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Farmland Dynamics and Its Grain Production Efficiency and Ecological Security in China's Major Grain-Producing Regions between 2000 and 2020

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Abstract: Understanding the land use/cover changes associated with agricultural production is essential for food security in increasingly urbanizing areas. Such studies have been widely conducted in different regions of China; yet, its major grain-producing regions (MGPRs) remain less studied. To address this knowledge gap, we conducted analyses of the land use conversion matrix, spatial hot spots, decoupling, and index evaluation from a spatiotemporal perspective, to quantify the MGPRs' farmland changes and its grain production efficiency and ecological security during 2000–2020. The results showed the following: (1) Farmland in the MGPRs experienced a net decline of 2.54×10^4 km^2, with significant spatial heterogeneity in the area, extent, and speed of loss/gain. (2) Farmland gain came from mostly forest, grassland, and unused land, with hotspots in northeastern China, while farmland loss increasingly changed to construction lands, with hotspots covering east-central China and in the suburbs surrounding capital cities. (3) Grain production in the MGPRs increased by 1.6 times in the past 20 years, via its strong decoupling from farmland quantity in especially central-eastern China. (4) Land ecological security in the MGPRs was less secure but has been improving with non-homogeneous regional differences, while it demonstrated a spatial pattern of "higher security in the north–south and lower in the middle". Our findings suggested that China's MGPRs would continue to lose farmland and China's food security should require a sustainable decoupling of grain production and farmland quantity while maintaining ecological security. This study has significant policy implications for farmland conservation in China's MGPRs, as well as highlighting the landscape sustainability opportunities of urbanization-associated farmland loss in densely populated human–environment systems in general.

Keywords: farmland; land use; food security; spatiotemporal analysis; major grain-producing regions; sustainability

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1. Introduction

Meeting the growing world demand for food—one of the most fundamental human needs—is a top challenge to enhance global sustainability, as exemplified in the Sustainable Development Goals by the United Nations [1]. Grain self-sufficiency in developing countries has been threatened due to farmland scarcity and the global drying tendency [2,3]. China has long been a worldwide concern [4,5], due to its 1000 m^2 per-capita farmland resource (vs. the world average of 2300 m^2) and 1.46 billion population (nearly one-fifth of the world population). Given the rapid urbanization, industrialization, and diet structure change in the past 40 years, the conflict between decreased farmland and increased grain demand has been increasingly significant [6,7]. It was predicted that China's total grain demand would grow faster than grain production in the near future. As a result, China has to rely more on grain import and international cooperation to ensure its food supply and ease resource pressures in the long run [8–10]. This is, however, unsustainable, particularly when globalization becomes uncertain with setbacks like trade wars. Therefore, it is critical for China to maintain at least its grain self-sufficiency.

The major grain-producing regions (MGPRs) are typical of China's farming area. Covering the major plains (Sanjiang Plain and Songneng Plain in the northeast, Huang-Huai-Hai Plain in the north, and the Mid-Lower Yangtze Plain in the central China) and Sichuan Basin of China, they outperform the other provinces in grain production and provide around 75% of the national grain output [11]. The MGPRs are in control of the lifelines of national gain production, so it is crucial to stress the conservation of farmland to ensure national food security.

After the rapid urbanization and industrialization in the past two decades, China's urban expansion and its associated urban–rural land use changes have been remarkable, with the phenomenon of farmland transition and farmland loss well documented [12–15]. Studies have focused on the relationship between farmland gain and loss in terms of quantity, quality, yield, and ecological effects under the dual effect of farmland protection and construction land expansion [16,17]. The conflict between rapid urbanization and food security is prominent, particularly in the most productive agricultural regions of the MGPRs. The expansion of construction land caused by urbanization has led to the occupation of a large amount of adjacent farmland, resulting in the loss and non-agriculturalization of farmland [18]. The competition for land resources between urban and rural areas is particularly obvious in more developed areas of MGPRs. The process of urbanization attracts a massive population from rural areas to cities, leading to a widespread abandonment of farmland in rural areas, which has a serious negative impact on grain production [19]. Most of the MGPRs in China have long been in the situation of "wealthy in gain, poor in economy", leading to the increasingly prominent conflict between grain production and urbanization.

Land use changes have been shown to be associated with regional natural geographical conditions, government land policies, and socio-economic context [20,21]. The spatiotemporal perspective of farmland transitions could provide basic data for land use pattern and characteristics analysis in terms of space and time, thus mapping out strategies for scientific and effective land space regulation [22–24]. Changes in the spatiotemporal pattern of farmland coupled with human economic activities seriously influence grain production and land ecological security, and together, they have an impact on national food security.

Grain production is mainly determined by farmland quantity and quality, grain yield per unit area, grain cropping ratio, and the multiple cropping index. Among those aspects, the top concern is often farmland loss. Farmland loss in China has become increasingly serious since the 2000s, due to rapid socio-economic development. It was reported that China's farmland increased by 1.9% during 1986–2000 [25], consistent with the findings of Liu [26] that China's farmland increased by 2.83×10^4 km^2 during 1990–2000. However, Liu [26] also reported that the trend shifted to a decline during 2000–2010, by a loss of 1.02×10^4 km^2 of farmland. China continued to lose farmland to mostly urbanization during 2010–2015, by a quantity of 0.49×10^4 km^2 [27]. Clearly, the urbanization of China since 2000 has indeed been causing farmland loss and consequent potential threats to national grain self-sufficiency. Simultaneously, grain yield and farmland use are inextricably linked. It was estimated that urban encroachment during 1990–2010 had decreased China's national grain production by 6.52% [28], and the urban expansion during 1992–2015 in China had reduced the mean annual grain self-sufficiency by 2% [6]. China has pledged to preserve the minimum quantity of farmland by drawing the "Red Line". But the reality is that "China is growing more food on less land, a situation that leaves little scope for expansion" [29]. In response, the Chinese government has launched the "Farmland Dynamic Balance" policy to protect farmland [30] and, more recently, declared to conserve a minimum amount of prime farmland by "(sustainability) Red Line"-based zoning [31]. These policies on farmland conservation have undergone a process of centralization, which has achieved a certain success but is still challenging in light of farmland loss [32]. Likewise, the pressures on grain production and food security caused by farmland loss still worthy of attention.

Farmland ecological security refers to the capacity of the farmland ecosystem to retain a reasonable functional structure for sustainable grain production and human living [33]. Studies on ecological security have been focused on regional ecological functions, landscape ecological planning, ecological security patterns, etc. [34–36]. Recent studies also connected land use with ecosystem services and ecological security for ecological network optimization and sustainable land use [37–40]. While attention on the ecological security of farmland has been scanty, relevant research is mainly concerned with ecological degradation, compensation, and land multifunctionality [41,42]. Farmland's ecological security is of importance for sustainable agricultural production and land resource conservation. However, the ecological condition of farmland in the MGPRs is less positive, due to soil erosion and fertilizer pollution, etc. In 2019, the total fertilizer usage was 35.93 million tons in the MGPRs, accounting for 66.5% of the national total. The amount of chemical fertilizer used per hectare of farmland was about 404 kg, which was 80% higher than the safety standard in developed countries [43]. Therefore, it is necessary to incorporate ecological security considerations into the dynamic changes of farmland and food security issues.

Overall, the decrease in farmland has been the critical one that negatively influences national food security; meanwhile, the ecological safety of farmland is directly linked to food security and is critical for sustainable land use. However, a critical knowledge gap still remains regarding the system dynamics of farmland while considering its grain production efficiency and ecological security in China's officially identified major grain-producing regions (MGPRs), the key areas for sustaining farmland resources and maintaining food security. This study aimed to bridge the above-mentioned knowledge gaps by answering two core questions: (1) What were the temporal trend and spatial patterns of farmland changes in China's MGPRs from 2000 to 2020? (2) What were the grain production efficiency and ecological security accompanied by these farmland dynamics in the MGPRs? The answers would be relevant to sustainable land use and agricultural production in China.

This study adopted a spatiotemporal perspective to make strategic judgment regarding the long-term trend of the coupled farmland–grain–ecology systems and to inform explicit policy design for navigating the MGPRs toward sustaining grain self-sufficiency of China. Specifically, we conducted land use conversion matrix analysis and hot/cold spots analysis to address the first research question, and conducted comparative analysis, decoupling analysis, and evaluation analysis for the second (Figure 1). Our study, with a focus on the specific challenge of food security in China, highlighted the critical role of China's MGPRs in farmland conservation and grain production. Our findings provided practical implications for improving farmland conservation and enhancing sustainable land use and food security in China's most productive agricultural regions. The study demonstrated how humans interact with nature, and provided broad research implications for enhancing the landscape sustainability of densely populated, rapidly developing human–environment systems in an era of global change.

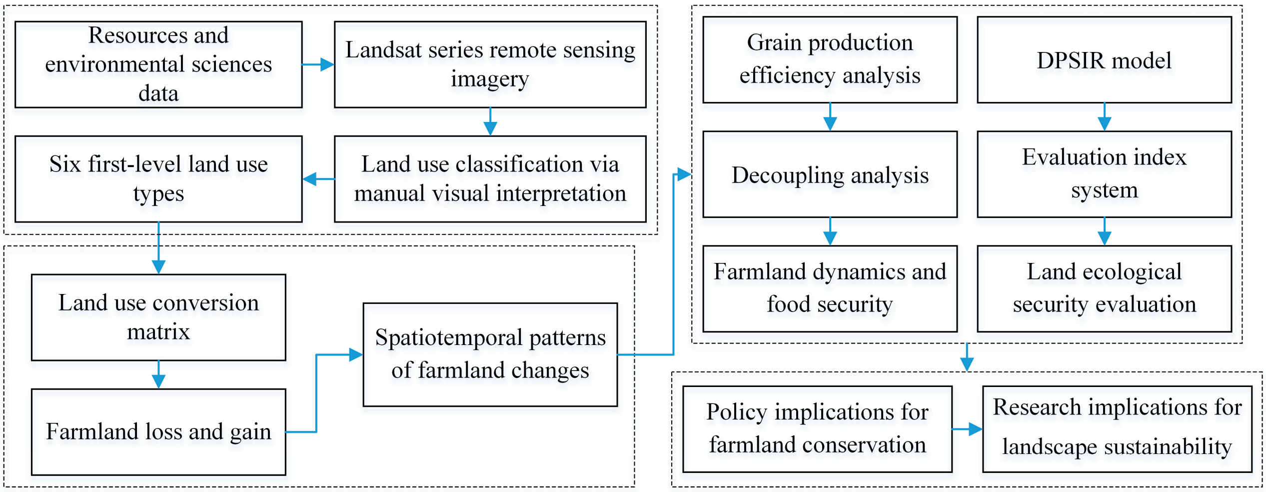

Figure 1. Technology procedure of the research.

2. Materials and Methods

2.1. Study Area

The major grain-producing regions (MGPRs) are 13 provinces strategically singled out by the Chinese government for targeted agricultural reform and development policies, including Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Henan, Shandong, Jiangsu, Anhui, Jiangxi, Hubei, Hunan, and Sichuan (Figure 2). The MGPRs are further divided into 6 grain-net-exporting (GNE) provinces (i.e., Heilongjiang, Jilin, Inner Mongolia, Henan, Shandong, and Anhui) and the other 7 non-GNE provinces. Farmland accounted for about 31% of the total area of the MGPRs and was mainly distributed in northern and northeastern regions. Although the area of construction land was not extensive, there was a visible expansion of construction land in every province from 2000 to 2020.

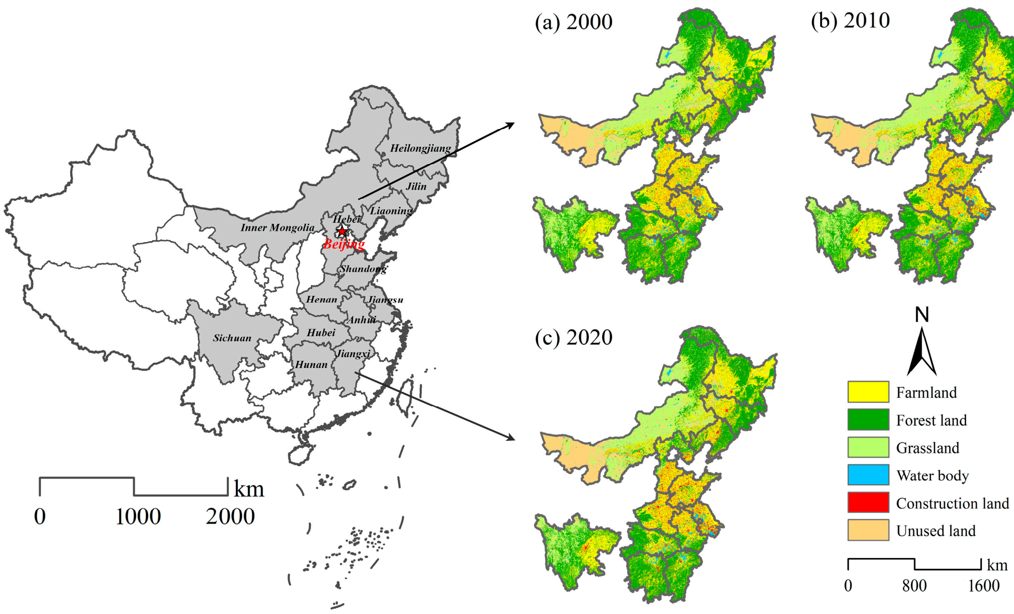

Figure 2. Location and spatial distribution of land use in the MGPRs of China.

2.2. Data

The land use classification products were obtained from the Resources and Environmental Sciences Data Center of Chinese Academy of sciences (http://www.resdc.cn, accessed on 10 January 2023), with a resolution of 1 km for the years of 2000, 2010, and 2020. They were produced based on Landsat series remote sensing imagery via manual visual interpretation, with 6 first-level land use types including farmland, forest land, grassland, water body, construction land (this category is a combination of "already-urban/developed" and "soon-to-be urban/developed" land, including urban land, rural living land, industrial and mining land), and unused land and 25 sub-types at the second level. The comprehensive evaluation accuracy of classification at the first level is above 93%, and that at the second level is above 90% [27,44,45]. As for grain production (grains in China includes mainly wheat, rice, corn, coarse grains, edible beans, and potato crops), data of grain-sowing area and total grain output were collected from China's regional economic statistical yearbook, China's social and economic statistical yearbook of cities, and county and statistical yearbooks of provinces in the MGPRs.

2.3. Methods

2.3.1. Farmland Change Analysis by Land Use Conversion Matrix

The land use conversion matrix was used to show the conversion relationships between different land use types [46]. The equation for land use conversion matrix analysis is as follows.

$$S_{ij} = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ s_{n1} & s_{n2} & \cdots & s_{nn} \end{bmatrix} \tag{1}$$

where S_{ij} represents the area converted from land use type i to land use type j; n represents the number of land use types. Rows are the sinks of land losses from each land use, while columns are the sources of land gains by each land use type.

2.3.2. Spatial Cold/Hot Spot Analysis of Farmland Loss and Gain

To reveal the hot and cold spots of land use changes, the optimized hot/cold spot analysis was applied via the Getis-Ord G_i^* tool in ArcGIS based on spatial autocorrelation analysis [13,47,48]. The Getis-Ord G_i^* can be mathematically expressed by Equations (2) and (3) [49,50].

$$G_i^*(d) = \sum_{j=1}^{n} w_{ij}(d)x_j / \sum_{j=1}^{n} x_j \tag{2}$$

$$Z(G_i^*) = \frac{G_i^* - E(G_i^*)}{\sqrt{Var(G_i^*)}} \tag{3}$$

where $Z(G_i^*)$ is the value of the standardized treatment of $G_i^*(d)$; $E(G_i^*)$ and $Var(G_i^*)$ are the mathematical expectation and variance of G_i^*, respectively; $w_{ij}(d)$ is the spatial weight matrix between i and j; x_i and x_j are the area of farmland of units i and j, respectively. Significantly positive $Z(G_i^*)$ indicates that the area of farmlands around unit i is relatively high (higher than the average), thus belonging to high-value spatial agglomeration (hot zone). On the contrary, significantly negative $Z(G_i^*)$ indicates that the area of farmlands around unit i is relatively low (below the average), thus belonging to low-value spatial agglomeration (cold zone).

2.3.3. Grain Production Efficiency and Decoupling between Grain Production and Farmland

To measure the variation in grain production efficiency with regard to the grain output per unit of farmland, we used the coefficient of C_{GL} defined as Equation (4):

$$C_{GL} = \frac{G_t/L_t}{G_i/L_i} \tag{4}$$

where C_{GL} is the coefficient of efficiency change; G_t and G_i represent the grain production in year t and year i, respectively; L_t and L_i refer, respectively, to the farmland area in year t and year i. The higher the value of C_{GL}, the greater the improvement in grain production efficiency.

The decoupling model [51] was adopted to measure the temporal relationship between grain production and farmland quantity. The terminology of "decoupling" was defined initially in economics as "breaking the link between 'environmental bads' and 'economic goods'" [52], and is now wildly used to analyze economic activities and their influence on the environment or dependence on material consumption [53–55]. In this study, a decoupling coefficient of D_{GL} was specified to identify the decoupling relationships between grain production and farmland quantity at the city/prefecture level. D_{GL} is defined as Equation (5):

$$D_{GL} = \%\Delta(L_{t-i}/G_{t-i}) \tag{5}$$

where D_{GL} is the decoupling coefficient between grain production and farmland quantity; ΔL_{t-i} represents the change in farmland area between year i and year t; ΔG_{t-i} refers to the change in grain production between year i and year t. The decoupling status, of eight possibilities, depends on the value of ΔG_{t-i}, ΔL_{t-i}, and D_{GL}. For instance, strong decoupling refers to the situation when grain production increased while farmland decreased, which implies that the stress of grain self-sufficiency could likely be relieved by gaining more grain production from less farmland.

2.3.4. Ecological Security of Farmland Use

In this study, the Driver-Pressure-State-Impact-Response (DPSIR) model was adopted to evaluate the ecological security of farmland use [56]. Ten indicators were selected from the five aspects of DPSIR to construct the land ecological security (LES) evaluation index system in MGPRs (Table 1). The entropy weight method was used to calculate the index weight and the LES index S. The study divided the land ecological security into five levels: very insecure, $S < 0.2$; relatively insecure, $0.2 \leq S < 0.4$; generally secure, $0.4 \leq S < 0.6$; relatively secure, $0.6 \leq S < 0.8$; very secure, $S \geq 0.8$ [43].

Table 1. Evaluation index system for land ecological security.

Category	Indicator	Measuring Unit	Attribute [1]	Weight
Driver	Population density	person per km^2	−	0.043
	Economy density	10 thousand yuan per km^2	+	0.223
Pressure	Urbanization rate	%	+	0.046
	Agricultural fertilizer usage	tons per hm^2	−	0.035
State	Farmland per person	hm^2 per person	+	0.199
	Water resource per person	m^3 per person	+	0.130
Impact	Grain yield per unit	tons per hm^2	+	0.036
	Proportion of tertiary industry	%	+	0.052
Response	Recovery area for soil erosion	hm^2	+	0.081
	Investment in pollution control	10 thousand yuan	+	0.153

[1] Attribute: "+", positive indicator; "−", negative indicator.

3. Results

3.1. Spatiotemporal Patterns of Farmland Change

3.1.1. Temporal Changes of Farmland during 2000–2020

Farmland dynamics was the dominant land use change in the MGPRs during 2000–2020, with farmland loss much related to construction land expansion and farmland gain involving more complex processes. The land use transition matrix of the MGPRs (Table 2) showed the dynamics of each land use type from 2000 to 2020. In terms of net area change, the construction land expansion ranked the top (5.37×10^4 km^2), followed by farmland loss (2.54×10^4 km^2) and grassland loss (3.19×10^4 km^2). The farmland gains were from a variety of sources, whilst farmland loss mostly went to forest and construction land.

Table 2. Land use transition matrix in the MGPRs of China in 2000–2020 (unit 10^2 km^2).

2000	2020					
	Farmland	**Forest Land**	**Grassland**	**Water Body**	**Construction Land**	**Unused Land**
Farmland	8683.58	1149.67	496.29	239.03	1062.89	98.39
Forest land	1163.48	8872.33	792.87	69.23	93.35	170.68
Grassland	599.00	881.46	6370.00	62.50	90.53	398.61
Water body	207.35	57.67	45.58	559.40	35.43	84.73
Construction land	632.65	36.31	35.72	51.38	473.59	10.32
Unused land	183.58	63.64	341.93	49.32	21.13	3127.88

The interconversion of land use (Figure 3) showed a period of somewhat severe shifts in 2015–2020 after a period of steady transitions in 2000–2015. The expansion of construction land has been the predominant and still growing consumer of farmland. This resulted in 45.59% to 77.64% of farmland loss between 2000 and 2020. Farmland conversion to forest land increased significantly between 2015 and 2020, whereas conversions to water bodies, grassland, and unused land remained mostly unchanged. Simultaneously, the forest land and grassland have been the main contributors to farmland gain. In contrast to the stable contributions from water bodies, grassland was the leading source of farmland gain before 2005; after that, farmland gain was mostly caused by the conversion of forest land and grasslands. Notably, there has been an increase in the percentage of farmland gain from rural construction land by means of land consolidation since 2015 [57–59].

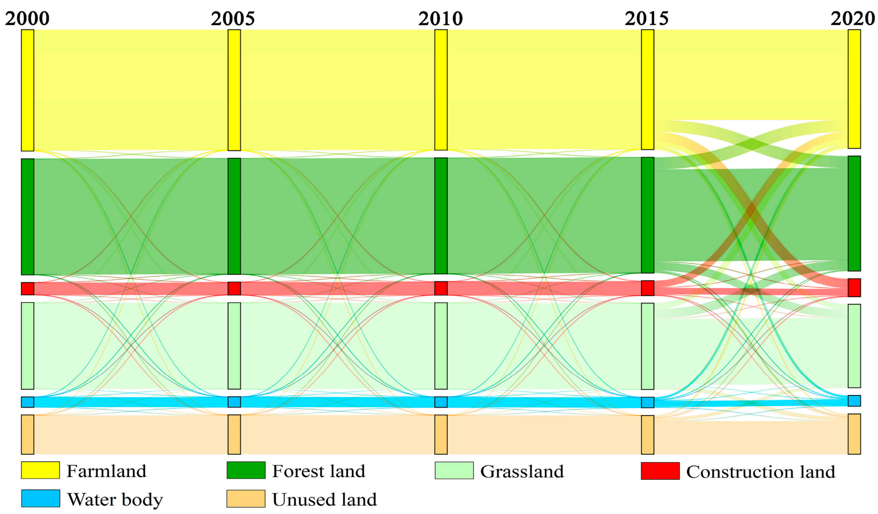

Figure 3. Land use changes in the MGPRs from 2000 to 2020.

3.1.2. Spatial Patterns of Farmland Loss and Gain during 2000–2020

From a spatial perspective, the MGPRs' farmland dynamics in terms of area demonstrated strong spatial heterogeneity. Regarding absolute farmland loss (Figure 4a), spatial agglomerations of large farmland loss (i.e., hot spots) were detected in, unsurprisingly, the economically developed areas. Specifically, a vast agglomeration existed along the Beijing-Shanghai Railway (an artery of China's economy), covering most of Shandong and Jiangsu as well as part of Henan and Anhui provinces. Additionally, several small agglomerations were distributed mostly around the capital cities of the MGPR provinces. Contrastingly, the spatial agglomerations of less farmland loss (i.e., cold spots) were detected in the areas biophysically unsuitable or socio-politically unfeasible for agricultural development and thus of low farmland quantity. Specifically, the cold spots included the montane north-western Sichuan that is occupied by the Hengduan Mountains, western Inner Mongolia, which is mostly desert, and the legally preserved Xing'an Mountains Forest in northeastern China. As for absolute farmland gain (Figure 4b), the hot spots were distributed mainly in the eastern part of the MGPRs, which is mostly plains, while the cold spots of farmland gain included almost all the cold spots and part of the hot spots of farmland loss. This is no surprise, since the hot/cold spots of farmland gain should be positively related to the quantity of natural lands (e.g., forest land and grassland) for agricultural cultivation, and negatively related to land demand for socio-economic development (i.e., construction land expansion). Finally, with regard to the net absolute change of farmland area (Figure 4c), its hot spots overlapped those of farmland loss whilst its cold spots overlapped largely with farmland gain's hot spots.

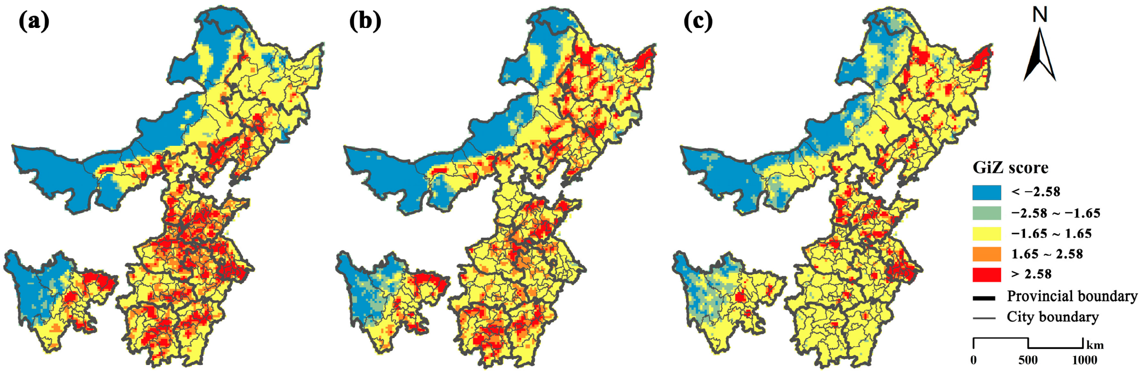

Figure 4. Hot (red) and cold (blue) spots of farmland changes of area in China's MGPRs in 2000–2020, in terms of (**a**) farmland loss, (**b**) farmland gain, and (**c**) net farmland change.

3.2. Grain Production Efficiency and Decoupling with Farmland Changes

3.2.1. Growth of Grain Production during 2000–2020 in the GNE and Non-GNE Areas

The grain production in the MGPRs showed a consistent increase tendency, increasing from 328 to 526 million tons from 2000 to 2020 with an average annual growth rate of 2.38% (Figure 5). Corresponding, the grain production in GNE areas increased from 158 to 313 million tons during 2000–2020 (annually 3.47%), while for the non-GNE areas, theirs increased from 170 to 213 million tons (annually 1.14%). In addition, the increase rate of the non-GNE areas' grain production had an increasing trend before 2015 yet remained lower than that of the GNE areas, while the increase rate of the GNE-areas' grain production, though relatively high, peaked during 2005–2015. Essentially, the grain production in the MGPRs was increasingly dependent on the GNE provinces, yet the high-rate increase in the GNE areas' grain production has been declining since 2010. Despite increasing grain output in both GNE and non-GNE regions, the GNE areas' share of global grain production increased from 48.28% to 59.50%.

3.2.2. Spatiotemporal Patterns of Grain Production Efficiency and Decoupling between Grain Production and Farmland

With the growth of grain production and net decline of farmland during 2000–2020, it should come as no surprise that the grain production efficiency improved coincidentally, albeit with spatiotemporal variations. Specifically, the GNE areas' C_{GL} (i.e., improvement of grain production efficiency) peaked during 2006–2010, while the non-GNE areas' C_{GL} peaked during 2011–2015. This was consistent with Figure 5 that the growth rate of the non-GNE areas' grain production peaked around 2015. A lower C_{GL} between 2015 and 2020 particularly resulted from a farmland increment in the GNE areas. In addition, the non-GNE areas' C_{GL} had always been lower than that of the GNE areas. In the long run, the non-GNE areas have more potential in increasing grain production. The non-GNE areas were responsible for most farmland loss in the MGPRs; however, its contributions to the

MGPRs' grain production increased continuously. The mathematics behind this implied that the grain production capability in the non-GNE areas could not be underestimated.

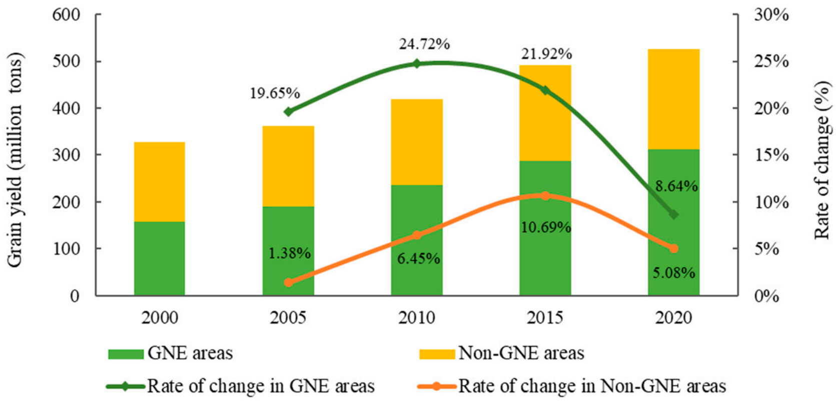

Figure 5. Grain productions and change rates in China's MGPRs in 2000–2020.

The MGPRs evolved toward expansive, strong, and positive decoupling of grain production and farmland quantity between 2000 and 2020: 'expansive' means that the grain production increased, 'strong' means that the farmland actually decreased, and 'positive' means that the grain production efficiency increased. Specifically, the non-GNE areas had a higher degree of strong decoupling than the GNE areas. In general, Table 3 shows that the grain production and farmland quantity had become strongly decoupled as the grain production efficiency continued to increase, especially in non-GNE areas.

Table 3. Relationships between grain production dynamics and farmland changes in 2000–2020.

Type of Change	Studied Period	Region					
		Grain-Net-Exporting (GNE) Areas		Non-GNE Areas		Major Grain-Producing Regions (MGPRs)	
		Amount	Rate of Change	Amount	Rate of Change	Amount	Rate of Change
Net change in grain production (ΔG, 10^4 t)	2000–2005	3111	19.6%	234	1.4%	3345	10.2%
	2006–2010	4683	24.7%	1110	6.5%	5793	16.0%
	2011–2015	5179	21.9%	1957	10.7%	7136	17.0%
	2016–2020	2489	8.6%	1029	5.1%	3518	7.2%
	2000–2020	15,463	97.6%	4330	25.5%	19,793	60.3%
Net change in farmland (ΔL, km^2)	2000–2005	−688	−0.1%	−4077	−0.8%	−4765	−0.4%
	2006–2010	−1229	−0.2%	−2993	−0.6%	−4222	−0.4%
	2011–2015	−421	−0.1%	−5166	−1.0%	−5587	−0.5%
	2016–2020	5260	0.8%	−16060	−3.1%	−10800	−0.9%
	2000–2020	2922	0.5%	−28,296	−5.3%	−25,374	−2.2%
C_{GL} (improvement of grain production efficiency)	2000–2005	1.20		1.02		1.11	
	2006–2010	1.25		1.07		1.16	
	2011–2015	1.22		1.12		1.18	
	2015–2020	1.08		1.07		1.08	
	2000–2020	1.97		1.33		1.64	
D_{GL} (decoupling grain production from farmland quantity)	2000–2005	−0.005		−0.558		−0.040	
	2006–2010	−0.008		−0.088		−0.023	
	2011–2015	−0.003		−0.093		−0.028	
	2015–2020	0.095		−0.611		−0.130	
	2000–2020	0.005		−0.209		−0.036	

A spatial perspective provides further details on the categorical differences—GNE areas versus non-GNE areas—in terms of grain production efficiency and decoupling status of grain production and farmland quantity. Grain production efficiency improved during 2000–2020 in all prefecture-level cities in the MGPRs. A larger improvement of grain production efficiency occurred in three GNE provinces, i.e., Heilongjiang, Jilin, and Inner Mongolia, with C_{GL} > 2.2 meaning the grain production efficiency more than doubled, whereas the other three GNE provinces (i.e., Henan, Shandong, and Anhui) and the seven non-GNE provinces (i.e., Liaoning, Hebei, Jiangsu, Jiangxi, Hubei, Hunan, and Sichuan) experienced a lower increase in grain production efficiency (Figure 6a). By contrast, though the MGPRs showed strong decoupling of grain production and farmland quantity (Table 3), there indeed existed five decoupling types in the 186 cities (Figure 6b). About 67% of the cities, which are distributed across the MGPRs but especially in Hebei, Shandong, Henan, Anhui, Jiangsu, Hubei, Hunan, and Jiangxi, had strong decoupling; cities with net farmland gains, mostly located in Heilongjiang, Jilin, and Inner Mongolia, had weak decoupling; while fewer cities, located in usually socio-economically developed areas and all having reduced grain production, presented recessive decoupling, recessive coupling, and weak negative decoupling, respectively.

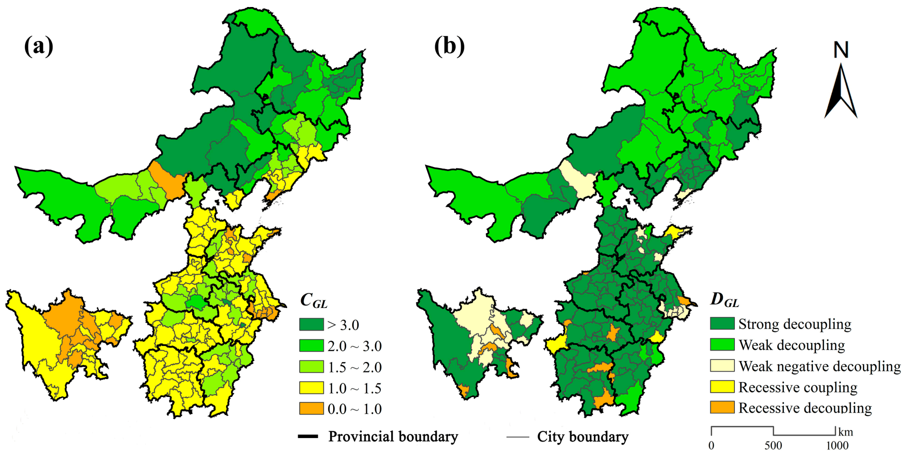

Figure 6. Relationships between grain production and farmland quantity in China's MGPRs in 2000–2020, as measured by (**a**) efficiency improvement C_{GL} and (**b**) coupling/decoupling status D_{GL}.

Note: the coupling/decoupling status includes strong decoupling ($\Delta G > 0$, $\Delta L < 0$, and $D_{GL} < 0$), weak decoupling ($\Delta G > 0$, $\Delta L > 0$, and $0 < D_{GL} < 0.8$), recessive decoupling ($\Delta G < 0$, $\Delta L < 0$, and $D_{GL} > 1.2$), recessive coupling ($\Delta G < 0$, $\Delta L < 0$, and $0.8 < D_{GL} < 1.2$), and weak negative decoupling ($\Delta G < 0$, $\Delta L < 0$, and $0 < D_{GL} < 0.8$) in this study.

3.3. Land Ecological Security and Its Spatial Pattern

During the studied period, the land ecological security (LES) in the MGPRs ranged between very insecure and generally secure ($S < 0.6$). The overall LES showed an "uneven growth" and the comprehensive values of LES in various regions improved to varying degrees (Figure 7). From 2000 to 2020, the average LES index in the MGPRs showed an overall upward trend, increasing from 0.21 to 0.35. This indicated that the overall LES in the MGPRs had improved. Regions of Inner Mongolia, Liaoning, Heilongjiang, Jiangxi and Sichuan saw a better LES. Meanwhile, the LES index in Jiangsu, Shandong, Henan, and Anhui provinces increased significantly, which over doubled between 2000 and 2020. Meanwhile, the LES index in the MGPRs showed a spatial pattern of "high in the north–south and low in the middle". The regions of generally secure and relatively insecure grew, and the very insecure regions shrunk. Overall, the number of very insecure regions decreased from 7 to 0, the number of relatively insecure regions increased from 6 to 10, and the number of generally secure regions increased from 0 to 3. The generally secure regions were mainly distributed in blocks with Heilongjiang as the center connecting Inner Mongolia and Jilin to the south. With Heilongjiang serving as its hub and a connection between Inner Mongolia and Jilin to the south, the typically safe areas were mostly dispersed in blocks. These regions contain considerable quantities of cropland, dense forest cover, and a healthy natural environment.

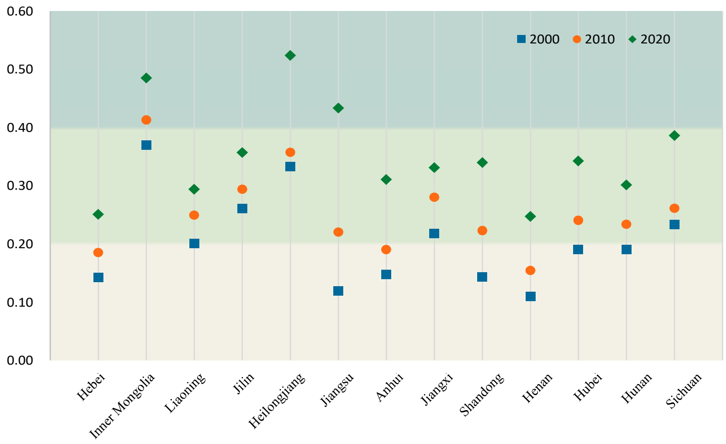

Figure 7. Land ecological security in China's MGPRs in 2000–2020.

4. Discussion

4.1. Policy Implications for Farmland Conservation in the MGPRs

In the coupled human and natural systems, human–environment interaction has become a prominent theme in sustainability science [60,61], while the contradiction between farmland conservation and urbanization is difficult to eliminate in a short period of time. In response to the international and domestic concerns about China's food security, the Chinese government has implemented a series of agricultural and land use policies for national grain self-sufficiency. Our findings highlighted the critical role of China's MGPRs in farmland conservation. We found that 2.54×10^4 km^2 of net farmland loss occurred in the MGPRs during 2000–2020, which accounted for over 95% of China's net farmland loss. Temporally, the lost farmland in the MGPRs since 2000 had been increasingly consumed by construction land uses and forest land (Figure 3). Spatially, the MGPRs' farmland loss occurred primarily in the national-level Yangtze economic agglomeration and secondly at regional-level economic agglomerations like provincial capitals (Figures 4 and 5). The spatiotemporal characteristics of the MGPRs' farmland loss imply that farmland conversion to construction land is driven by economic development, as also concluded in the econometric analysis of Bai [62] that built-up areas and economic growth have a bidirectional causal relationship. Given that China is very likely to continue its relatively fast economic growth for at least another decade, it is reasonable to expect that, in a "business-as-usual" scenario, China will inevitably lose another considerable amount of farmland to construction land uses in predominantly the MGPRs of China.

Our study found that the MGPRs' grain production strongly decoupled from farmland quantity and increased from 3.28×10^8 tons to 5.26×10^8 tons during the period from 2000 to 2020 (Figures 5 and 6), due to the improvement of grain production efficiency. We have provided spatial details (Figure 6a) for targeted policy design, since the grain production efficiency in northeastern China and Inner Mongolia demonstrated a remarkable increase. This likely resulted from increased cropping intensity [63], and also improved agricultural technology and organization [64]. On the other hand, however, we have also shown that the grain production of 19 MGPRs cities presented weak negative decoupling from farmland change, which indicates the loss of farmland and, worse still, the decrease in grain production efficiency (Figure 6b). This likely resulted from the insufficient incentive power from the grain subsidy programs due to the larger opportunity cost of rural labor in those economically developed regions [65] and from the decrease in labor-intensive subsistence farming due to the rise of agrarian capitalism [66]. Meanwhile, the spatial heterogeneity accompanied by an overall increase in land ecological security (Figure 7) suggested establishing a synergistic mechanism between high- and low- ecological-security areas and taking advantage of local resource endowments to promote a synergistic development of integrated systems of farmland cultivation.

The MGPRs need to transition to new and more sustainable human–environment development pathways with different 'formulas' embedded for making land use tradeoffs in terms of economic, social, and ecological uses [67]. Such transitions can be triggered and leveraged by transformative socio-ecological, socio-technical, socio-institutional, or socio-cultural changes [68,69], but in the first place, socio-cultural changes [70] for the recognition of food insecurity risks and the valuing of farmland especially from the local and regional governments, as well as the public, are of importance. In this complex transition, land management is an effective approach for solving diverse and conflicting human demands on land systems, especially for feeding more of the population while sustaining the multi-function of land [71,72].

Certain measures could be effective: Firstly, transferring approval rights for farmland conversion to the central government, the application of new technology and responsibility in the central government's inspections of local land use regulation, reforming the supply mechanism of construction land, and raising compensation standards for farmland expropriation [73]. Secondly, priority protection of farmland with high-quality, high-yield, contiguous, and stable cultivation, particularly in the grain-net-exporting areas. Strictly protect and improve the quality of the permanent basic farmland. Policy priorities would be identifying high-quality farmland for protection from urban encroachment [6,28,74] and reclaiming farmland from rural residential land in hollowing villages [30,75,76]. Thirdly, providing farmland consolidation opportunities and promoting high-standard farmland construction in the MGPRs, such as conservation tillage to improve soil nutrients and tolerance to external environmental impacts, for increased grain farm sizes and food security [77–79]. Fourthly, increasing region-specific investment in rural, agricultural, and technical transformations in the MGPRs. Establishing a national food security guarantee fund and a financial compensation system to strengthen the transfer of payments and promote the farming enthusiasm of the MGPRs. Exploring advanced farmland utilization technologies and agricultural modernization to support agricultural production efficiency and ecological security. Finally, establishing a synergistic mechanism between high- and low-ecological-security areas to enhance the overall ecological security in the MGPRs. This could be realized by optimizing the spatially linked environment of farmland use and production, promoting interoperability in farming behavior, ecological technology, and environmental regulation policies in the MGPRs.

4.2. Research Implications for Landscape Sustainability of Densely Populated, Rapidly Developing Human–Environment Systems

Our study, with a focus on the specific challenge of farmland conservation in China, provided broad research implications for enhancing the landscape sustainability of densely populated, rapidly developing human–environment systems in general. The underdeveloped regions typically experience a series of land use regime shifts over the course of long-term development, following the predominant land use transition trajectory: From the frontier clearance of forests driven by the agricultural expansion of subsistence farming, to agricultural intensification fueled by agrarian capitalism, and for a considerable scale to landscape urbanization with increasing protected recreational lands, though urbanization is not always the end [80,81]. In the case of densely populated areas where land resources are relatively scarce, the pristine landscape has long been modified for farmland cultivation. During the subsequent industrialization and urbanization processes, navigating the land use tradeoffs between sustaining farmland and developing construction land toward improving human well-being is the principal landscape sustainability challenge in these densely populated, rapidly developing areas like India [82] and Vietnam [83]. Such urbanization-associated farmland loss unsustainability is projected to be widespread across

Asia and Africa in the upcoming decade [84]. Yet, this landscape sustainability challenge is far from being addressed.

We have found that, during the long-term development, farmland is mainly encroached by urban expansion in the most fertile plains, while farmland gain comes typically from natural lands like forest, grassland, and unused land, which are relatively marginal and of lower fertility (Figures 3 and 4). This means that, in addition to the need of keeping track of farmland quantity, the dynamic monitoring of farmland quality and ecological security is also important. Ultimately, farmland conservation in densely populated areas is for ensuring grain production, which relies on both the quantity and quality of farmland. Though the loss of high-quality farmland has raised crying concerns, little can be said about how the farmland transition in terms of both decreasing quantity and quality at the landscape scale will affect food production. A central question is what kind of urban growth can minimize the uptake of farmland, about which empirical studies are rare. The few existing exceptions [85–88] seem to suggest that many small cities/towns for population urbanization will take a lower quantity and quality of farmland than will a few large cities. The idea runs counter to the scale economy hypothesis, which favors (reasonably) large cities since they use land resources more intensively. In this vein, our research can be extended to include the dimensions of farmland quality and urbanization mode.

Our research should be expanded to include the factors of farmland quality and urbanization mode, as well as by archetypal investigations of the human–environment transition pathways underlying the sustainable versus unsustainable decoupling of grain production from farmland, in order to address the challenge of landscape sustainability brought on by urbanization-associated farmland loss in densely populated, rapidly developing regions generally. In-depth field investigations are needed regarding the exact human–environment feedback loops behind the significant improvement of grain production efficiency in northeastern China and Inner Mongolia and behind the unexpected decrease in grain production efficiency in places like southern Jiangsu province. Archetypal investigations of such sustainability versus unsustainability transition pathways will be fruitful for spatially differentiated policy design, which should go beyond farmland planning and land reclamation toward place-based socio-institutional reform for incentivizing sustainable agricultural intensification in these densely populated, rapidly developing human–environment systems.

5. Conclusions

Significant farmland loss and the resulting food self-sufficiency risk are prevalent landscape sustainability concerns in densely populated human–environment systems. Coordinated development between grain production and ecological security in the context of farmland transition is a crucial issue for national food security. In this study, we have sought to investigate the dynamics of farmland and its grain production efficiency and ecological security specifically in China's Major grain-producing regions (MGPRs) during China's fast developing period of 2000–2020, by applying methods of the land use conversion matrix, spatial hot spots, decoupling, and index evaluation from a spatiotemporal perspective. The present study showed that over 95% of China's farmland loss during 2000–2020 occurred in China's MGPRs, and despite that, grain production in the MGPRs had increased by 1.6 times in the twenty years via its strong decoupling from farmland quantity. Farmland in the MGPRs reduced by 2.54×10^4 km^2, and construction land always and forest land in recent years were the major sinks of farmland losses. Meanwhile, the increase in farmland came from forest land, grassland, and unused land conversion. The change in farmland showed regional differentiation in terms of area, extent, and speed. The hot spots of farmland losses were concentrated in the central-eastern regions of MGPRs, where the grain yield has generally decoupled from farmland. The hot spots of farmland gains were mainly distributed in the northeastern MGPRs, with higher grain production efficiency and weak decoupling between grain yield and farmland. Regions with drastic farmland changes focused on the Grain-net-exporting (GNE) areas, where both the quantity of farmland and the efficiency of grain production have increased by 2.9×10^3 km^2 and 1.97 times, respectively. The efficiency gravity center of grain production has been shifting from south to north crossing the MGPRs, which showed the direction for high-yield farmland conservation. Extensive non-agriculturalization in developed regions has resulted in a descending grain production, which requires a stricter policy for the requisition-compensation of farmland, although strong decoupling was observed. At the same time, the general land ecological security in the MGPRs was less secure but has been improving with non-homogeneous regional differences, which demonstrated a spatial pattern of "high in the north–south and low in the middle" of ecological security.

Our findings suggested that China's MGPRs would keep losing farmland in the upcoming decade. However, there could be a long-term equilibrium relationship between grain production and urbanization. The financial support, professional farmer training, large-scale farming, and agricultural modernization that accompany urbanization, if applied appropriately, could be conducive to improving the efficiency of gain production and sustainable farmland cultivation. The grain production of the MGPRs would depend on implementing more effective strategies for farmland preservation and cultivation policies as well as furthering its strong decoupling from farmland quantity. The land ecological security in the MGPRs would rely on the equilibrium of land use, social economy, and environment. The food security goal should be built on an integrated consideration of quantity, quality, and sustainability of farmland use. Policy responses must take into account regional differences in agricultural production efficiency and land use characteristics in the MGPRs for China's sustainable grain production. This can be performed through farmland conservation, coordinated land use zoning, regional prioritization strategies, farming enthusiasm incentives, benefit compensation mechanisms, etc. Further studies of full-spectrum policies are needed regarding the socio-ecological planning of prime farmland, socio-technical engineering of reclaimed farmland, socio-institutional reform of farmland rights, and social-cultural appreciation of farmland conservation.

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