


Article

Assessing Grain Productivity Coupled with Farmers' Behaviors Based on the Agro-Ecological Zones (AEZ) Model

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Abstract: This study presents a method that dynamically embeds constraints of farmers' management and input levels to improve a traditional agro-ecological zones (AEZ) model to solve the problem of overestimation of grain production capacity. The proposed method is applied to Yuanjiang county in central China to evaluate the grain productivity of farmland and analyze its spatial distribution characteristics. Our results indicated that (1) The feasibility of the AEZ method coupled with farmers' behavior had been verified, and the revised model can better improve the accuracy of the evaluation results. (2) Low-value areas of grain production potential are mainly distributed in the central region, high-value areas are mainly distributed in the southwest and northeast regions, and the spatial differentiation characteristics of production potential and total production capacity are the same. (3) The total grain productivity is 935,800 tons, and the total yield gap is 470,100 tons, which is 1.01 times the actual yield, indicating a large potential to increase grain production under the current technicality. The main contribution of this study is to propose a method to dynamically embed farmers' behavioral factors into the traditional AEZ model, and apply this method to the actual farmland productivity evaluation in small-scale areas, which improves the reliability of the actual regional productivity evaluation results.

Keywords: grain productivity capacity; production potential; AEZ model; farmers' behavior; "non-grain"



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1. Introduction

Grain security is an important issue worldwide [1]. The grain production capacity of farmland has always been the basis of social and economic development. China's large population has led to significant grain consumption. Using the limited arable land resources to protect 1.4 billion people from starvation has always been an important topic for the Chinese government. China is also a major grain importer. However, the current epidemic of COVID-19 [2] and the uncertainty of international grain trade have greatly enhanced the external market risks and pressures facing China's grain market [3]. Grain security has again become the focus of scholars' attention, especially the level of grain self-sufficiency. Furthermore, the demand for grain continues to increase with the continuous growth of China's population and the transformation of the dietary structure. China's grain security strategy faces a severe problem: can the grain supply of farmland meet the growing grain demand? The key to answering this question is accurately calculating the farmland's grain production capacity. Determining the background of grain security and formulating targeted grain production strategies are of great significance.

The grain production capacity of farmland refers to the highest yield of grain crops that can be achieved on a certain area of arable land, which is determined by local natural conditions and the current technical and economic level [4]. At present, research has mostly

estimated the grain production capacity by measuring the grain production potential (the concept of yield per unit area) and coupling the area of farmland [5,6]. Thus, the scientific and accurate measurement of grain production potential is particularly important. Many studies are about the potential of grain production, and the research methods are relatively mature. The representative methods mainly include the following three categories: the potential decay method [7], comprehensive methods of climate factors (Miami model, Wageningen method, and Agro-Ecological zones (AEZ) method [8,9]) and the crop growth simulation method (CERES model, EPIC model, and CROPGRO model) [10,11]. However, given the limitation of data accuracy and parameter correction schemes, these models have the problem of systematic overestimation in estimating the production potential of farmland in China [12]. For example, the problem of model and data uncertainty exists in the Wageningen model [13]. The AEZ model is a method developed and applied by the United Nations Food and Agriculture Organization (FAO) and the International Institute for Applied Systems and Analysis (IIASA) to assess the potential of global agricultural production in the 21st century [14]. The potential productivity of each basic analysis unit is closely linked to agroclimatic conditions. It is a scientific tool for estimating farmland productivity and one of the most widely used models for measuring crop production potential worldwide [15]. The AEZ model evaluates crop production potential by simulating crop biological growth characteristics. During the simulation, the model considers soil properties and climatic characteristics, such as radiation levels and temperature conditions. Its characteristics of being suitable for evaluating the relationship between biological productivity and environmental limiting factors are exactly the simulation tools needed for estimating farmland productivity in China. Its effectiveness in estimating farmland productivity has been previously proven [16]. In addition, the key technology of this model is to select appropriate parameters and correction functions. In fact, the influencing factors of the final formation of farmland productivity include natural conditions, such as light, temperature, precipitation, soil, and terrain. Furthermore, it is also affected by human factors, such as farmland management measures, especially related to the limiting factors of local management and input levels. However, although the above models consider natural factors, their inputs are difficult to embed with socioeconomic restrictive factors, such as local management and input levels, dynamically. Thus, the traditional AEZ model cannot meet the needs for the dynamic assessment of agricultural productivity. Many scholars have previously explored this issue. For example, some studies have calculated the comprehensive productivity of farmland by constructing an evaluation index system of farmland quality and improving the AEZ model based on the farmland quality index [17]. Some scholars also use the irrigation guarantee rate as a correction factor for socioeconomic factors [18] or empirically determine the correction coefficient of fertilization on crop production potential, and then correct the land production potential. Research has proven that the AEZ model parameters can be modified by improving the accuracy of basic data and data processing methods on the basis of natural factors [19]. In addition, correcting land production potential with constraints of local management and input levels can improve the accuracy of assessment results [20].

In existing relevant research, some scholars have tried to revise the AEZ model, which has improved the scientificity and validity of the model evaluation results. However, the selection of production potential correction factors in existing research is relatively simplified, most studies mainly focus on a certain type of socioeconomic factor, management level or input factor, and the correction coefficient of the variable factor of production is mostly determined by experience. Furthermore, most scholars calculate the correction coefficient of production potential based on provincial and city (county) statistical data, which is usually the mean value of the county-level scale. This algorithm tends to ignore the difference in the region's correction coefficients of evaluation units. Based on the formation mechanism of grain production capacity, the influencing factors of grain production potential can be divided into two categories. One is the natural factors that evaluate the suitability of crop growth [21,22], such as temperature, rainfall, and soil. The other is farmers' behavior,

such as farmland management and substance input level. As the main grain producers, farmers' farmland use behavior is the basis and direct impact factor of grain production, which determines grain output. Based on natural factors, the influence of farmers' behavior factors is further considered, so that the evaluation results of production potential are closer to the actual output level of farmland. However, most of the existing research mainly considers the limitations of natural factors and socioeconomic factors [23], and studies on the calculation of farmland productivity by integrating natural factors and farmers' behavior factors are limited.

Thus, we dynamically embed the restrictive factors of farmers' management and input levels and develop an estimation method of grain production capacity coupled with farmers' behavior on the basis of the traditional AEZ model. This paper focuses on major grain-producing areas, and the research objectives are (1) to calculate the land production potential based on the traditional AEZ model; (2) to analyze the effects of farmers' behavior on grain production potential; and (3) to assess farmland grain productivity coupled with farmers' behaviors. Overall, the grain production potential coupled with farmers' behaviors based on the AEZ model enriches the method system and theoretical achievements of the AEZ model and has important practical application value for improving regional grain production capacity and ensuring food security.

2. Materials and Methods

2.1. Study Area

Yuanjiang County is located in northern Hunan Province, China (Figure 1) and is a county-level city according to China's administrative management system. Yuanjiang County has jurisdiction over 10 townships, 2 streets, and 2 reed fields. The landform is dominated by plains, and the land area of Yuanjiang is 2177 km². The climate is a subtropical humid monsoon climate in Yuanjiang County, which has good light and heat conditions, sufficient precipitation, an annual average temperature of 16.9 °C, and a long frost-free period. The accumulated temperature conditions support "double cropping" or "treble cropping" a year. The place has superior agricultural production conditions. In 2018, the arable land of Yuanjiang was 58,460 hm², and the resident population was 698,800. Yuanjiang is an important commercial grain production base in China. The area grain sown is 71,259 hm² (multicropping of cultivated land), accounting for 1.71% of the grain sown area in Hunan Province. The total grain output is 448,100 tons, accounting for 1.48% of the total provincial grain output. Yuanjiang County is of great significance to ensuring regional and even national food security. Therefore, calculating the grain production capacity of Yuanjiang County and proposing targeted grain production improvement measures to ensure regional grain security are of practical significance.

2.2. Data Acquisition and Processing

The data used in this study included meteorological data, soil data, land use data, farmers' behavior data, and other related data (see more in Supplementary Material Table S1). The original meteorological data are of the text type. First, we converted the text data into a space vector point file and chose the appropriate projected coordinate system in ArcGIS. The space vector data were then interpolated into 1 × 1 km raster data by the kriging interpolation method. In addition, the farmer survey was carried out in December 2019. The survey content mainly includes farmers' characteristics, farmers' management and input levels, and farmers' willingness to plant grain crops. In this study, stratified random sampling was conducted according to the four types of administrative villages divided by China's "Rural Revitalization Strategic Plan" [24]. The samples covered all townships, and one or two villages were selected from the same type of administrative villages in a certain township to carry out a household survey through questionnaires and interviews. A total of 400 questionnaires were sent. Excluding the questionnaires that could not be recovered and with incomplete data, 383 questionnaires were finally selected, and the effective recovery rate of the questionnaires was 95.75%.

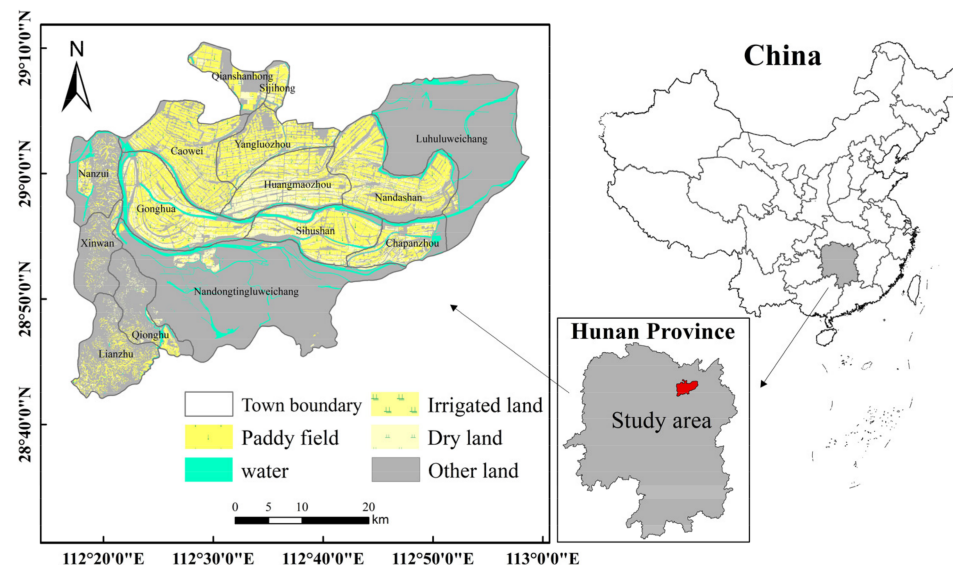


Figure 1. Location of the study area and land use of Yuanjiang county in 2018.

2.3. Research Process

The research process adopted here can be divided into the following four steps (Figure 2): (1) calculation of land production potential based on the traditional AEZ model and the reliability analysis of the estimated results; (2) effects of farmers’ behavior on grain production potential, and calculation and visualization of the fertilization correction coefficient and comprehensive correction coefficient; (3) coupling farmers’ behaviors to improve land production potential, and reliability verification of the revised estimation results; and (4) assessing farmland total grain productivity coupled with farmers’ behaviors.

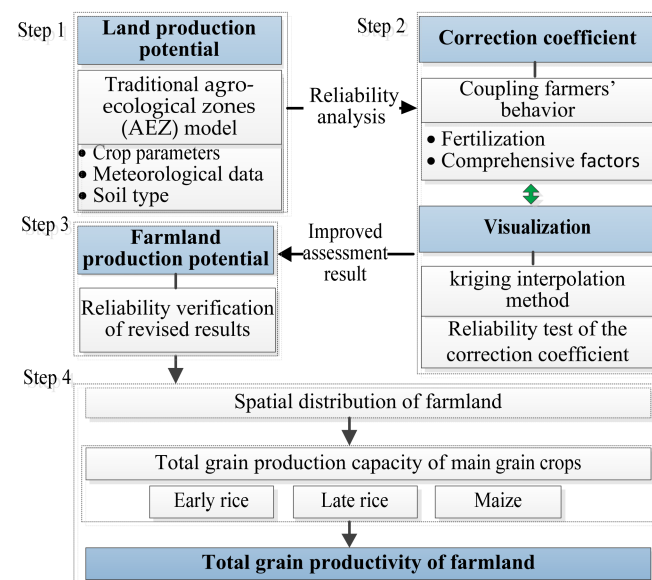


Figure 2. The research framework for assessing farmland grain productivity coupled with farmers’ behaviors. The arrow shows the logical nexus between the sections.

2.3.1. Calculation of Land Production Potential Based on the Traditional AEZ Model

The logical starting point for the AEZ model is the interaction of crop photosynthesis and its environmental conditions [25]. It obtains the crop production potential by inserting the limitations of natural conditions, such as light, temperature, water, and soil [26,27]. The principle of the AEZ model has been described in many studies [28,29] and thus will not be

repeated in the present study. The calculation method of the model parameters refers to the GAEZ 3.0 manual [30]. The main calculation formula is expressed as Equation (1):

$$Y_4 = Y_1 \times f_1 \times f_2 \times f_3 = Y_2 \times f_2 \times f_3 = Y_3 \times f_3 \quad (1)$$

where Y_1 is the photosynthetic production potential, f_1 is the effective temperature coefficient, Y_2 is the light-temperature production potential, f_2 is the effective water coefficient, Y_3 is the climate production potential, f_3 is the effective soil coefficient, and Y_4 is the land production potential.

2.3.2. Effects of Farmers' Behavior on Grain Production Potential

- Fertilization correction coefficient

Land production potential reflects crop production potential under soil fertility but does not consider the impact of farmers' behavior on grain yield. Fertilization has a significant effect on crop yield and is one of the fastest, most effective, and most important production substances. Fertilization plays a key role in changing soil microbial diversity, which is essential for determining crop yields [31]. Many scholars have studied the effect of fertilization on crop yield. They believed that appropriate fertilization methods and high efficiency of fertilizers were crucial to achieving high yields [32,33]. Chemical fertilizer plays an extremely important role in increasing grain yield in China, and the contribution rate of chemical fertilizer input to the increase in grain output exceeded 56% from 1978 to 2006 in China [34]. Thus, the research idea of this study is that we start by analyzing the influence of farmers' fertilization behavior on grain production, and then try to correct the grain production potential according to the actual amount of fertilizer.

The effect of fertilization on grain yield is mainly caused by increasing grain yield per unit area. According to previous research [35], the relationship between the amount of fertilizer per unit area and grain yield per unit area satisfies the quadratic functional Equation (2):

$$Y = A + BX + CX^2 \quad (2)$$

where Y is grain yield per unit area (kg/hm^2), A is the grain yield (kg/hm^2) without fertilizer, X is fertilizer per unit area (kg/hm^2), and B and C are partial regression coefficients.

Based on the law of diminishing marginal returns to land [36], yield shows a characteristic of rising first and then decreasing with the continuous increase in variable production factors. In this study, we draw the relationship between FPUA and YPUA in Figure 3. The fertilization amount corresponding to the maximum grain yield was regarded as the optimum fertilization value.

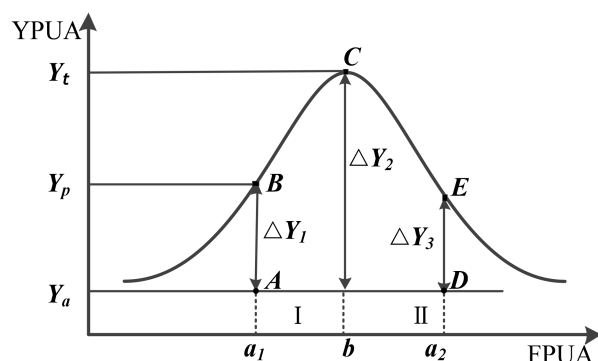


Figure 3. Schematic diagram of the relationship between fertilizer and yield. Note: YPUA is the grain yield per unit area; FPUA is the fertilizer per unit area; Y_t is the maximum grain production potential; Y_p is the predicted yield; Y_a is the actual yield; ΔY_1 , ΔY_2 , and ΔY_3 are the yield gaps; a_1 and a_2 are the actual fertilization amounts.

According to the value between the actual fertilization and the optimum value (b), fertilization was divided into two stages (I and II), representing insufficient and excessive fertilization, respectively. In the first stage, fertilization has a positive effect on grain yield. However, the actual fertilization amount (a_1) is less than the optimum fertilization value, indicating that the actual fertilization amount has not reached the optimum fertilizer that meets the demand of crops. The effect of fertilization on increasing yield has not been fully exerted. In Figure 3, Point A is the actual yield (Y_a) under the fertilization level of a_1 . Point B is the potential yield of the crop under this fertilization amount, and the yield gap (ΔY_1) could be increased by fertilization. Thus, the proportion of grain yield increase under this fertilization amount is $\Delta Y_1/Y_a$. When the fertilization amount increases to the optimum value, it will further promote an increase in grain production [37]. Furthermore, when the fertilization changes from a_1 to b , the grain production potential reaches the maximum (Y_t) at Point C. With the further increase in fertilization, the actual fertilization amount (a_2) is greater than the optimum value, and the fertilization stays at the second stage, indicating that the fertilization is excessive, and the fertilization amount exceeds the demand of crops. In this stage, increasing the application of chemical fertilizers will lead to a decrease in grain yield [38], and the current fertilization has a negative effect on yield. In Figure 3, Point D is the actual yield under the fertilization level of a_2 , and Point E is the crop's yield potential under the fertilization level. When the fertilization amount increases from a_1 to a_2 , the grain yield does not reach the maximum, but rises to the highest point (Point C) first and then begins to decline. Thus, the yield gap caused by fertilization level a_2 is ΔY_2 , and the proportion of grain yield reduction under this fertilization amount is $\Delta Y_2/Y_t$.

Based on the above analysis, we used the survey data of farmers to fit the fertilization yield effect function, and the maximum value of grain production potential (Y_t) and the corresponding fertilization amount (b) were obtained through the function. The actual fertilization amount (a) was further substituted into the function to obtain the predicted yield (Y_p). Finally, the correction coefficient of fertilization to the grain production potential was determined by calculating the proportion of grain yield increase (decrease) based on the fertilization interval in which the actual fertilization was located.

When the actual fertilization amount is less than the optimum value, fertilization has a positive effect on grain yield, and the fertilization correction coefficient is expressed as Equations (3) and (4):

$$F_1 = (Y_p - Y_a)/Y_a \quad (3)$$

$$F_f = 1 + F_1 \quad (4)$$

When the actual fertilization amount is greater than the optimum value, fertilization has a negative effect on grain yield, and the fertilization correction coefficient is expressed as Equations (5) and (6):

$$F_2 = (Y_t - Y_a)/Y_t \quad (5)$$

$$F_f = 1 - F_2 \quad (6)$$

where F_1 and F_2 are the proportions of grain production increase and decrease caused by fertilization, respectively. F_f is the correction coefficient of fertilization to grain production potential.

- Comprehensive correction coefficient for management and input levels

Farmers' management and input levels have a significant impact on grain yield. Except for fertilization, the final formation of grain output is also affected by factors such as the farmers' age [39], the number of laborers, the actual area of farmland operated, and the agricultural science and technology level [40]. However, the challenges associated with aging of farmers [41], low education level of farmers, shortage of agricultural laborer, and weak willingness of farmers to plant grain crops are common in rural China [42,43], which have become important factors restricting the sustainable production of grain in China. Moreover, the Chinese government is cautious about the use of chemical fertilizers and pesticides. In 2021, China's "No. 1 Document" mentioned "Reduce the amount but

increase the efficiency of fertilizers and pesticides” again [44], indicating that optimizing the application amount and improving the efficiency of pesticides and chemical fertilizers on grain production are important contents of sustainable agricultural development in the future in China. Furthermore, pesticides, fertilizers, and machinery are controllable factors of production and the main inputs for farmers’ agricultural production. Analyzing their impact on grain production has practical significance for guiding sustainable agricultural production. Thus, referring to the indices of the relevant research [45] and given the availability of survey data, this study analyzes the comprehensive impact of farmers’ management and input factors on grain production potential mainly from the characteristics of farmers (age, education level, and number of agricultural laborers), factor inputs (cultivation area, pesticide, and machinery input), and management level (agricultural technology level and farmers’ willingness to plant grain [46]).

This study regards grain production as an open “input output” system. The input information includes production factors such as land, labor, material, and technology [47], and the output information refers to the production potential of crops. In the system, a single factor plays a role in promoting or inhibiting grain production. However, the grain output is reflected from different aspects through various factors, and the influence of all factors on grain production can be regarded as a comprehensive effect. Thus, we used the multifactor comprehensive evaluation method [48] to analyze the comprehensive correction coefficient of management and input factors. The calculation formula is expressed as Equation (7):

$$f_M = \sum_{i=1}^n W_i \times A_i \quad (7)$$

where f_M is the comprehensive correction coefficient of management and input levels on grain production potential, n is the number of factors of farms’ behavior (mainly management and input factors), and W_i and A_i are the score value and the weight of Factor i , respectively. Furthermore, the weight of each factor was obtained by the analytic hierarchy process (AHP) method [49]. Moreover, we interviewed five professors in the field of agriculture, who have extensive experience in dealing with agricultural issues. During the interviews, experts judged the difference in the degree of influence of different values of farmers’ behavior factors on grain production, and each index was divided into one to four grades. In addition, they assigned scores according to the degree of influence of each index on grain production. On this basis, we comprehensively considered the opinions of all experts and combined them with the clustering and grading method in Statistical Product Service Solutions 19.0 software [50] (SPSS 19.0 is a statistical analysis software developed by the International Business Machines Corporation (IBM) in the United States) (<https://www.ibm.com/analytics/spss-statistics-software>, accessed on 27 June 2022) to determine the final grade and score of each index. The grading scores and weights of the factors are shown in Table 1.

Moreover, differences in the farmers’ farmland use behavior are observed in different regions at the county scale. That is, the correction coefficient of farmers’ management and input levels on grain production potential is distinct in separate regions. If the same correction coefficient is applied to correct the land production potential in different county regions, the evaluation results may deviate greatly from the actual situation. In this study, the Theil index was used to verify the difference in indicators between towns, which could effectively measure the difference between different regions [51]. The main calculation process of the correction coefficient is as follows:

- a. According to the survey data of farmers, we substituted the value of fertilization into Formula (2) to calculate the maximum value of the analytical grain production potential (Y_t) and the corresponding optimum value of fertilization (b).
- b. According to the relationship between the actual average fertilization amount of each township and the most appropriate value of fertilization, the fertilization correction coefficient of each township was calculated using Equations (3) and (4) or

Equations (5) and (6). Given the small sample size of each township (the number of questionnaires per township is less than 100), the statistical data requirements cannot be met. Therefore, we used the “fertilization yield” function of all county farmers to calculate the township’s potential yield corresponding to the average amount of fertilization in each township.

- c. We calculated the average value of farmers’ management and input level indicators in each township, determined the weight and the score of each indicator, and obtained the comprehensive correction coefficient of all indicators using Formula (7).

Table 1. Classification and weight of farmers’ behavior factors.

1st Index	2nd Index	Indicator Meaning	Metrics (Levels)/Scores				Weights
			(1)/1.0	(2)/0.9	(3)/0.7	(4)/0.6	
Farmers’ behavior	Age	Actual age of farmer	47 to 52	53 to 55	56 to 60	Other	0.0378
	Educational level	Education level of farmer	University or college	High school	Junior high school	Primary school and below	0.0503
	Proportion of agricultural laborer	Agricultural laborer divided by household laborer	0.63 to 1.00	0.54 to 0.62	0.45 to 0.53	≤0.44	0.0764
	Cultivation area/hm ²	Area of farmland	0 to 0.53	0.54 to 0.73	0.74 to 1.00	>1.00	0.0809
	Pesticide input/(yuan/hm ²)	Pesticide input cost	>4365	1695 to 4364	225 to 1694	0 to 224	0.1230
	Agricultural machinery input/(yuan/hm ²)	Mechanical input cost	≥2241	1592 to 2240	1209 to 1591	≥1208	0.1822
	Agricultural technology training/time	Number of agricultural technical training	>4	2 to 4	1 to 2	0 to 1	0.1571
	Willingness to plant	Farmers’ willingness to plant grain crops	Very high	High	Generally	Low	0.2923

Note: The higher the grade of the indicator is, the greater the positive effect it has on grain production; Yuan is the unit of RMB, the legal currency of China.

- Visualization of the correction coefficient

Farmers have differences in land dependence, value cognition, and property rights preferences in different regions of the county, which make their farmland use behaviors differentiated [52]; that is, the correction coefficients of farmers’ management and input levels on grain production potential are distinct in different regions. Suppose the same correction coefficient is used to correct the production potential of farmland in different areas of the county. In that case, it may lead to a large deviation between the evaluation results and the actual situation. According to spatial similarity theory, adjacent regions can easily achieve convergence because of similar economic structures and similar initial per capita income levels [53]. As for agricultural production, the management and investment behaviors of farmers often imitate the experience of other farmers, and farmers usually show a “following the trend” effect. The farmland utilization behaviors of households are similar between villages and villages and between towns and towns, as manifested in the spatial convergence of farmer management and substances input levels. Furthermore, to ensure the consistency of the data scale of the AEZ model, the fertilization correction coefficient and the comprehensive correction coefficient are spatially processed to generate the county-level section data of the fertilization and comprehensive correction coefficient and the grid data of the correction coefficient of production potential (1 × 1 km). The main process of data processing is as follows:

First, we saved the correction coefficient of fertilization and comprehensive factor data of each town in the Excel table. We then transferred it to DBF format and opened the township administrative division data and the DBF table in ArcGIS. We then select the

township code column in the DBF and township administrative division data. We use the JOIN command to link the DBF table to the township administrative division data, and generated the township vector data including the correction coefficients of fertilization and comprehensive factors.

Second, we converted the polygon data of the township administrative into spatial vector point data by using the 'Feature-to-Point' tool in ArcGIS, and generate the township spatial location point data with the correction coefficients.

Third, we generated the raster data (1×1 km) of the fertilization correction coefficient and comprehensive correction coefficient according to the spatial vector points of each township by using the kriging interpolation method in ArcGIS, which is an advanced geo-statistical procedure that generates an estimated surface from a scattered set of points with z-values and applicable to the existence of spatial correlation of regionalized variables [54].

- Reliability test of the correction coefficient

We used the interpolation method to obtain the fertilization correction coefficient and the comprehensive correction coefficient at the county scale. To test the scientificity of the method and the reliability of the results, we selected a number of sample points, calculated the actual correction coefficient of the sample points based on the household survey data, and compared the correlation between the actual value and the correction coefficient obtained by the interpolation method. The main calculation process is as follows:

- a. The household survey data in this study were collected based on administrative villages. In the reliability test of the correction coefficient, we took the average value of the household survey data on farmers' behavioral factors as the value of the corresponding indicator in the administrative village. On this basis, we randomly selected 21 administrative villages as the test samples in the study area, and the spatial location points of administrative villages were generated and numbered from 1 to 21. Furthermore, the land in southwest and northeast Yuanjiang County is not used for agriculture, and we had fewer household survey samples. Thus, this study did not select sample points for reliability verification in these areas.
- b. Based on the above spatial distribution of the fertilization correction coefficient and the comprehensive correction coefficient obtained by the interpolation method, the spatial position vector layer of the sample points was superimposed and analyzed with the fertilization correction coefficient and comprehensive correction coefficient layer in ArcGIS. Thus, we obtained the correction coefficient of corresponding sample points (1 to 21).
- c. We calculated the actual correction coefficient of the sample points using Formulas (3)–(7) based on the household survey data and drew a scatter plot between the actual values and the spatial correction coefficients, which were obtained using the interpolation method. We fit the function and intended to analyze the changing trend. Finally, we further calculated the correlation between the two types of coefficients.

2.3.3. Coupling Farmers' Behavior to Improve Land Production Potential

The county-level cross-sectional data of the fertilization correction coefficient and comprehensive correction coefficient were generated according to the operations of data format conversion, data link, spatial discretization, spatial sampling, and spatial interpolation in ArcGIS software. The 1×1 km raster data of the correction coefficients were then generated. Then, we used these correction coefficients to revise the land production potential calculated by the traditional AEZ model to obtain the farmland production potential (Y_L), which is close to the actual grain yield per unit area. The calculation formula is expressed as Equation (8):

$$Y_L = Y_4 \times F_f \times f_M \quad (8)$$

2.3.4. Assessing Farmland Grain Productivity Coupled with Farmers' Behaviors

The total grain production capacity depends on the area of farmland and the yield per unit area. We calculated the farmland production potential, which is regarded as the yield per unit area. Thus, based on the spatial distribution of farmland, we multiplied the farmland production potential by the farmland area of a grid to obtain the total production capacity of the main grain crops at the grid level. Furthermore, the sum of the production capacity of the three main grain crops was calculated as the total grain productivity of farmland in the study area.

3. Results

3.1. Land Production Potential Based on the Traditional AEZ Model

We calculated the land production potential of the main grain crops using the traditional AEZ model (Figure 4). The calculation results show that the land production potential of early rice (13,538.9–19,229.0 kg/hm²) was greater than that of late rice (7598.17–10,684.90 kg/hm²), the high-potential areas were mainly concentrated in the western region, and the potential in the central area was lower. The land production potential of maize (13,343.5–18,402.5 kg/hm²) showed the characteristics of “sporadic high value and low agglomeration value” in space, indicating that natural climatic conditions in most parts of Yuanjiang County have heavy restrictions on maize growth. Based on the land production potential of the main grain crops, the comprehensive production potentials of the grain crops under the planting systems of “early rice and late rice” and “maize and late rice” were 12,762.74 and 11,497.55 kg/hm² through weighted calculation of the sowing area, respectively. However, the statistical data from the Statistical Yearbook show that the average yield per unit area of main grain crops (early rice and late rice) was 8250 kg/hm² in 2018. A large gap is seen between the potential of grain production under different cropping systems and the actual yield per unit area. The main reason for this gap is that the traditional AEZ model only embeds the limitations of natural factors on grain production and does not consider the possible impact of regional farmers' management and input levels on grain production. Thus, this study used the behavior factors of farmers to improve the land production potential based on the evaluation results of the traditional AEZ model so that the evaluation results are expected to be closer to the actual output level of farmland.

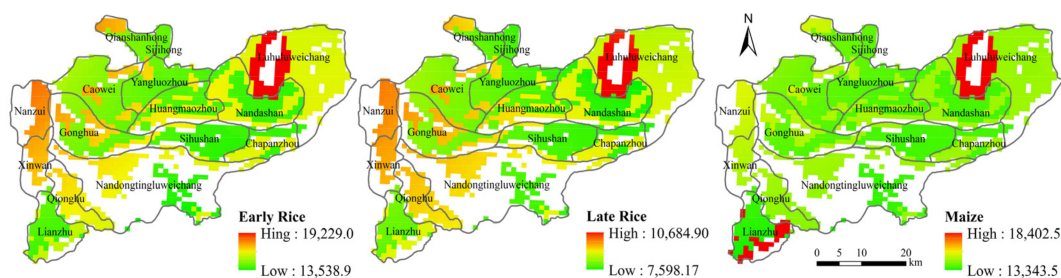


Figure 4. Land production potential of the main grain crops in Yuanjiang County.

3.2. Farmland Production Potential Coupled with Farmers' Behavior

- Correction Coefficient of Fertilization and Comprehensive Factors

The measurement results show that the total Theil index of each indicator is 0.012–0.532, indicating significant differences between indicators in towns. Thus, we took the township as a unit and used the survey data of farmers to calculate each township's fertilization and comprehensive correction coefficient in Table 2. Furthermore, the sample points for reliability verification and the visualization of the fertilization correction coefficient and the comprehensive correction coefficient are shown in Figure 5.

Table 2. Correction coefficient of management and input level in towns.

Townships	Fertilization (kg/hm ²)		Yield (kg/hm ²)			Fertilization Correction Coefficient		Comprehensive Correction Coefficient
	Actual Value	Optimum Value	Optimum Yield	Actual Yield	Potential Yield	Effect	Coefficient	
Caowei	295.35	631.73	15,632.48	12,375.00	15,210.68	+	1.23	0.67
Chapanzhou	367.28	631.73	15,632.48	14,928.38	15,371.93	+	1.03	0.75
Gonghua	521.18	631.73	15,632.48	15,000.00	15,587.10	+	1.04	0.80
Huangmaozhou	241.88	631.73	15,632.48	14,970.08	15,065.85	+	1.01	0.74
Nandashan	601.35	631.73	15,632.48	15,000.00	15,629.10	+	1.04	0.73
Nanzui	501.30	631.73	15,632.48	13,500.00	15,569.25	+	1.15	0.75
Sijihong	174.75	631.73	15,632.48	13,309.65	14,853.75	+	1.12	0.74
Sihushan	441.53	631.73	15,632.48	15,000.00	15,497.78	+	1.03	0.74
Yangluozhou	888.30	631.73	15,632.48	12,000.00	15,386.25	-	0.77	0.77
Xinwan	511.28	631.73	15,632.48	11,250.00	14,143.80	+	1.00	0.77

Note: “+” and “-” indicate that fertilization has yield-increasing and yield-reducing effects, respectively.

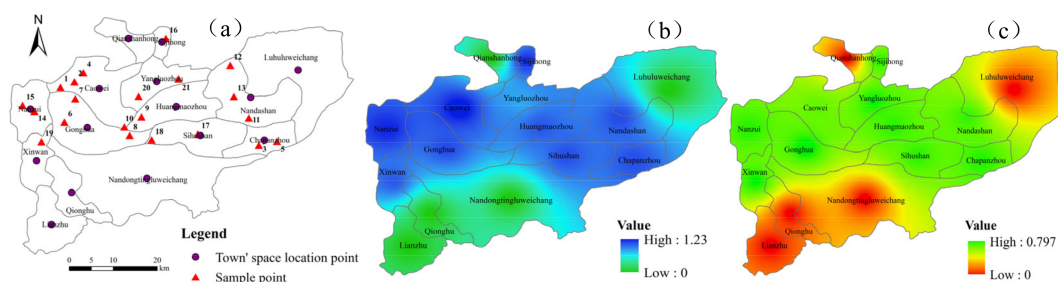


Figure 5. Spatial distribution of the correction coefficients according to the interpolation method: (a) town’ location point in space and sample point for the reliability test in space, (b) fertilization correction coefficient, and (c) comprehensive correction coefficient.

The results showed that the maximum value of the analytical grain production potential was 156,32.48 kg/hm², and the corresponding optimum value of fertilization was 631.73 kg/hm². The impact of fertilization on grain production potential in most areas of Yuanjiang is in Stage I. Fertilization has a positive effect on grain production, and the amount of fertilization is less than the appropriate value, indicating that increasing the amount of fertilization can help to improve grain yield. Appropriately increasing the application amount of fertilizer can help to meet the fertilizer demand for crop growth. Moreover, there are few farmlands in towns southwest and northeast Yuanjiang, and the main land types of the South Dongting Reed Field and Luhu Reed Field are waters and tidal flats, which are mainly used for planting reeds. The fertilization and comprehensive correction coefficient are calculated based on the data from the household survey, and the land in these areas is not mainly used for agriculture. Almost no farmers plant grain crops; thus, we had fewer household survey samples. Therefore, the management and input levels of farmers are low. As a result, the fertilization correction coefficient and comprehensive correction coefficient are low. In addition, the comprehensive correction coefficient varies from 0.67–0.80, indicating that farmers’ behavior has certain restrictions on grain production. It should be improved mainly by improving farmers’ agricultural management level and production technology, especially in Caowei town and other areas with greater restrictions.

- Reliability Test of the Correction Coefficient

The results showed that the actual correction coefficients based on the farmer survey data are close to the correction coefficients obtained by the interpolation method (Figure 6) (see more in Supplementary Material Table S2). The correlation between the actual fertilization correction coefficient and the coefficient obtained by the interpolation is 0.85, and the actual comprehensive correction coefficient and the coefficient obtained by the interpolation is 0.75, indicating that the above method to obtain the fertilization correction coefficient and the comprehensive correction coefficient at the county scale is scientific, and the results are credible. Therefore, we can use the correction coefficient by interpolation at the county scale to revise the land production potential.

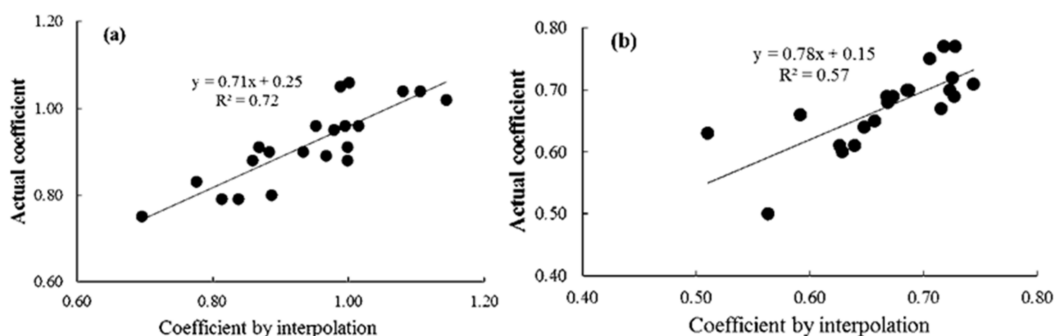


Figure 6. Comparison between the actual coefficient and the coefficient obtained by the interpolation method: (a) fertilization correction coefficient and (b) comprehensive correction coefficient.

On this basis, according to Formula (8), the land production potential of early rice, late rice, and maize was multiplied by the fertilization correction coefficient and the comprehensive correction coefficient in ArcGIS to obtain the production potential of farmland (Figure 7). The results showed that the production potentials of early rice, late rice, and maize were 10,262.8–19,229.0 kg/hm², 5850.02–10,684.90 kg/hm², and 9913.3–18,402.5 kg/hm², respectively, in Yuanjiang county. The spatial distributions of early and late rice production potentials were similar. The rice production potential in the western and southern regions is greater than that in the central region. The production potential of maize was high in the south and north but low in the central region. The high-value areas of grain production potential are mainly concentrated in Gonghua town, Nanzui town, Yangluozhou town, Sijihong town, and Chapanzhou town, which are key towns suitable for grain production. The low-value areas are mainly concentrated in Caowei Town, Huangmaozhou Town, Sihushan Town, and Nandashan Town, which are the main towns that enhance the potential of grain production.

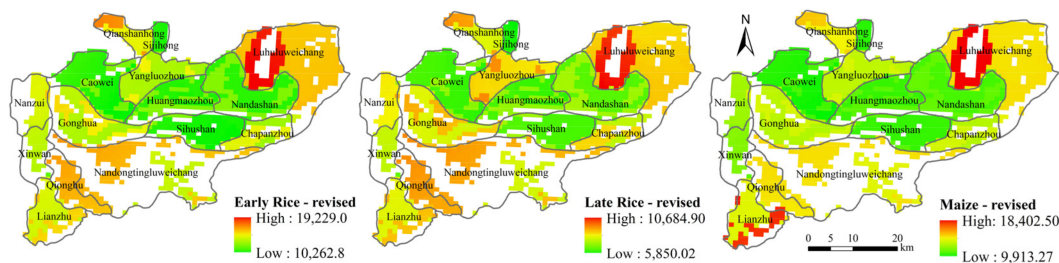


Figure 7. Farmland production potential of the main grain crops in Yuanjiang County.

- Reliability Verification of Estimation Results Based on the AEZ Model coupled with farmers’ behavior

The production potential of rice and its actual yield were used for comparative analysis to verify the accuracy of the evaluation results from the revised model. Given that the

grain production potential is the evaluation result on the grid scale, the actual output is the average value of the survey data based on the administrative village. Thus, to improve the accuracy of the model verification, we counted the average grain production potential of each administrative village in ArcGIS. After comparison with the actual yield per unit area, a significant correlation was found between the grain production potential and the actual yield; the correlation was 0.82, and the average actual yield of all administrative villages was 85.96% of the estimated yield. Therefore, the correction scheme based on farmers' behavior can improve the accuracy of the traditional AEZ model, and the model evaluation results can better reflect the basic situation of regional grain production. The application of the AEZ model and the proposed parameter correction scheme to evaluate regional total grain production capacity is scientific and reliable.

3.3. Total Grain Productivity Assessment of Farmland

The production capacity of early rice (PCER), late rice (PCLR), and maize (PCM) at the grid scale is calculated based on the production potential of grain crops and the spatial layout of cultivated land. The sum of the production capacity of the three main grain crops is calculated as the total grain production capacity of farmland (PCF) in Yuanjiang county (Figure 8).

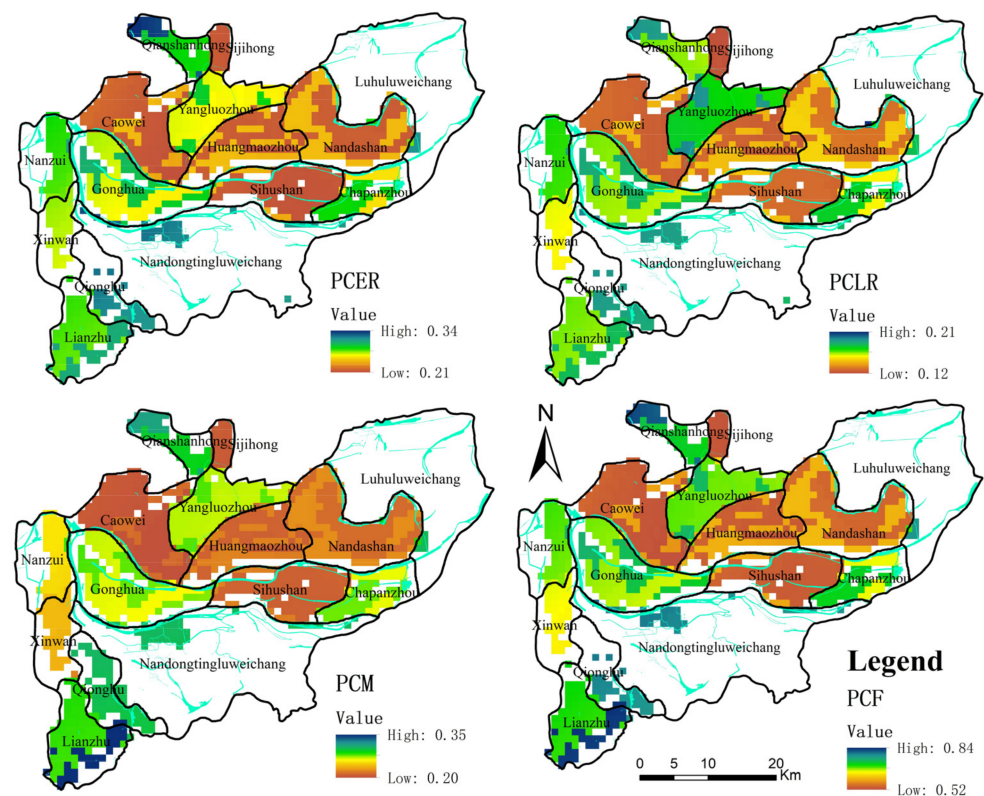


Figure 8. Production capacity of farmland in Yuanjiang county (unit: tons).

The total production capacity of early rice, late rice, and maize at the grid scale vary from 0.21 to 0.34 tons, 0.12 to 0.21 tons, and 0.20 to 0.35 tons, respectively. In addition, the total grain production capacity of farmland in Yuanjiang County varies from 0.52 to 0.84 tons. According to the statistical summary of each grid value, the total grain production capacity of farmland in Yuanjiang county is 935,800 tons. Moreover, from the spatial distribution characteristics of the farmland total grain production capacity, it can be seen that the high-value areas of grain production capacity are mainly concentrated in Lianzhu town in the southern region, Gonghua town in the western region, Yangluozhou town and Qianshanhong town in the northern region, and Chapanzhou town in the western

region. The low-value areas are mainly distributed in Caowei town, Huangmaozhou town, Sihushan town, and Nandashan town in the central region.

4. Discussion

4.1. Methodological Advantages of Coupling Farmers' Behavior

The AEZ model is a scientific tool for estimating farmland productivity. However, the traditional AEZ model focuses on considering the limitations of natural factors on crop production potential. Thus, given the limitation of data accuracy or parameter correction scheme, the estimation of the AEZ model has the problems of low parameter accuracy and insufficient dynamic estimation, which leads to systematic overestimation in previous studies [55] using this model to evaluate the productivity of farmland.

Farmers are the main producers of agricultural production and management, and their farmland use behavior is the most direct factor affecting grain production. Thus, considering the impact of farmers' behaviors on grain production when evaluating grain production capacity is necessary. On the one hand, based on the parameters and correction scheme of the traditional AEZ model, this study dynamically embeds the restrictive factors of farmers' management and input level, integrates county-level cross-sectional data, generates spatial data of farmers' behavior correction coefficients, embeds farmers' behaviors into the revision scheme of model parameters, and develops a dynamic estimation method of grain production capacity. On the other hand, the correction scheme coupled with farmers' behavior causes the evaluation scale of the correction coefficient from provinces and cities to counties and townships and realizes refined management of correction coefficients in small-scale research areas; thus, improving the accuracy of the model correction coefficient. Therefore, the model evaluation results can more accurately reflect the actual output level and spatial characteristics of regional farmland and effectively solve the common overestimation problem in previous research on farmland productivity evaluation. Compared with the traditional AEZ model, the proposed revision scheme of grain production potential applies the model to evaluate the productivity of farmland in small-scale areas.

4.2. Qualitative Comparison of Farmland's Total Grain Productivity with the Actual Yield and the Effects of "Non-Grain" Level

We discussed the gap between the actual yield per unit area and the land production potential calculated based on the traditional AEZ model. The result showed that the production potential calculated based on the traditional AEZ model is almost 1.5 times the actual yield. Therefore, the precision deviation of the evaluation results is low. After dynamically embedding farmers' behavioral factors into the AEZ model, we improved the evaluation results of the traditional AEZ model. On this basis, we evaluated farmland's total grain production capacity based on farmland's production potential in Yuanjiang county. The total grain production capacity of farmland is 935,800 tons, however, Statistical Yearbook data showed that the actual output was 465,700 tons in 2018, and the total grain yield gap of farmland was 470,100 tons, which is 1.01 times the actual output. Moreover, the low total grain productivity areas are mainly distributed in Caowei town, Huangmaozhou town, Sihushan town, and Nandashan town in the central region, which has a certain amount of farmland. However, due to the low grain production potential, the total grain production capacity is low. Thus, to increase regional grain production and decrease the yield gap, making full use of the superior farmland conditions and natural climatic conditions in these areas is necessary. By constructing more complete farmland irrigation facilities, improving farmers' management and input levels are effective ways to improve the grain yield per unit area.

Furthermore, with rapid urbanization and industrialization, the phenomenon of the nonagricultural transfer of rural labor has intensified, and the rural industrial structure has been continuously adjusted in China. As a result, the problem of "non-grain" of farmland (all farmland utilization behaviors other than grain crops, such as planting, breeding, tree

planting, and farmland abandonment, are regarded as non-grain conversion of farmland) has become increasingly prominent [56,57], and food security has been continuously threatened. Statistical data showed that the planting structure (the ratio of the sown area of grain crops to the sown area of crops) [58] of farmland in Yuanjiang County was 0.48–0.50 from 2011 to 2019. The proportion of farmland for grain cultivation is low, and non-grain crops occupy a large space for grain production. Thus, we used the actual planting structure data to test the impact of the “non-grain” level of farmland on grain production capacity. According to the average grain production potential, area of farmland, and planting structure of each town, we calculated the total grain production capacity of Yuanjiang County, which was 467,900 tons in 2018. The total grain yield gap was 22,000 tons, accounting for 0.47% of the actual yield, indicating that the evaluation result of total grain production capacity is close to the regional reality. The results again confirm the rationality of the parameter correction scheme based on farmers’ behaviors, and the AEZ model coupled with farmers’ behavior improves the reliability of the regional actual production capacity assessment results. Thus, the important reason for the large gap between the grain production capacity and the actual output in the study area is the “non-grain” level of cultivated land, and the actual output of the region is only half of the total production capacity of farmland. Therefore, curbing the “non-grain” increase in farmland, increasing the sown area of grain, and tapping the potential of farmland for grain production are important measures to reduce the yield gap and increase grain output.

4.3. Importance and Main Application of the Research Results

Grain has always been an important foundation for social stability and economic development. The United Nations World Food Program (WFP) released the Global Food Crisis Report 2022 [59], which states that the food crisis is expected to worsen in 2022, with the number of severely hungry globally rising to a staggering 323 million, with close to 193 million people acutely food insecure and in need of urgent assistance across 53 countries/territories. Given the war’s repercussions on global food, energy and fertilizer prices and supplies have not yet been factored into most country-level projection analyses. The outlook for global acute food insecurity is expected to deteriorate further. Globally, the levels of hunger remain alarmingly high.

With 7% of the world’s land, China feeds 22% of the world’s population. China’s grain production plays an important role in maintaining world food security. It can provide scientific support for formulating and optimizing grain production policy by accurately evaluating the capacity of farmland and the population it can feed in China. Yuanjiang county is the main grain-producing area in Hunan Province and China’s important agricultural product production area. Grain production in Yuanjiang is of great significance to ensuring regional food security. We calculated that the total production capacity of farmland, which is 2.01 times the actual output of the region (465,700 t), indicating that the regional grain yield of farmland has a large room for improvement. Furthermore, referring to the per capita nutritional calorific value standard published by the Food and Agriculture Organization of the United Nations (FAO) [60] and the standard published by the Chinese Health Commission, we calculated the population that could be supported by farmland under the affluent living standard (the per capita grain consumption standard of 550 kg per year). The results show that the population capacity is 850,700, exceeding the actual population (697,700) by 21.93%, which indicates that the region has a high potential for population growth. The research results provide data support for confirming the baseline of grain security.

Moreover, the Chinese government proposed the “farmland red line” (at least 1.2 million km²) to ensure national grain security, but urban expansion has often increased at the expense of farmland, leading to increasing pressure to maintain the red line. In addition, economic development and ecological protection always present the risk of occupying farmland. The contradiction between local economic development, grain production and ecological protection has become increasingly prominent. To mitigate this issue, the Chi-

nese government has formulated a control strategy to delineate “three lines”, namely the ecological protection red line, permanent basic farmland red line, and urban development boundary. The three control lines are taken as insurmountable red lines for adjusting economic structure, planning industrial development, and promoting urbanization. However, there are problems of conflict of the three control lines in actual work, and the demarcation of the “three lines” is progressing slowly. As the basic administrative unit of local planning management, county is the key to optimize the layout of “three lines” and implement spatial control. This study proposes a feasible “three lines” delineation scheme according to the spatial differentiation characteristics of total grain production capacity. It is expected to provide a reference for the establishment of local land use planning and urban development planning. For areas with high levels of productivity and concentrated farmland, such as Gonghua and Nanzui in the west, and Yangluozhou and Qianshanhong in the north of Yuanjiang, undertaking the main task of local grain production, they should be delimited in the permanent basic farmland red line. However, low grain planting profits have a negative impact on local economic development and farmers’ incomes. The government must develop a series of agricultural policies, such as grain subsidies and cross-regional farmland protection compensation, to promote grain cultivation. For the southwestern and northern of Yuanjiang, given its proximity to the urban area, it is greatly affected by the radiation of urban development. Therefore, they should be delimited in the urban development boundary, and comprehensively considering regional resource endowments and development conditions and exploring an industrial development model that is suitable for the integration of primary, secondary, and tertiary industries are necessary. Furthermore, for the southwestern and eastern regions, given that the land use types are mainly waters and tidal flats, which are important water conservation areas and ecological protection areas, the productivity of farmland is relatively low. Therefore, they should be delimited in the ecological protection red line, and fallow or return of farmland may be appropriate to prevent soil and water pollution and damage to the ecological environment in the future.

4.4. Research Limitations and Future Directions

Farmland productivity is affected by many factors, such as natural, social, ecological, economic, and human factors. In this study, the modified AEZ model coupled with farmers’ behavior was constructed based on household survey data. However, given the availability of survey data and the complexity of the influence mechanism of farmers’ behavior factors on grain productivity, we used the multifactor comprehensive evaluation method to calculate the comprehensive correction coefficient of management and input factors. Although this method we proposed successfully reflects the influence of various factors on grain productivity, it was used to improve the evaluation results based on the traditional AEZ model. However, there may be the following existing problem: considering the impact of each factor on grain production as a comprehensive coefficient may mask the real promoting or limiting effect of the factor itself on grain production. Therefore, the next research direction is the establishment of a practical quantitative nonlinear model to analyze the mechanism of the main farmer’s behavior factors on farmland productivity and calculate the correction coefficient of each factor on grain production potential. In addition, public policy has a huge impact on the grain production behavior of farmers in China. Thus, we intend to quantify policy and regulatory factors and other conceptual factors, and then embed them in the model to form an open and scalable decision-making system.

Furthermore, through the application of the modified model at the county scale, the model can analyze the regional differences in grain production potential well, whereas the application of parameters we calculated on large scales, such as provincial and national scales, needs further study. Thus, further study methods for dividing different agricultural production areas according to China’s main functional zoning or agricultural type areas are necessary and analyzing the correction coefficient of farmers’ behavior in different types of areas on grain production potential to form a normative guide for the calculation and correction of grain production potential is necessary.

5. Conclusions

This study dynamically embeds farmers' behavior on grain production potential and evaluates farmland productivity in the study area. The results showed that the parameter correction scheme of the AEZ model coupled with the behavior of farmers can improve the accuracy of the model evaluation results. The rationality and scientificity of the proposed method were verified by comparing the grain production potential by the improved AEZ model and the actual yield according to the statistical data. A significant correlation was found between grain production potential and actual yield per unit area, with a correlation coefficient of 0.82, and the average actual yield of all administrative villages was 85.96% of the estimated yield, indicating that the evaluation results of the AEZ model based on the modification of farmers' behavior can better reflect the changing trend of regional grain yield. Farmland's total grain production capacity is 935,800 tons, and the grain output gap is 470,100 tons, which is 1.01 times the actual output in Yuanjiang county, indicating a large space for regional grain output growth under the current technical conditions. Compared with the traditional AEZ model, the proposed revision scheme of grain production potential coupled with farmers' behavior applies the model to evaluate the productivity of farmland in small-scale areas.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/xxx/s1>, Table S1: List of main data used in this study; Table S2: Comparison of the actual correction coefficient of sample point and the coefficient obtained by interpolation method.

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References

1. Shabanali, F.H.; Aramyan, L.H.; Sijtsema, S.J.; Alambaigi, A. The relationship between household food waste and food security in Tehran city: The role of urban women in household management. *Ind. Mark. Manag.* **2021**, *97*, 71–83. [[CrossRef](#)]
2. Béné, C.; Bakker, D.; Chavarro-Mónica, J.; Even, B.; Melo, J.; Sonneveld, A. Global assessment of the impacts of COVID-19 on food security. *Glob. Food Sec.* **2021**, *31*, 100575. [[CrossRef](#)] [[PubMed](#)]
3. Yan, J.M.; Zhao, Z.; Xia, F.Z. Strategic consideration on China's "Natural Resource Security Governance" in the post-epidemic era. *China Land Sci.* **2020**, *34*, 1–8.
4. Skoglund, M.K. Climate variability and grain production in Scania, 1702–1911. *Clim. Past.* **2022**, *18*, 405–433. [[CrossRef](#)]
5. Singh, I.P. The trends and growth rate of area, production and yield of total food grain production and comparison between production and population: Indian context. *Adv. Appl. Res.* **2022**, *13*, 22–26. [[CrossRef](#)]
6. Li, S.T.; Zhang, D.J.; Xie, Y.; Yang, C. Analysis on the spatio-temporal evolution and influencing factors of China's grain production. *Adv. Cem. Res.* **2021**, *29*, 23834–23846. [[CrossRef](#)]
7. Kurtz, S.M.; Acharya, J.; Kaspar, T.C.; Robertson, A.E. Influence of spatial planting arrangement of winter rye cover crop on corn seedling disease and corn productivity. *Plant Dis.* **2022**, *105*, 4014–4024. [[CrossRef](#)]
8. Fischer, G.; Shah, M.; Tubiello, F.N.; Van, V.H. Socio-economic and climate change impacts on agriculture: An integrated assessment, 1990–2080. *Philos. Trans. R. Soc. Biol. Sci.* **2005**, *360*, 2067–2083. [[CrossRef](#)]
9. Amim, M.E.S.; Mohamed, E.S.; Belal, A.A.; Jalhoum, M.E.M.; Abdellatif, M.A.; Nady, D.; Ali, A.M.; Mahmoud, A.G. Developing spatial model to assess agro-ecological zones for sustainable agriculture development in MENA region: Case study northern western coast, Egypt. *Egypt. J. Remote Sens. Space Sci.* **2022**, *25*, 301–311.

10. Addis, T.T. Seasonal analysis of maize production using DSSAT-CERES model in central rift valley of Ethiopia. *J. Climatol. Weather Forecas.* **2021**, *9*, 291.
11. Neeraj, K.; Nain, A.S.; Suman, K. Impact assessment of climate change through CROPGRO and CERES model for tarai region of Uttarakhand. *Indian J. Soil Conserv.* **2017**, *45*, 12–20.
12. Liu, L.; Xu, X.L.; Liu, J.Y.; Chen, X.; Ning, J. Impact of farmland changes on production potential in China during recent two decades. *Acta Geophys. Sin.* **2014**, *69*, 1767–1778.
13. Van Ittersum, M.K.; Leffelaar, P.A.; Van Keulen, H.; Kropff, M.J.; Bastiaans, L.; Goudriaan, J. On approaches and applications of the Wageningen crop models. *Eur. J. Agron.* **2003**, *18*, 201–234. [[CrossRef](#)]
14. Widodo, B.; Lupyanto, R.; Sulistiono, B.; Harjito, D.A.; Hamidin, J.; Hapsari, E.; Yasin, M.; Ellinda, C. Analysis of environmental carrying capacity for the development of sustainable settlement in Yogyakarta Urban Area. *Procedia Environ. Sci.* **2015**, *28*, 519–527. [[CrossRef](#)]
15. Higgins, G.M.; Kassam, A.H.; Shah, M. Land, food and population in the developing world. *Resour. Nat.* **1984**, *20*, 2–10.
16. Fischer, G.; Prieler, S.; Van, V.H. Biomass potentials of miscanthus, willow and poplar: Results and policy implications for eastern Europe, northern and central Asia. *Biomass Bioenergy* **2005**, *28*, 119–132. [[CrossRef](#)]
17. Zhu, X.S.; Wang, B.Y.; Huang, K.L.; Cao, T.B. Analysis of spatial distribution and factors influencing productivity of cultivated land in Zhonglou District of Changzhou City, China. *J. Agric. Resour. Environ.* **2020**, *37*, 672–680.
18. Shmuel, A. A simple method to design irrigation rate and duration and improve water use efficiency. *Water Resour. Res.* **2019**, *55*, 6295–6301.
19. Thiombiano, L.; Andriessse, W. Research priority setting by a stepped agro-ecological approach: Case study for the Sahel of Burkina Faso. *Neth. J. Agric. Sci.* **1998**, *46*, 5–14. [[CrossRef](#)]
20. Studnicki, M.; Wijata, M.; Sobczyński, G.; Samborski, S.; Rozbicki, J. Assessing grain yield and quality traits stability of spring wheat cultivars at different crop management levels. *Cereal Res. Commun.* **2018**, *46*, 180–190. [[CrossRef](#)]
21. Karimi, T.; Stockle, C.O.; Higgins, S.; Nelson, R. Climate change and dryland wheat systems in the US Pacific Northwest. *Agric. Syst.* **2018**, *159*, 144–156. [[CrossRef](#)]
22. Li, Y.; Li, F.; Yang, F.S.; Xie, X.D.; Yin, L.C. Spatiotemporal impacts of climate change on food production: Case study of Shaanxi Province, China. *Environ. Sci. Pollut. Res.* **2020**, *27*, 19826–19835. [[CrossRef](#)] [[PubMed](#)]
23. Kara, T.; Guler, M. Agro-ecological zoning by GIS: A case study of the Bafra and Carsamba plains in Turkey. *Asian J. Chem.* **2007**, *19*, 2277–2284.
24. Rural Revitalization Strategic Plan. Available online: https://www.gov.cn/zhengce/2018-09/26/content_5325534.htm (accessed on 27 June 2022).
25. Haverkort, A.J.; Franke, A.C.; Steyn, J.M.; Pronk, A.A.; Caldiz, D.O.; Kooman, P.L. A robust potato model: Lintul-Potato-Dss. *Potato Res.* **2015**, *58*, 313–327. [[CrossRef](#)]
26. Shi, M.; Hou, S.B.; Sun, Y.Y.; Dang, H.Y.; Song, Q.Y.; Jiang, L.G.; Cao, W.; Wang, H.L.; He, X.H.; Wang, Z.H. Regional wheat grain manganese and its potential risks affected by soil pH and precipitation. *J. Clean. Prod.* **2020**, *264*, 121677. [[CrossRef](#)]
27. Ji, X.J.; Xu, Y.H.; Zuo, X.; Fang, W.S.; Lu, Y.Y. Estimating the Climatic Capacity of Food Security in Henan Province, China Under the Future Climate Change Scenarios. *Chin. J. Appl. Ecol.* **2020**, *31*, 853–862.
28. Kadiri, W.; Fasina, A.S.; Babalola, T.S. Soil organic carbon concentration and stock of arable land use of two agro-ecological zones of Nigeria. *J. Saudi Soc. Agric. Sci.* **2021**, *20*, 180–189. [[CrossRef](#)]
29. Shi, T.R.; Jin, C.H.; Guan, J. Collision attacks against AEZ-PRF for authenticated encryption AEZ. *China Commun.* **2018**, *15*, 46–53. [[CrossRef](#)]
30. IASA; FAO. *Global Agro-Ecological Zones (GAEZ v3.0)*; Verso: Rome, Italy, 2012.
31. Shu, X.Y.; He, J.; Zhou, Z.H.; Xia, L.L.; Hu, Y.F.; Zhang, Y.L.; Zhang, Y.Y.; Luo, Y.Y.; Chu, H.Y.; Liu, W.J.; et al. Organic amendments enhance soil microbial diversity, microbial functionality and crop yields: A meta-analysis. *Sci. Total Environ.* **2022**, *829*, 154627. [[CrossRef](#)]
32. Irfan, M.; Abbas, M.; Shah, J.A.; Depar, N. Contrasting response of wheat to one-time root zone fertilization of ordinary and polymer coated urea for grain yield and nitrogen use efficiency. *J. Plant Nutr.* **2022**, *45*, 1722–1733. [[CrossRef](#)]
33. Mróz, T.; Dieseth, J.A.; Lillemo, M. Historical grain yield genetic gains in Norwegian spring wheat under contrasting fertilization regimes. *Crop. Sci.* **2022**, *62*, 997–1010. [[CrossRef](#)]
34. Qian, C.; Li, F.; Li, X.D. Analysis of fertilizer-use optimization under the joint framework of economic rationality and environmental sustainability: Evidence from wheat farmers in Handan, Hebei province. *J. Nat. Resour.* **2021**, *36*, 1481–1493. [[CrossRef](#)]
35. Zhou, Z.G.; Cao, W.X.; Wang, S.H.; Wang, Q.M.; Meng, Y.L. Potential analysis of regional crop production system based on GIS. *Trans. Chin. Soc. Agric. Eng.* **2003**, *19*, 124–128.
36. Dewit, C.T. Resource use efficiency in agriculture. *Agric. Syst.* **1992**, *40*, 125–151. [[CrossRef](#)]
37. Nave, S.; Jacquet, F.; Jeuffroy, M.H. Why wheat farmers could reduce chemical inputs: Evidence from social, economic, and agronomic analysis. *Agron. Sustain. Dev.* **2013**, *33*, 795–807. [[CrossRef](#)]
38. Debaeke, P.; Hilaire, A. Production of rainfed and irrigated crops under different crop rotations and input levels in southwestern France. *Can. J. Plant Sci.* **1997**, *77*, 539–548. [[CrossRef](#)]

39. Franke, A.C.; Baijukya, F.; Kantengwa, S.; Reckling, M.; Vanlauwe, B.; Giller, K.E. Poor farmers-poor yields: Socio-economic, soil fertility and crop management indicators affecting climbing bean productivity in northern Rwanda. *Exp. Agric.* **2019**, *55*, 14–34. [[CrossRef](#)]
40. Dong, F.Y.; Qi, B.; Jie, Y.Y. Comparative static analysis of provincial agricultural science and technology level based on grey clustering. *Grey Syst. Theory Appl.* **2018**, *8*, 481–493. [[CrossRef](#)]
41. Ma, L.; Wang, S.J.; Wastfelt, A. The Poverty of Farmers in a Main Grain-Producing Area in Northeast China. *Land* **2022**, *11*, 594. [[CrossRef](#)]
42. Xu, R.M.; Wu, Y.R.; Luan, J.D. Analysis of farmers' willingness to adopt genetically modified insect-resistant rice in China. *China Agric. Econ. Rev.* **2016**, *8*, 368–382. [[CrossRef](#)]
43. Li, X.; Guo, H.F.; Feng, G.W.; Zhang, B.B. Farmers' Attitudes and Perceptions and the Effects of the Grain for Green Project in China: A case Study in the Loess Plateau. *Land* **2022**, *11*, 409. [[CrossRef](#)]
44. Opinions on Comprehensively Promoting Rural Revitalization and Accelerating Agricultural and Rural Modernization. Available online: http://www.gov.cn/zhengce/2021-02/21/content_5588100.htm (accessed on 27 June 2022).
45. Wu, J.F.; Li, D.; Liu, X.J.; Xiao, R.R.; Qi, Y.L. The spatio-temporal evolving pattern and the influencing factors of grain production in the Yangtze River economic belt. *Res. Agric. Mod.* **2021**, *42*, 407–417.
46. Kiboi, M.N.; Ngetich, K.F.; Diels, J.; Mucheru-Muna, M.; Mugwe, J.; Mugendi, D.N. Minimum tillage, tied ridging and mulching for better maize yield and yield stability in the Central Highlands of Kenya. *Soil Tillage Res.* **2017**, *170*, 157–166. [[CrossRef](#)]
47. Liao, L.W.; Long, H.L.; Gao, X.L.; Ma, E.P. Effects of land use transitions and rural aging on agricultural production in China's farming area: A perspective from changing labor employing quantity in the planting industry. *Land Use Policy* **2019**, *88*, 104152. [[CrossRef](#)]
48. Zhang, K.L.; Peng, X.; Zhang, S.X.; Zhan, H.W.; Lu, J.H.; Xie, S.S.; Zhao, S.H.; Li, X.Y.; Ma, Y.L. A comprehensive evaluation of factors affecting the accuracy of pig genotype imputation using a single or multi-breed reference population. *J. Integr. Agric.* **2022**, *21*, 486–495.
49. Pietro, A.; Antonio, L.; Gabriella, M. On the choice of weights for aggregating judgments in non-negotiable AHP group decision making. *Eur. J. Oper. Res.* **2021**, *288*, 294–301.
50. Kuang, L.X.; Wang, Z.Q.; Zhang, J.Y.; Li, H.F.; Xu, G.F.; Li, J. Factor analysis and cluster analysis of mineral elements contents in different blueberry cultivars. *J. Food Compos. Anal.* **2022**, *109*, 104507. [[CrossRef](#)]
51. Cui, Y.; Khan, S.U.; Deng, Y.; Zhao, M.J. Spatiotemporal heterogeneity, convergence and its impact factors: Perspective of carbon emission intensity and carbon emission per capita considering carbon sink effect. *Environ. Impact Assess. Rev.* **2022**, *92*, 106699. [[CrossRef](#)]
52. Su, Q.; Wang, F.F.; Chen, J. Rural-household differentiation and land transfer behavior. *Resour. Sci.* **2016**, *38*, 377–386.
53. Antonio, J.C.; Nuria, G.H. Use of similarity indexes to identify spatial correlations of sodium void reactivity coefficients. *Nucl. Eng. Technol.* **2020**, *52*, 2442–2451.
54. Oliver, M.A.; Webster, R.; Taylor, F.O. Kriging: A Method of Interpolation for Geographical Information. *Int. J. Geogr. Inf. Syst.* **1990**, *4*, 313–332. [[CrossRef](#)]
55. Li, F.; Zhou, M.J.; Hu, M. Climate change in different geographical units and its impact on land production potential: A case study of Shaanxi Province, China. *Environ. Sci. Pollut. Res.* **2019**, *26*, 22273–22283.
56. Sheng, Y.; Song, L.G. Agricultural production and food consumption in China: A long-term projection. *China Econ. Rev.* **2018**, *53*, 15–29. [[CrossRef](#)]
57. Bren, D.A.C.; Reitsma, F.; Baiocchi, G.; Barthel, S.; Güneralp, B.; Erb, K.H.; Haberl, H.; Creutzig, F.; Seto, K.C. Future urban land expansion and implications for global croplands. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 8939–8944. [[CrossRef](#)]
58. Ma, Q.; Han, W.T.; Huang, S.J.; Dong, S.D.; Li, G.; Chen, H.P. Distinguishing Planting Structures of Different Complexity from UAV Multispectral Images. *Sensors* **2021**, *21*, 1994. [[CrossRef](#)]
59. Global Report on Food Crises 2022. Available online: <https://www.wfp.org/publications/global-report-food-crises-2022> (accessed on 27 June 2022).
60. Nutrition in Numbers. Available online: <https://docs.wfp.org/api/documents/WFP-0000139584/> (accessed on 27 June 2022).