide a reference for CLULA in other similar areas. While delineating the adjustment areas and determining the implementation unit, the guidance of farmers in different CLULA areas should be strengthened, and it is an important way to effectively implement the CLULA. For the rice, stable production area, soybean dominant area, and maize dominant area, the cultivation of dominant crops should be guided. Special attention should be paid to expanding soybean in soybean dominant areas and reducing maize in non-dominant maize areas, to alleviate the current structural contradiction between grain supply and demand. It should be noted that soybean continuous cropping for 2 years will lead to a yield decline. Therefore, soybean–wheat, soybean–tuber, and other crop rotation models should be supported in the soybean dominant area, and the selection of specific crop rotation models also needs to consider the suitability of other crops. Considering the differences in production costs and prices of different crops, the CLULA will lead to changes in the economic interests of farmers, and planting income is an important factor affecting farmers' planting decisions. It is necessary for the government to improve the price policy of agricultural products and guide farmers to adjust the planting structure according to market demand. For the maize–soybean rotation area, combined with the soil, climate, and other natural conditions in the region, the "maize–soybean" annual rotation or "maize–maize–soybean" rotation pattern should be adopted. The specific pattern can be selected based on market prices and the actual demand, which not only guarantees economic benefits, but is also conducive to land recuperation. Additionally, it is advisable to carry out pilots for cultivated land rotation in units of towns or villages, and gradually expand the scope of cultivated land rotation by summing up the experience of the pilots. In addition, advancing agricultural technological innovation and improving the level of agricultural machinery are also crucial to promote CLULA.

CLULA is a complicated systematic project, which not only involves the optimal allocation of spatial factors for cultivated land use, but also involves the specific implementation process, including coordinating the interests of the participants, constructing a scientific adjustment model, formulating safeguard measures, and designing policy systems, etc. This study mainly guided the precise implementation of CLULA from the spatial level. How to establish a scientific guidance mechanism to ensure the effective implementation of CLULA needs further discussion. Furthermore, under the guidance of the agricultural planting structure adjustment policy in China, the imbalance of the grain planting structure in the Northeast region has been alleviated to some extent, but the scientific nature of the quantitative structure remains to be discussed in depth. To further ensure the scientificity and rationality of the adjustment of the planting structure in terms of quantity and space allocation, it is necessary to simultaneously optimize the quantitative structure and spatial structure of crops while taking into consideration the natural and management conditions of crops, as well as the needs of socio-economic development at the current stage. Cultivated land use layout research that takes into account the optimization of quantitative structure and spatial structure will become the focus of the next step of exploration.

4. Conclusions

To alleviate the current planting structural imbalance and the grain structural contradiction in China, this paper is based on the planting suitability of food crops, taking into account the crop suitability level and the CLUL concentration level, to optimize the spatial layout of the main food crops in the study area. By coordinating the spatial relationship of different food crops for cultivated land use, the adjustment plan for CLUL is determined.

The results from the present study show that, affected by factors such as terrain and climate, there are obvious differences in the suitability level of rice, soybean, and maize planting in the study area. The current layout of the three crops needs to be further optimized and adjusted, and the crop planting suitability provides an important basis for the optimization of crop layout. Selecting areas with high suitability for crop planting will be conducive to enhancing the production potential and efficiency of cultivated land.

Compared with the current distribution of the crop, the optimized crops layout cover areas with high land suitability, and the spatial pattern of CLUL is more concentrated and contiguous. The optimized layout of rice is concentrated in the north of central Yi'an County and the south of Keshan County, the optimized layout of soybean is concentrated in the north of Yi'an County and the north and west of Keshan County, and the optimized layout of maize is concentrated in the north of Yi'an County and the west of Keshan County. The optimized results are conducive to the implementation of large-scale crop structure adjustment and optimization, and effectively promote the large-scale management of cultivated land.

The adjustment plan for CLUL fully considers the characteristics of food crop planting, planning policy orientation, and cultivated land ecological security factors. Four adjustment areas for CLUL were delineated: Rice stable production area, maize-soybean rotation area, maize dominant area, and soybean dominant area. Town or village was identified as the implementation unit for CLULA in the study area. The research results achieved a reasonable spatial matching of multiple cultivated land use factors such as climate, terrain, soil, and management of different crops, which will be conducive to the sustainable use of cultivated land that adapts to the laws of natural ecology and coordinates multiple development goals. Furthermore, enhancing regional guidance to farmers and improving agricultural product price policies are the key paths to ensure the effective implementation of CLULA.

This study provides useful guidance that can be used to make fine management for regional crop planting structure adjustment and cultivated land layout optimization. Additionally, the study on CLULA is used to refine and deepen land use transition on the basis of grasping the dominant morphology and recessive morphology characteristics of cultivated land use. Through the guidance and control of land use morphology by means of CLULA, land use transformation will achieve the expected goal, and then realize the sustainable and efficient use of urban and rural land resources.

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