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Farmland Suitability Evaluation Oriented by Non-Agriculturalization Sensitivity: A Case Study of Hubei Province, China

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Abstract: Farmland is one of the key factors affecting national or regional food security, and farmland suitability evaluation can provide critical information for the spatial layout of farmland. Previous studies have mainly focused on the role of natural factors in suitability evaluation, while ignoring the important influence of socio-economic activities. This study selects natural factors such as elevation and slope and non-agriculturalization sensitivity factors to build a farmland suitability evaluation framework of "natural non-agriculturalization sensitivity", quantify the farmland suitability, and uses GIS technology to classify the evaluation results into four levels: highly, moderately, barely, and unsuitable. The results show that the non-agriculturalization sensitivity of farmland in Hubei Province shows the spatial characteristics of multi-point clustering, with density increasing from west and north to central and east; the overall farmland suitability in Hubei Province is high, and the areas of highly, moderately, barely, and unsuitable farmland account for 2.32%, 67.69%, 11.49%, and 18.50%, respectively. In terms of spatial distribution, there are obvious spatial differences in the farmland suitability, with highly and moderately suitable areas mainly distributed in the central and eastern regions and barely suitable and unsuitable areas mainly distributed in the western, northeastern, and southeastern parts of Hubei Province.

Keywords: land planning; framework; socio-economic factors; geographic information system

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1. Introduction

Farmland is the basis of food production. Farmland protection is related to food security and social stability. Rational development, utilization, and protection of farmland is an inevitable requirement to promote social stability and healthy economic development [1]. Farmland suitability evaluation (FSE) can provide key information for the spatial layout of farmland and is the main content of land evaluation. In the 1830s, incipient systematic land evaluation activities were developed in the UK; the British Land Surveyors Club established in 1834 made land evaluation activities more professional and standardized on the basis of systematization. Subsequently, land evaluation activities have developed relatively rapidly, and their development history can be generally divided into four stages: (1) Land classification and grading stage. The research activities in this stage have lasted for nearly a century for the purpose of land taxation, among which well-known research results include the "Storie Index Rating" in the United States, "Cornell System", and *Land Appraisal Materials* in Germany, etc.; (2) land potential evaluation stage. The research activities in this stage began with the land potential classification proposed by the U.S. Department of agriculture in 1936. After which, many achievements have been obtained in the evaluation of climate productivity, soil productivity, and other indicators, such as the soil productivity index (1970), the agro-ecological regional method (1977), and the Miami model (1971) [2]; (3) land suitability evaluation stage. In the 1970s, many countries represented by the United

States and Germany started to conduct research activities on land suitability evaluation. *A Framework for Land Evaluation*, published by FAO in 1976, provides direction and guidance for land suitability evaluation; (4) stages of sustainable land use evaluation. Since the 1990s, the strategy of sustainable development has gradually become a global consensus and more attention has been paid to the sustainable use and evaluation of land resources. FAO promulgated *An International Framework for Evaluating Sustainable Land Management* in 1993, which provides a basis for a sustainable land-use evaluation around the world. A worldwide sustainable land-use evaluation was initiated [3].

China's land suitability evaluation was fully launched in the late 1970s. Under the idea of the outline of land evaluation, the government and scholars conducted land suitability evaluations in some areas of China, in this process, a land evaluation system suitable for China was formed, such as *Technical Regulations for Land Evaluation at County-Level (Trial draft)*, *Outline of the National Land Use Master Plan* in different periods, etc. Since the 1990s, the academic community has actively applied GIS technology and mathematical methods to evaluate the suitability of non-agricultural land [4,5] and achieved fruitful results [6]. So far, land suitability evaluation is still an important part of land evaluation, which can be roughly divided into the suitability evaluation of non-agricultural land such as construction land [7,8] and agricultural land such as cultivated land [9,10], attracting extensive attention of scholars and policymakers.

Farmland non-agriculturalization is a land allocation problem caused by the competition between farmland and construction land. It is the inevitable result of the development of industrialization and urbanization. The third national land resource survey of China shows that the total area of farmland in China is 1.32 million km^2, a decrease of 75,333 km^2 compared with 10 years ago. According to the data in the *China Land and Resources Statistical Yearbook*, from 2013 to 2017, the cumulative area of farmland occupied by non-agricultural construction in Hubei Province was up to 818.67 km^2, accounting for 87.4% of the total area of farmland reduction. The non-agricultural transformation of farmland has become an important factor affecting farmland stability; therefore, we constructed the indicator of "non-agriculturalization sensitivity" and incorporated it into the framework of farmland suitability evaluation. The term "sensitivity" is widely used in various fields such as finance, physiology, and politics, and scholars have defined sensitivity according to the application scenarios of each discipline. For example, "ecological sensitivity" was proposed earlier by Suffling (1980) [11]; the Chinese scholar Ouyang Zhiyun (2000) defined it as the degree of ecosystem response to human activities and natural environmental changes, which can indicate the degree of difficulty and likelihood of regional ecological problems [12]. Drawing on the definition of "ecological sensitivity", the non-agriculturalization sensitivity of farmland is defined as the possibility of converting farmland agricultural use to non-agricultural use under the influence of socio-economic factors. A parcel of land, even if it is suitable for agricultural cultivation in its natural attributes, is not conducive to farmland stability if it is easily occupied by non-agricultural activities and is clearly not suitable for layout as farmland. The layout of farmland needs to consider not only natural factors but also non-agriculturalization sensitivity factors. In view of this, it has important practical application value for considering the non-agriculturalization factors in FSE on the basis of the existing farmland suitability evaluation system.

In the current research on FSE, scholars commonly introduce natural factors such as soil, terrain, and climate. Although some scholars have paid attention to the impact of economic and social conditions on farmland suitability and take factors such as traffic accessibility and per capita GDP into account, the factors of non-agriculturalization sensitivity of farmland have not been fully valued and discussed; how to quantify farmland non-agriculturalization sensitivity and incorporate it into the appropriateness evaluation framework needs to be further studied.

In view of the above reasons, this study builds a non-agriculturalization sensitivity indicator to describe the impact of non-agriculturalization sensitivity on farmland layout from three aspects: distance from the city center, socio-economic density, and road network density. The improved evaluation framework of "nature-non-agriculturalization sensitivity" not only considers the impact of traditional natural factors on the layout of farmland but also innovatively integrates the indicators of non-agriculturalization sensitivity of farmland into the framework. The improved evaluation framework of FSE develops from static system to dynamic process, making FSE more effectively and accurately. It provides key information for exploiting farmland reserve resources and supports the optimization of farmland resource layout.

2. Literature Review

Farmland suitability evaluation is a process of assessment of farmland performance in order to determine whether it is suitable for cultivation [13–15], which can provide a key reference for decision making and the adjustment of the layout of agricultural production activities, and it is conducive to the sustainable development of farmland resources. Based on literature reviews (Table 1), it can be known that the frameworks of farmland suitability evaluation is mainly composed of natural indicators, for example: the framework of "climate-topography-soil" [16], "landform-climate-soil-location" [17], "climate-slope-soil-water [18], "soil-site" [19], "soil nutrients-location-physical and chemical properties-soil management" [20], and "climate-location-physical-chemical properties-soil nutrients" [21]. With the development of economy and society, scholars began to realize that farmland suitability is not only affected by natural factors but also disturbed by social and economic conditions to a considerable extent. Therefore, on the basis of natural factors, scholars began to try to incorporate economic factors such as traffic accessibility and distance from the market as evaluation factors in farmland suitability evaluation [9,22–24]. For example, in order to solve the soil erosion caused by deforestation and rotation cultivation in the Himalaya region of East India and take protective measures in time, scholars did not only introduce the indicators of climate, soil, topography, and ecology. They also took into account the actual local situation and fully considered the impact of socio-economic factors such as the location of existing road network settlements and drainage networks [22]. Maddahi et al. [23] also used a traffic accessibility indicator to analyze the suitability of rice planting areas in central Amur, Iran; in order to improve and solve the limited conditions of citrus planting in the western Nghe An region through advanced technology, this study not only selects natural indicators such as climate and terrain but also fully considers the impact of the distance to roads and markets on agricultural planting [24].

In terms of evaluation methods, the analytic hierarchy process [25–28], multi-criteria decision-making method [29–32], and spatial fuzzy evaluation model [33,34] have been widely used in farmland suitability evaluation. Since the 1990s, with the emergence and development of geographic information systems (GIS) technology, the latter has been widely used in suitability evaluation; using it for spatial analysis overcomes the disadvantages of heavy workload and low efficiency of traditional methods and makes the analysis more accurate and quicker [27,35,36]. For example, based on GIS technology and analytic hierarchy process, scholars applied the multiple-attribute decision-making method from natural factors to evaluate regional farmland suitability and identify different grades [8,37–39].

Through the literature analysis, we can know that there are rich studies on FSE which have important academic value. These studies provide important support for follow-up research, but there is still research space: in the construction of the evaluation framework, scholars mostly introduce natural factors such as soil, terrain, and climate, although some scholars have paid attention to the impact of economic and social conditions on FSE, but the impact of farmland non-agriculturalization factors on FSE has not attracted enough attention and discussion. This study constructs the non-agriculturalization sensitivity evaluation indicator and brings it into the FSE framework to measure the key impact of farmland non-agriculturalization factors on suitability so as to improve the evaluation framework and thus improve the accuracy of FSE.

Table 1. Framework and methodology for FSE.

Framework	Methods	Study Area	References
Climatic-Topographic-Soil properties	Pair-wise rating method; GIS technology	Zambia rainfed paddy rice production region	[16]
Climate-Slope percentage-Soil types-Water wells distributions	Multi-criteria decision-making method	Ma'an Governorate, Jordan	[18]
Soil nutrients-Location-Physico-Chemical properties-Soil management	Hierarchical analysis process; GIS technology	Yongding District, Zhangjiajie City	[20]
Climate-Location-Physico-Chemical properties-Soil nutrients	Expert scoring; Hierarchical analysis process; GIS technology	Maize growing area	[21]
Soil properties-Terrain-Climatic-Accessibility	FAHP (fuzzy hierarchical process); GIS technology	Central Amol District, Iran; rice	[23]
Climate-Slope-Soil	Expert scoring method; Hierarchical analysis process; GIS technology	Agamsa sub-basin, Ethiopia; sorghum crop	[27]
Slope-Soil-Drainage class-Land use/cover-Water availability	Multi-criteria evaluation decision-making (MCE) techniques; GIS technology	Ethiopian Rift Valley Basin	[38]
Climatic-Soil-Terrain	Expert scoring method; hierarchical analysis process; parametric method; GIS technology	Northeastern Iran; oak, pine	[39]
Soil-Vegetation-Location-Production	Expert scoring; hierarchical analysis process; GIS technology	Huanghe Island	[40]
Terrain and Landforms-Soil environment	Integrated evaluation method; hierarchical analysis process; GIS technology	Yong'an City; agricultural land	[41]
Terrain-Soil-Water	GIS technology; Remote Sensing Technology	Zhangzhou City	[42]
Soil-Terrain-Temperature-Water	Hierarchical analysis process; expert scoring method; GIS technology	Xiasiwan Town, Ganquan County, Shaanxi Province	[43]
Climate-Terrain-Soil physical properties-Moisture conditions-Chemical fertility	Laboratory analysis; productivity indices	Southwest Cameroon coastal plain; oil palm land	[44]

3. Methodology

3.1. Study Area

Hubei Province is in the central region of China, bordering six provinces with superior geographical location. It is between 108°21′42″–116°07′50″ E and 29°01′53″–33°6′47″ N. Most areas are subtropical monsoon climate, with sufficient light, abundant precipitation, and the same season of rain and heat; it is located in the transition zone from the second ladder to the third ladder of China's terrain, the landform types are complex and diverse, and the mountainous area is vast, accounting for about 56% of the total area. The terrain of the eastern, western, and northern regions is mostly mountainous, and the south-central part is the Jianghan Plain (Figure 1). On the whole, Hubei Province has unique agricultural production conditions and occupies an important position in national grain production. In 2019, the farmland area in Hubei Province was 52.35 km^2. Affected by economic growth and rapid urbanization, a large number of farmland was transformed into construction land, and the farmland resources in Hubei Province are gradually decreasing. The accurate evaluation of farmland suitability can provide key information for farmland protection and the supplement of farmland reserve resources in Hubei Province so as to ensure food security and sustainable development.

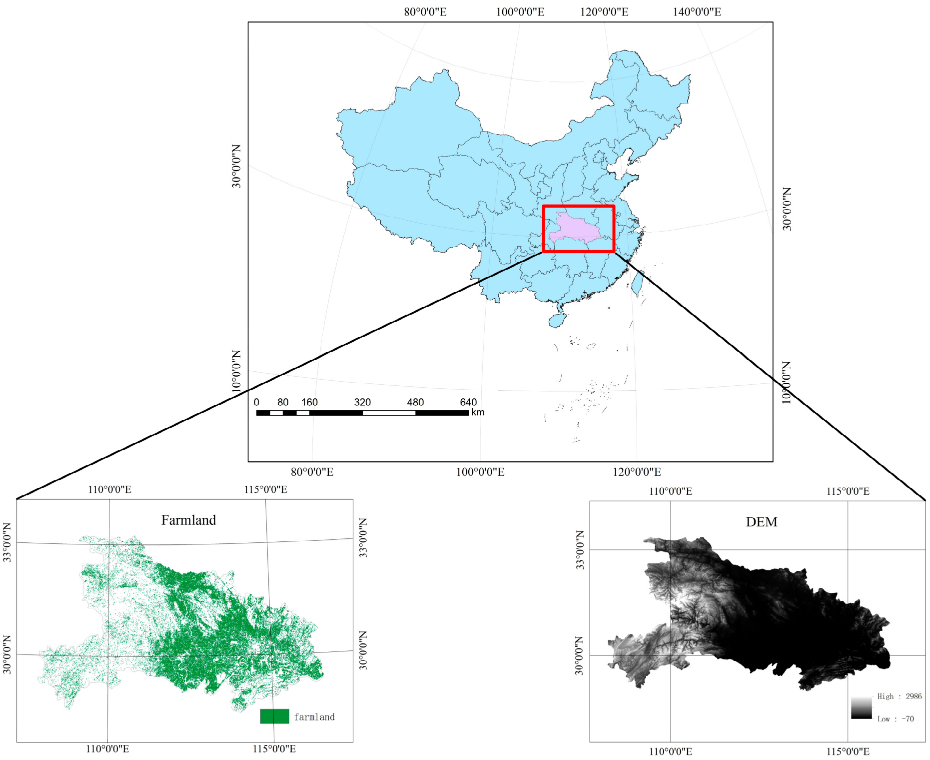


Figure 1. Location of Hubei Province in China.

3.2. Methods

Taking soil conditions, terrain conditions, climatic conditions, and non-agriculturalization sensitivity as indicators, this study constructs the framework of FSE, comprehensively using the Delphi method and analytic hierarchy process to calculate the weight of each evaluation factor, and then using the "Raster Calculator" tool of ArcGIS10.2 (Environmental Systems Research Institute Inc., Redlands, CA, USA) to synthesize the four indicators to obtain the value of farmland suitability. Finally, according to *A Framework for Land Evaluation* (Food and Agriculture Organization of the United Nations, 1976), the suitable value is divided into four categories: highly suitable, moderately suitable, barely suitable, and unsuitable (Figure 2).

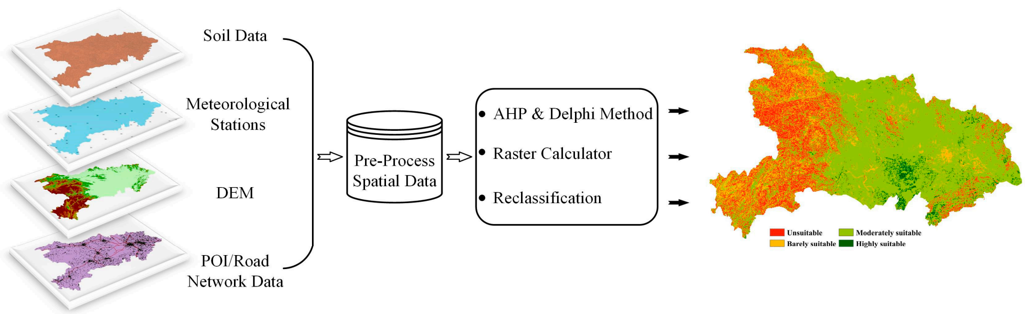


Figure 2. Workflow of FSE oriented by non-agriculturalization.

3.2.1. Evaluation Framework of FSE

On the basis of literature reviews, combined with *A Framework for Land Evaluation*, this study selects four indicators: soil conditions, terrain conditions, climatic conditions, and non-agriculturalization sensitivity to form the suitability evaluation framework (Table 2).

Table 2. Framework of farmland suitability evaluation.

Objective Level	Criteria Layer	Indicator Layer
Suitability evaluation of farmland	Soil conditions	Soil thickness Soil organic matter Soil pH value
	Terrain conditions.	Elevation Slope
	Climatic conditions	Annual average precipitation ≥10 °C accumulated temperature
	Non-agriculturalization sensitivity	Socio-economic activity density Distance from the city center Road network density

(1) Soil

Soil is one of the key factors to determine whether a plot is suitable for planting crops. Soil contains minerals, organic matter, air, and water that are necessary for crop growth, the quality of soil conditions is one of the most important factors affecting crop survival and growth. In this study, three factors, namely soil thickness, soil organic matter, and soil pH value are selected to measure soil conditions.

The soil thickness affects the level of soil fertility and plays a key role in the growth quality of crops. Deep soil is not only conducive to the deep and wide distribution of crop roots but also can effectively avoid the loss of crop nutrients. The thicker the soil of the plot, the more suitable it is for farmland.

As an important component of soil nutrients, soil organic matter is one of the essential nutrients for crop growth. Rich soil organic matter can not only promote the growth and development of crops but also improve the soil structure. The higher the soil organic matter content of a parcel, the better it is for farming production.

Soil pH value, also known as soil acidity, plays a key role in the maturation cycle and quality of crops. Soils with pH values between 6.5 and 7.5 are neutral, those below 6.5 are acidic, and those above 7.5 are alkaline. Acidic or alkaline soil not only hinders the root growth of crops but also have a negative impact on the transformation of soil nutrients; the more neutral the soil tends to be, the higher suitability of the farmland.

(2) Terrain

Terrain is one of the key factors affecting farmland suitability. It has a significant impact on the suitability of crops, the type of crops suitable for cultivation, and the growth of crops. In this study, elevation and slope are chosen to measure terrain factors.

On the one hand, elevation has an important impact on temperature, the higher the elevation, the lower the temperature and the greater the temperature difference between day and night, which in turn affects the growing environment of crops; on the other hand, too high an elevation can have an impact on the coherence of the land, which is not conducive to large-scale agricultural production and has a negative impact on farming efficiency.

In addition to this, the slope of the plot can cause loss of soil nutrients, resulting in uneven soil fertility, which is not conducive to the absorption of nutrients by crops; the slope can have an effect on temperature, with the temperature distribution at the top and bottom of the slope not being the same, which may result in uneven heat and light exposure to crops. The topography of western, north-eastern, and south-eastern regions of Hubei Province is undulating and unsuitable for the layout of farmland.

(3) Climate

As crops grow and develop under natural conditions, climate has a very important influence on crop growth. Climatic conditions directly affect the amount of light, heat, and water necessary for crop growth. This study intends to measure the importance of climatic conditions for farming using cumulative temperatures greater than or equal to 10 °C and average annual precipitation.

A cumulative temperature greater than or equal to 10 °C is a good indicator of the heat necessary for crop growth. The higher the accumulated temperature, the lower the risk of frost damage and the higher the yield. In addition, higher cumulative temperatures can increase the replanting index of land and improve the efficiency of land cultivation; precipitation largely affects the type of crop planting, which can effectively ensure the water required for crop growth, with higher cumulative temperatures and higher average precipitation being more suitable for the layout of farmland. Except for extreme weather, there is little difference in overall precipitation and accumulated temperature in Hubei Province, which has relatively little impact on the classification of farmland suitability.

(4) Non-agriculturalization sensitivity

With further development of urbanization, the demand for construction land for economic development and population growth is increasing year by year, so it is inevitable that farmland is encroached upon. Under the existing research system and research results, the non-agriculturalization sensitivity of farmland can effectively represent local socio-economic conditions; the level of socio-economic activity density, the proximity to the city center, and the road network density determine the level of infrastructure and the number of social services. Therefore, it is feasible to measure the non-agriculturalization sensitivity of farmland from three aspects: socio-economic activity density, distance from the city center, and road network density.

Firstly, socio-economic activity is an important factor affecting non-agriculturalization sensitivity. The more concentrated the population and the higher the economic and social activity of a region, the more vulnerable the land use of the region to human socio-economic activities. Then, the stronger the non-agriculturalization sensitivity of farmland in the region, the less suitable it is for the layout of farmland.

Secondly, land too close to the city center is vulnerable to the interference of social and economic development due to its special geographical location, which is not suitable for large-scale production activities, so it is not suitable for development as farmland. The closer the land is to the city center, the less suitable it is for agricultural production.

Finally, the construction of roads is one of the most important aspects of urban development and has an important impact on economic production and the daily life of inhabitants. On the one hand, the construction of roads itself generates the occupation of farmland, and on the other hand, the construction of roads promotes the concentration of population and the development of industry, which lead to the occupation of farmland by non-agricultural activities. Therefore, road network density has a very important influence on the rational layout of farmland.

Then, based on the construction of the framework, the Raster calculator tool in ArcGIS is used to calculate the comprehensive score of farmland suitability, that is, it is synthesized according to the assignment and weight of the evaluation factors in the four criteria layers of soil conditions, terrain conditions, climate conditions, and non-agriculturalization sensitivity. The specific formula is as follows:

$$S = \sum_{i=1}^{n} W_i A_i$$

S is the composite score of arable land suitability; W_i is the weight of the ith factor; A_i is the graded score of the ith factor; n is the number of participating factors.

3.2.2. Indicators for Suitability

(1) Calculation of soil condition indicators

In the calculation of soil conditions, this study selects three secondary indicators: soil pH value, soil organic matter content, and soil thickness. The data of all indicators are Raster data obtained by directly extracting elements on the basis of soil condition vector data. On this basis, this study standardizes the raw data by scoring the evaluation factors for different attributes on a scale of 1–10.

(2) Calculation of terrain condition indicators

The elevation data in the terrain conditions come from the 30 m digital elevation data in Hubei Province. The slope data are extracted from the elevation data through the "slope" tool in the "surface analysis" of ArcGIS10.2 software(Environmental Systems Research Institute Inc., Redlands, CA, USA). On this basis, the elevation and slope are still standardized in this study.

(3) Calculation of climatic condition indicators

The climatic conditions are mainly obtained from the meteorological station data of China in 2018, intercepting Hubei Province and its surroundings (Shaanxi Province, Chongqing City, Hunan Province, Jiangxi Province, Anhui Province, and Henan Province). On the basis of this, the "kriging interpolation" method in ArcGIS software's "interpolation analysis" was used to spatially interpolate the cumulative temperature greater than or equal to 10 °C and average annual precipitation of the six provinces. The data of Hubei Province were extracted by "extraction by mask" and standardized.

(4) Calculation of non-agriculturalization sensitivity indicator

Non-agriculturalization sensitivity can be used to measure the possibility of a parcel of land becoming non-agricultural land. The higher the non-agriculturalization sensitivity of the land, the more likely the land is to be non-agricultural. This study selects three factors: socio-economic activity density, distance from the city center, and road network density. Among them it can be noted the closer to the city center, the higher the road network density and socio-economic activity density and the higher the non-agriculturalization sensitivity of land. For the indicator of distance from the city center, the higher the original value, the higher the standardized value, while for the indicators of road network density and socio-economic activity density, the higher the original value the lower the standardized value, the less suitable the area is for agricultural production.

When measuring the socio-economic activity density, this study extracted the POI data of six areas in Hubei: food and beverage services, scenic spots, science, education and culture, commercial and residential buildings, living services, and government institutions, and then calculated the socio-economic activity density of Hubei Province through point density analysis. According to the principle "the lower the socio-economic activity density, the lower the non-agriculturalization sensitivity of farmland", the assignment calculation is carried out for different densities of land.

In measuring the distance between the plot and the city center, the primary issue is how to confirm the city center. Qin et al. [45] used the local spatial autocorrelation method and natural discontinuity method to identify the urban pattern of Nanjing based on mobile phone signaling data, business type POI data, and urban building big data; Wu et al. [46] used the local spatial autocorrelation method based on POI data, night lighting data, and administrative district data, using kernel density estimation methods to identify the spatial structure of megacities, etc. Identifying urban centers is very complex work, so this study does not carry out separate work on it. Through the summary and induction of existing research results, it is found that population, road network, pedestrian flow, and other indicators are often used to identify urban centers, while the urban business district has the characteristics of convenient transportation, dense population, and large passenger flow. Based on this, this study plans to use the traditional business center as the alternative point of the urban center, and then select it according to the historical development and origin of each business center in the city. The data were mainly obtained from urban planning maps published by the natural resources and planning bureaus of prefecture-level municipalities. Firstly, the distance to the city center is calculated by using the "Euclidean distance" tool in ArcGIS software, and then the Euclidean distance is reclassified according to the principle of "the closer to the city center, the easier the land is to be non-agricultural; the farther away from the city center, the more suitable it is to carry out agricultural production".

When measuring road network density, this study extracts the highway lines (except expressways) in Hubei Province and uses the "line density analysis method" in the "nuclear density analysis" in ArcGIS to calculate road network density in Hubei Province. The higher the road network density, the stronger the sensitivity of farmland non-agriculturalization.

(5) Criterion scores for indicators

Based on the extracted evaluation factors, each indicator was assigned a graded value on a scale of 0–10 (Table 3). In 1984, the China Agricultural Zoning Commission issued *The Technical Regulations for the Survey of Current Land Use*. Due to the great difference in the impact of different grades of ground slope on the use of farmland, the slope of farmland is divided into five grades: ≤2°, 2°~6°, 6°~15°, 15°~25°, and >25°; in terms of pH value, the soil of 6.5–7.5 is divided into neutral soil, the soil below 6.5 into acidic soil, and the soil above 7.5 into alkaline soil. Soils that are acidic or alkaline have an adverse effect on crop growth, so neutral soils are generally considered more suitable for farmland layout, In addition, this study classifies the organic matter content into six different classes according to the national soil nutrient classification table: >4%, 3.01–4%, 2.01–3%, 1.01–2%, 0.6–1%, and <0.6%. The remaining indicators are graded according to the actual situation in Hubei Province according to the equal spacing method, Table 3 shows the graded assignment of each evaluation indicator.

Table 3. Criterion scores for indicators.

Score	Soil Thickness (cm)	Soil Organic Matter Content (%)	Soil pH Value	Altitude (m)	Slope (°)	≥10 °C Accumulated Temperature (°C)	Annual Average Precipitation (mm)	Socio-Economic Activity Density	Distance from Downtown (km)	Road Network Density (km/km^2)
10	>100	>4	6.5–7.5			>6000	>1600	<2	>150	0–0.2
9				<200	0–2°					
8	80–100	3–4	7.5–8.5	200–500		5400–6000	1300–1600	2–4	120–150	0.2–0.4
7					2–6°					
6	50–80	2–3	5.5–6.5	500–800		4800–5400	1000–1300	4–6	80–120	0.4–0.6
5					6–15°					
4	20–50	1–2	>8.5	800–1000		4200–4800	800–1000	6–7	40–80	0.6–0.8
3					15–25°					
2	<20	0.6–1	<5.5	>1000		<4200	<800	>7	0–40	>0.8
1		<0.6			>25°					

3.2.3. Weights of FSE Indicators

Weight can represent the influence degree of a factor. This study mainly uses analytic hierarchy process to calculate and determine the weights of factors (Table 4). Analytic hierarchy process divides each factor in a complex system into interrelated levels and determines the weights of each index through pairwise comparison between each factor. After calculating the R matrix, in order to measure the credibility of the results presented by this judgment matrix R, this study carries out a consistency test on the basis of the calculated matrix and obtains the CI, RI, and CR values. The results show that CI is 0.019, which is less than 1, so the matrix has a good consistency. Based on this judgment matrix, this study derived the weights of each indicator, as shown in Table 4.

3.2.4. Classification of FSE

According to the *A Framework for Land Evaluation* promulgated by the United Nations Food and Agriculture Organization (FAO) in 1976, the *Regulations for Classification on Agricultural Land*, and other relevant regulations, and considering the actual situation in Hubei Province, the grading of farmland in Hubei Province is divided into the following four categories: highly suitable (S1), moderately suitable (S2), barely suitable (S3), and unsuitable (N).

Table 4. Weights of FSE indicators.

Criterion Layer	Soil Condition (0.2534)	Terrain Condition (0.2798)	Climatic Conditions (0.1039)	Non-Agrochemical Sensitivity (0.3629)	Comprehensive Weight
Soil thickness	0.3919				0.0993
Soil pH value	0.2332				0.0591
Soil organic matter content	0.3749				0.095
Altitude		0.4031			0.1128
Slope		0.5969			0.167
Annual precipitation			0.4783		0.0497
≥10 °C accumulated temperature			0.5217		0.0542
Socio-economic activity density				0.3894	0.1413
Distance from downtown				0.3306	0.12
Road network density				0.28	0.1016

Highly suitable (S1): the suitability level of farmland is the highest, all evaluation factors are at the highest or higher level, farmland has the highest productivity, the agricultural layout is in the optimal state, and the economic income generated by farmland is the highest; moderately suitable (S2): the quality of farmland is good, all indicators in the evaluation framework are in a relatively average state, and the economic benefit and productivity of farmland are general; barely suitable (S3): the overall quality of farmland is low, some selected indicators are restrictive to the use of farmland, and the productivity and economic benefits of farmland are low. If it is put into agricultural production for a long time, it is easy to cause the degradation of farmland; unsuitable (N): this kind of land is absolutely limited as farmland, which is not suitable for farming. It is not recommended to put it into agricultural production, and agricultural production is not sustainable.

Based on the theoretical meaning of the suitability reclassification assignment and the distribution of farmland suitability scores in Hubei Province, this study classifies the farmland suitability in Hubei Province into four classes, with 0–4 being unsuitable (N), 4–6 being barely suitable (S3), 6–8 being moderately suitable (S2), and 8–10 being highly suitable (S1). *The Technical Regulations for the Survey of the Current Land Use Situation* (1984) issued by the Chinese Agricultural Zoning Committee classifies the slope of farmland into five classes and considers that slopes below 25° can be developed into farmland for growing crops through a combination of techniques such as terracing and contour planting. *The Law of the People's Republic of China on Soil and Water Conservation* (2010) stipulates that the slope limit for open land is 25° and that slopes above 25° should be fallowed and planted with trees and grasses as they are prone to erosion problems. Therefore, in this study, farmland with a slope greater than 25° is set as an unsuitable area.

3.3. Data

The terrain condition data in this study includes elevation and slope. The digital elevation data of Hubei Province comes from the National Earth System Science Data Center (http://www.geodata.cn, accessed on 2 October 2021); the slope data is extracted and analyzed from the elevation data. The soil thickness, soil organic matter content, and soil pH value are extracted from the soil data of Hubei Province, which is from the China Soil Database (http://www.vdb3.soil.csdb.cn, accessed on 2 October 2021) from the second national soil survey. The cumulative temperature and precipitation data in climatic conditions are obtained by kriging interpolation using GIS based on the data of China's meteorological stations in 2018. The data of the meteorological stations are mainly from the China Meteorological Network (http://www.cma.gov.cn, accessed on 2 October 2021).

4. Results

4.1. Single Factor Evaluation

4.1.1. Soil Conditions

Figure 3 shows the calculation results of soil conditions. As shown in Figure 3, the overall soil thickness of Hubei Province is generally distributed between 0–200 cm, and there are certain differences between regions. The central region is located in the middle and lower reaches of the Yangtze River Plain and soil thickness is the deepest, while soil thickness in the vast areas of the west and southeast is in a relatively average state; soil organic matter content in Hubei Province is 0–12.31% and most areas are 0–2%, with relatively high organic matter content in the southwest and southeast; in terms of pH value, most of the soils in the southwest and southeast of Hubei province are brown soil, limestone soil, and waterloggogenic paddy soil which is more fertile and has a neutral soil pH between 6.5–7.5, making it suitable for cultivating crops. Most of the northwest and northeast parts belong to yellow-brown soil that is acidic and prone to leaching, resulting in the loss of organic matter, which is not conducive to crop cultivation and production.

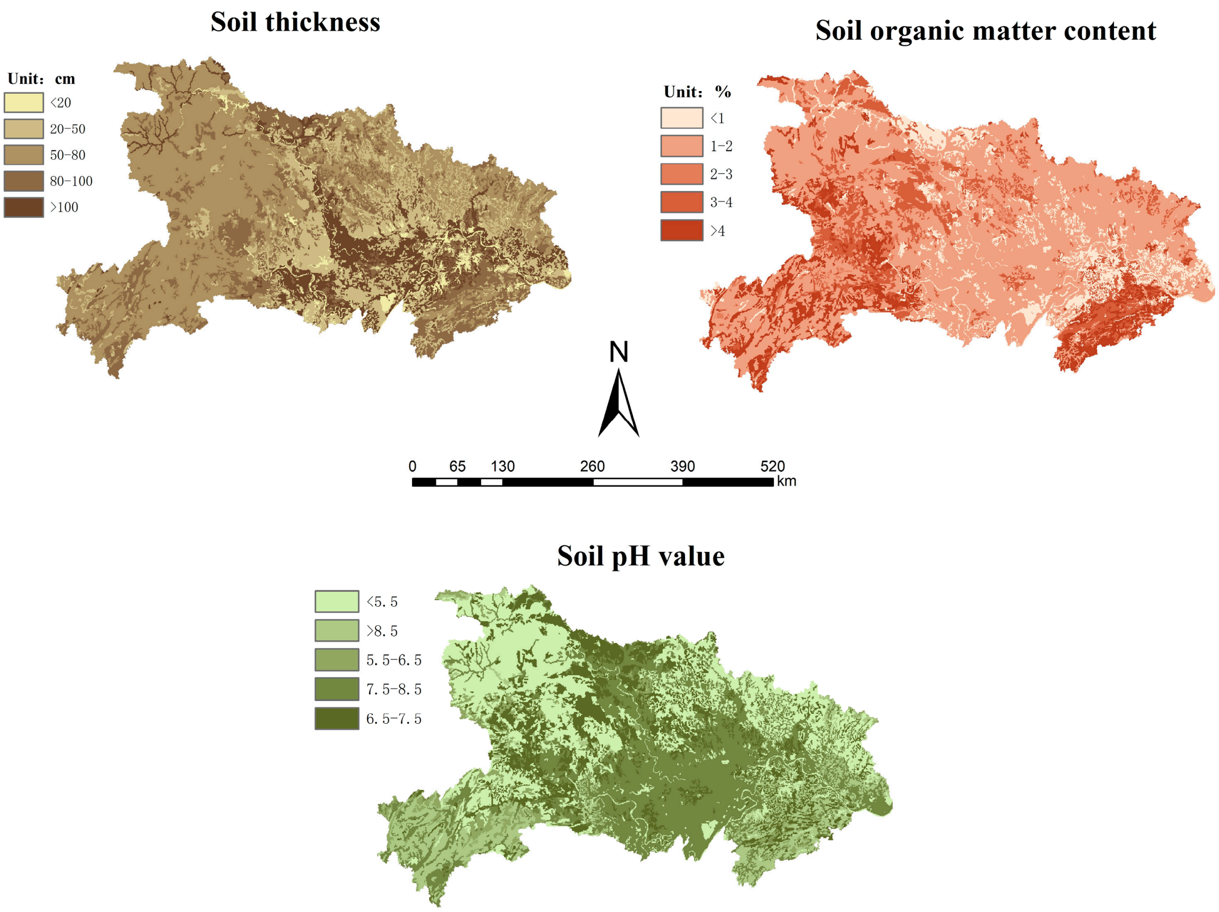


Figure 3. Soil conditions.

4.1.2. Terrain Conditions

Figure 4 shows the calculation results of terrain conditions. As shown in Figure 4, there are significant spatial differences in the elevation and slope of the terrain in Hubei Province, generally showing a trend of high in the east, west, and north and low in the middle. Elevation and slope have an impact on surface fluctuation, crop organic matter conservation, and water and soil loss. Flat terrain area is more beneficial to agricultural farming and soil organic matter conservation. Jianghan Plain in central Hubei Province is more suitable for farming and agricultural production.

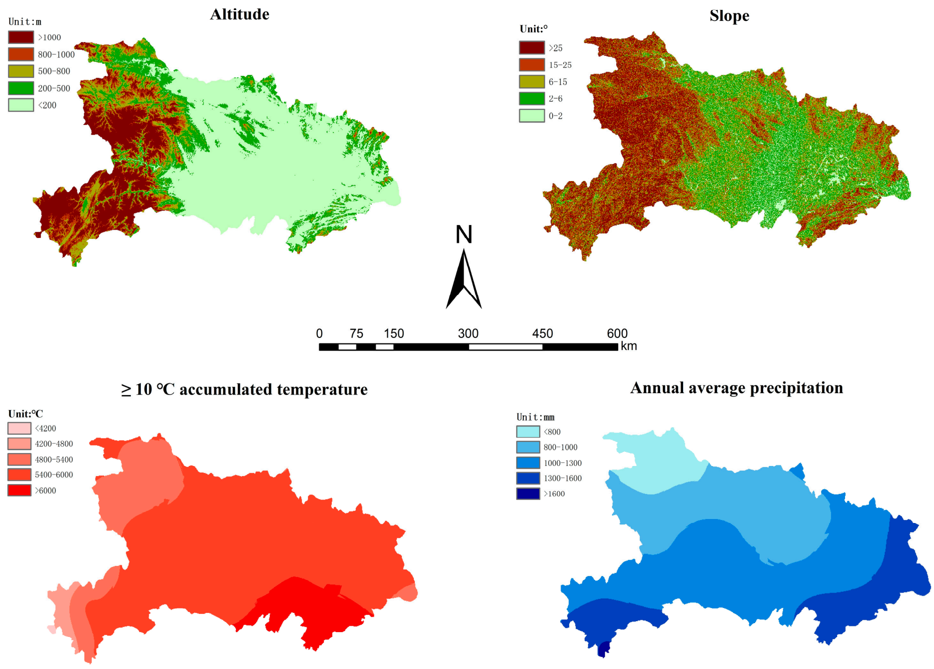


Figure 4. Terrain-Climatic conditions.

4.1.3. Climatic Conditions

Figure 4 shows the calculation results of climatic conditions. As shown in Figure 4, Hubei Province is located in the north temperate zone and in the south of China. Most areas in the province have a subtropical monsoon climate, and the annual temperature is basically above zero, which is suitable for the development of agricultural production; affected by the terrain difference, the precipitation in Hubei Province shows a decreasing trend from southeast to northwest. Crop growth has certain requirements for temperature. The higher the accumulated temperature, the shorter the crop maturity cycle and the more conducive to crop cultivation. The cumulative temperature in Hubei Province is greater than or equal to 10 °C and is between 4011 and 6207 °C, with high cumulative temperatures in the central and eastern parts of the province and relatively lower cumulative temperatures in some western areas. However, due to the small latitude span in the province, the spatial differences between temperature and precipitation are small, so they have little impact on suitability of the farmland.

4.1.4. Non-Agriculturalization Sensitivity

Figure 5 shows the calculation results of non-agriculturalization sensitivity indicators. As shown in Figure 5, from the indicator of socio-economic activity density, the non-agriculturalization sensitivity of farmland in Hubei Province shows the characteristics of "one super and many strong", with Wuhan City having the most prominent sensitivity to non-agriculturalization and other prefecture-level cities having a more even distribution of sensitivity; from the point of view of the distance from the city center, it shows the characteristics of multi-point agglomeration, and the distribution location of the agglomeration points is roughly consistent with that of the municipal urban centers. Due to the mononuclearization of urban development, the non-agriculturalization sensitivity of Shiyan City, Enshi City, Xiangyang City, and Suizhou City shows characteristics of decreasing from the urban area to the suburbs and rural areas. The coordinated development of Yichang City, Jingzhou City, and Jingmen City in the central part of Hubei Province makes the non-agriculturalization sensitivity in the central part show the characteristics of multi-core distribution and multi-point concentration, then decreasing outward. The development of the eastern Hubei Province cluster around Wuhan has, to a certain extent, determined the distribution of non-agriculturalization sensitivity in the eastern region, which is higher and more widely distributed but also shows the characteristic of decreasing from inner to outer cities; from the indicator of road network density, the non-agriculturalization sensitivity of Hubei Province shows the characteristics of single-core distribution, with the maximum area being Wuhan City and the surrounding areas also having a high non-agriculturalization sensitivity, except for other areas in the province where the non-agriculturalization sensitivity is low and evenly distributed

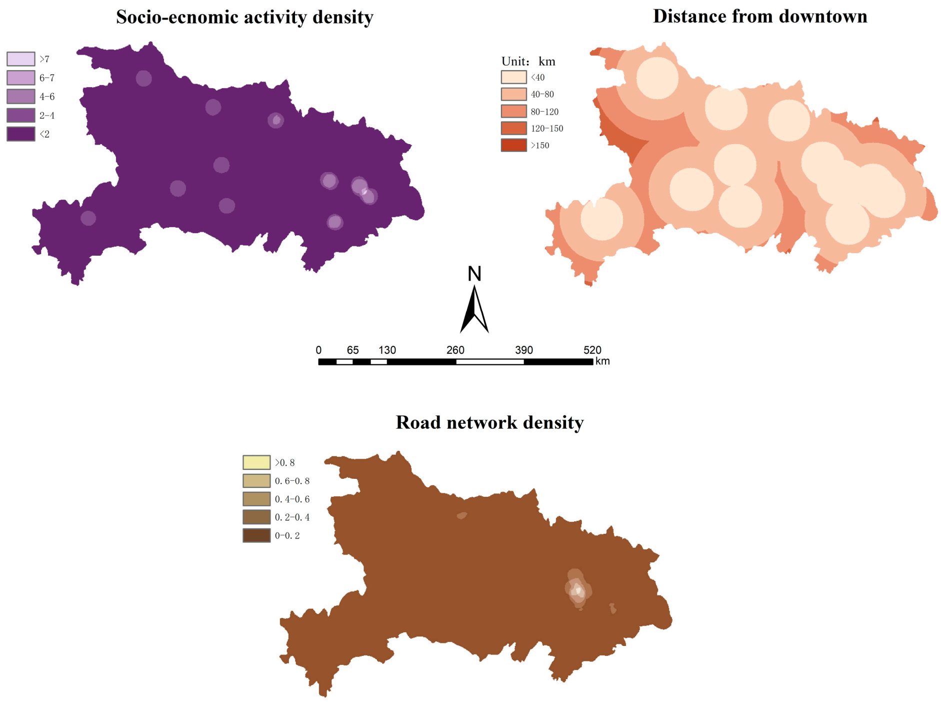
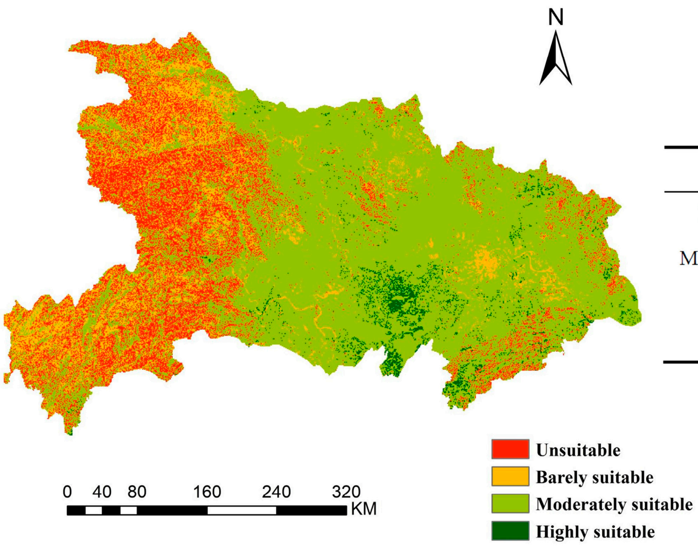


Figure 5. Non-agriculturalization sensitivity.

4.2. Suitability Evaluation

The average quality of farmland in Hubei province is high, but there are significant spatial differences, showing the characteristics of high in the east and low in the west. Specifically, the moderately suitable area is larger, accounting for 67.69%, the highly suitable area is small, accounting for only 2.32%, and the barely suitable and unsuitable farmland areas account for 11.49% and 18.50%, respectively (Figure 6).



Grade	Score	Proportion
Highly suitable	8-10	2.32%
Moderately suitable	6-8	67.69%
Barely suitable	4-6	11.49%
Unsuitable	0-4	18.50%

Figure 6. Farmland suitability classes in Hubei Province.

The distribution of farmland with different suitability levels shows that the farmland with highly suitable levels in Hubei Province is mainly distributed in the south-central and southeastern regions—namely Jianghan Plain—which are flat and have high soil fertility and are high food-producing areas in China. This region is typical of the subtropical monsoon climate, with plenty of light and precipitation, and has been a famous grain-producing area in China since ancient times, making it a natural location for agricultural production and rich in agricultural resources. In addition, there are many rivers in the region, including the Han River, an important tributary of the Yangtze River, and seven major rivers such as the Dongjing River, the Neijing River, the Tianmen River, etc., providing the necessary irrigation and water resources for agricultural cultivation, which makes it very suitable for agricultural production; in 2020, the area of irrigated agricultural land in the region was about 8710.0 km^2. The southeast of Hubei Province is also a highly suitable area. From the perspective of terrain factors, this area has relatively large fluctuations compared with Jianghan Plain, but it is still within the scope of suitable distribution of farmland. Many rivers pass through this area and bring rich minerals to it, making its soil organic matter content high and fertile. In addition, this area has sufficient light and heat, it provides very favorable conditions for the layout of farmland, so it is also very suitable for the development of agricultural production.

Most of the farmland in Hubei Province is moderately suitable, and the moderately suitable areas are mainly distributed in the central and eastern parts. Hanjiang River, Qingjiang River, Xishui River, and other rivers flow through these areas, providing abundant water sources and fertile soil for the development of agricultural production. In addition, this area is far away from the central urban area and is relatively less affected by social and socio-economic activities, and consequently, is not easy for this farmland to be non-agricultural, so the suitability grade is mostly moderate. The barely suitable and unsuitable areas are mainly distributed in the vast western region and the northeast and southeast regions. The terrain of this region is high and the slope is steep, some areas in the region have slopes greater than 25°. Areas with slopes greater than 25° should not be laid out for cultivation but should be fallowed and planted with trees and grass to ensure sustainable land use.

5. Discussion

This study proposes an improved evaluation framework of "natural-non-agriculturalization sensitivity" and uses Hubei Province, a major grain-producing region in China, as the study area for farmland suitability evaluation. There has been rich research on the farmland suitability evaluation, but previous studies have mostly considered natural factors in constructing FSE framework, such as "climatic conditions-slope-soil conditions" [27] and "climatic conditions-topographic conditions-soil properties" [16], and a few studies have addressed social factors such as GDP per capita and distance from market traffic accessibility [23,24,47], but few studies have included non-agriculturalization sensitivity in the assessment. Non-agriculturalization sensitivity refers to the possibility of converting farmland agricultural use to non-agricultural use due to the influence of socio-economic factors, which have an important impact on the layout of farmland. A parcel of land, even if its natural conditions are very suitable for developing agricultural production, may be too vulnerable to socio-economic factors to be planned as farmland. Compared with previous studies, the improved evaluation framework is based on natural factors such as soil, terrain, and climate and takes more in-depth consideration of socio-economic factors, incorporating non-agriculturalization sensitivity into the framework. In addition, the use of the improved framework for assessment can provide critical and reliable information for farmland planning, ensure the stability of farmland, and achieve long-term conservation.

Therefore, based on the results of farmland suitability evaluation, differentiated farmland protection and utilization policies should be put forward according to farmland suitability grade and zoning. Specifically, for highly suitable areas, the primary task is to maintain an appropriate state, take the road of sustainable and intensive utilization, improve the utilization efficiency of farmland, accelerate the construction of professional agricultural production bases, improve the local specialization and concentration in the regional division of labor, make use of the natural advantages of farmland resources to improve agricultural output, and develop agricultural economy. For moderately and barely suitable areas, on the one hand, we should develop and introduce advanced technology to improve limiting factors and improve the overall suitability of farmland. On the other hand, we should select crop types based on the market, develop agricultural production according to local conditions and improve the utilization value of limited farmland resources. For the unsuitable area, if it is caused by natural factors, it should be returned to forest and grass, and vegetation suitable for the natural environment should be planted to improve the ecological quality and ensure the sustainable utilization of land resources. If it is caused by non-agricultural factors, it is necessary to undertake various economic functions and reduce the crowding pressure of urban space expansion on other suitable areas.

Hubei province is in a period of rapid urbanization development [48], which has enhanced non-agriculturalization sensitivity and reduced farmland suitability. So, on the one hand, the Internet of Things, cloud computing, and 3S technology should be integrated to cultivate the industrial system of intelligent agriculture, promote the industrial application of intelligent agricultural products technology, and promote the intensification of agricultural development and the efficient production of farmland; on the other hand, each region should develop agricultural production according to local conditions based on the results of the suitability evaluation and the distribution of each individual evaluation factor. For example, depending on the slope, different types of crops can be planted. Rice, maize, wheat, and other crops are usually suitable for planting in areas below 15°, while high slopes result in poor water retention and are not conducive to crop growth, while fruit trees such as jujube and hawthorn have relatively low slope requirements and are suitable for planting in areas with high slopes. Soil types also have an important impact on crop types. Different crop types have different types and contents of soil nutrients, which should be arranged according to the differences of soil nutrient contents. In addition, with rapid social economy development, non-agriculturalization sensitivity of farmland has become more and more influential on the rational layout of farmland. Through the research results, the suitability level of farmland in some areas with superior natural conditions is still low due to too frequent socio-economic activities, so measures should be developed to guarantee that high-quality farmland is not occupied by non-agricultural activities in order to guarantee food security in China.

By evaluating the farmland suitability in Hubei Province, this study not only deepens the understanding of farmland suitability in Hubei Province. Moreover, the framework of non-agriculturalization sensitivity can evaluate farmland suitability more accurately and providing basic data support for territorial spatial planning. The inclusion of indicators related to “natural-non-agriculturalization sensitivity” allows people to pay more attention to current economic and social impacts on the quality of farmland, to recognize the impact of non-agriculturalization on food security, and to formulate targeted measures to ensure food security in China. In future research, we will strengthen the support of machine learning and artificial intelligence methods for FSE; theoretically, we will consider the integration of landscape ecology theory into the framework of FSE and pay attention to the role of patches and corridors in farmland suitability.

6. Conclusions

In this study, a “natural-non-agriculturalization sensitivity” framework was constructed using four dimensions: soil conditions, terrain, climate conditions, and non-agriculturalization sensitivity, and it was applied to evaluate farmland suitability in Hubei Province. The findings are as follows: (1) Farmland sensitivity in Hubei Province shows the spatial characteristics of multi-point clustering, and the clustering density increases from the west and north to the middle and east, among which the non-agriculturalization sensitivity in Wuhan City is the most prominent, and the sensitivity of other prefecture-level cities is more evenly distributed; (2) the overall farmland suitability in Hubei Province is high, with a large area of moderately suitable areas, and the areas of highly suitable, moderately suitable, barely suitable, and unsuitable farmland account for 2.32%, 67.69%, 11.49%, and 18.50%, respectively; (3) in terms of spatial distribution, there are spatial differences in the farmland suitability level in Hubei Province, with highly and moderately suitable areas mainly distributed in the central and eastern regions, while barely suiFigure and unsuitable areas are mainly distributed in the western region and some areas in the northeast and southeast of Hubei Province.

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