

Article

Coupling Coordination Analysis Between Farmland Transfer and Agricultural Eco-Efficiency in China

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Abstract: The transfer of farmland refers to the process of transferring land contracting and management rights, during which various changes occur in production entities, management behaviors, and management methods. This process fosters positive changes in grain yield and farmers' income. However, there is no consensus on the ecological impacts of farmland transfer. The objective of this study is to explore the coupling and coordination relationship between the process of farmland transfer and regional agricultural eco-efficiency across 30 provincial units in China. The following conclusions can be drawn from the results: (1) The level of farmland transfer in China exhibits an overall upward trend, primarily influenced by the average farmland area per household in each region and the number of large grain producers, with Heilongjiang consistently maintaining the highest level. (2) The agricultural eco-efficiency value remains relatively stable at approximately 1.1, with high-efficiency areas concentrated in Beijing, Qinghai, Hainan, Shanghai, Fujian, and Guizhou, where lower agricultural carbon emissions are a significant influencing factor. (3) The coupling degree between farmland transfer and agricultural eco-efficiency in various provinces of China is predominantly in a state of adjustment, with the coupling coordination level improving year by year. However, the coupling coordination level does not demonstrate a clear "high-high" or "low-low" synchronous state with grain yield per unit area, indicating that the levels of farmland transfer and agricultural eco-efficiency have not yet established a robust interactive relationship with farmland production efficiency.



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Keywords: farmland transfer; agricultural eco-efficiency; agricultural carbon emissions; coupling coordination degree model; China

1. Introduction

"Zero Hunger" is one of the Sustainable Development Goals (SDGs), aiming to eliminate hunger, achieve food security, improve nutrition, and promote sustainable agriculture. The farmland transfer practices of various scales in the United States, Germany, France, and several East Asian countries have underscored the crucial role of farmland transfer in ensuring food security [1,2]. Farmland transfer involves farmers who have the right to operate contracted farmland, transferring the land rights to other farmers or economic organizations for agricultural production and operation. (The transfer of farmland in China must adhere to the principles of legality, voluntariness, and compensation. This process involves various methods for transferring farmland that is contracted to and operated by a family to other operators. Prior to 2019, the methods of farmland transfer included rental (subcontracting), sale, exchange, and equity cooperation. However, official statistical data from 2020 onward indicate that the current methods of farmland transfer now only encompass rental (subcontracting) and equity cooperation. Among the various methods of farmland transfer, rental (subcontracting) refers to the practice of a contractor renting out part or all of the land management rights to others for agricultural production and

operations. Equity cooperation involves the contractor contributing the value of the land management rights as capital to become a shareholder or member of a company or co-operative economic organization, while the land continues to be utilized for agricultural production and operations. This highlights that the most significant characteristic of farmland transfer in China is the limited-term leasing of land contracting management rights.) This concept differs from the land ownership transactions or land sales commonly examined in related research in Western countries, as it possesses distinct Chinese characteristics. This unique approach is closely linked to the national land property rights system and market economy [3,4]. However, regardless of whether it is farmland transfer or land transactions, research, both domestically and internationally, has expanded beyond resource endowment, production efficiency, farmer income, property rights system, market system, etc., gradually shifting from focusing mainly on food security and economic benefits to encompassing the ecological environment aspect [5–8].

China's practice of transferring farmland has played a crucial role in enhancing grain production and increasing farmers' incomes. As this transfer process enters a new phase, it is essential to closely examine its impact on the ecological environment and the relationship between the two. The concept of farmland transfer in China originated in 1984, and significant promotion of this practice has been ongoing for approximately 15 years. The increasingly proactive and clear policy direction from the Chinese government has not only expedited the process of farmland transfer but has also effectively stimulated agricultural production growth and improved farmers' incomes [9]. In 2022, the total area of farmland transferred under the household land contracting management rights in China accounted for 36.7% of the overall cultivated area. The grain output and farmers' income reached 68.6528 million tons and CNY 20,132.8, respectively, representing increases of 1.69 and 56.66-fold compared to 1984, and of 1.28 and 4.23-fold compared to 2008, respectively. Since 2008, China's per capita grain output has consistently remained above the international food security threshold. It can be concluded that the phased objectives of promoting farmland transfer at both the policy and practical levels have been successfully achieved. However, with the acceleration of urbanization, the young and middle-aged labor force in rural areas is migrating to cities, leading to serious issues of rural hollowing and aging. As a result, the focus of food security has shifted to addressing the questions of "who will farm" and "how to farm". This also means that farmland will increasingly be concentrated in the hands of a small group, and the transfer of farmland will inevitably enter a new stage of development. Green agricultural development is a common choice and direction for China and the world. Currently, more than one-third of farmland in China is in a state of transfer. How to coordinate the socioeconomic benefits of farmland transfer with the cultivation of ecological foundations is the most pressing issue that needs attention in the ongoing process of farmland transfer. Only by fully emphasizing and valuing the ecological attributes in the transfer of farmland can we ensure that the transfer does not alter the agricultural production characteristics of the land and effectively avoid the phenomena of "non-agriculturalization" and "non-grainization" during the transfer process [10,11].

Recent studies have significantly advanced the comprehension of the characteristics associated with the transfer of farmland, including the influencing factors, regional impacts, ecological compensation mechanisms, performance assessments, and other pertinent subjects. Nevertheless, certain issues remain contentious and lack a consensus within the academic community. An analysis of the existing body of research reveals that the phenomenon of farmland transfer is shaped by a multitude of factors. These encompass natural elements such as topography, precipitation patterns, soil quality, and the inherent land resource endowments of a region [12], alongside socioeconomic variables including the level of regional economic development, land productivity, the degree of urbanization, the dynamics of transfer markets, and the presence of policy subsidies [13–16]. Research examining the influence of farmers' subjective willingness and familial characteristics on the transfer of farmland from a microeconomic perspective indicates that several factors significantly affect this transfer [17–23]. These factors include land resource endowment, the

age of the household head, land rental rates, grain prices, policy subsidies, non-agricultural employment opportunities for farmers, and demographic trends such as population aging [24–26]. The transfer of farmland has profound implications for rural development, the agricultural economy, and farmers' income. Numerous qualitative and quantitative studies suggest that such transfers not only result in alterations to the input of material resources such as fertilizers, pesticides, water, electricity, and machinery but also lead to substantial changes in household structure, planting patterns, land use configurations, industrial chains, agricultural social service systems, and the income structure of farmers [27–30]. Numerous research findings indicate that the transfer of farmland effectively mitigates the challenges of land fragmentation and abandonment, thereby contributing positively to rural development, the agricultural economy, and farmers' income [27,31]. However, several issues have emerged during these studies that remain contentious [32]. For instance, is the impact of farmland transfer on the productivity of farmland beneficial? Does farmland transfer inherently lead to a reduction in the intensity of chemical fertilizer usage? Can farmland transfer facilitate sustainable agricultural development [33,34]? These unresolved questions shift the discourse surrounding farmland transfer from socio-economic dimensions to ecological considerations. Some investigations are currently examining the relationship between farmland transfer and agricultural production efficiency [35–38], and interest in this area is steadily increasing.

Studying the relationship between farmland transfer and agricultural ecological efficiency from the perspective of coupling coordination can provide a more comprehensive understanding of the environmental impacts associated with farmland transfer. While there have been studies examining the effects of farmland transfer on the environment—primarily focusing on land use and cover changes [39], as well as regional ecological security—there remains a significant gap in research regarding the coupling and coordination between farmland transfer and agricultural eco-efficiency. We have chosen to explore the relationship between farmland transfer and the environment by examining the coupling and coordination of farmland transfer and agricultural eco-efficiency, as these two aspects are closely interconnected. During the process of farmland transfer, the agricultural production and operational responsibility shift from small-scale to large-scale farmers. Consequently, the new operators will experience changes in their selection of agricultural production inputs, such as fertilizers, pesticides, and machinery. These changes will result in a series of impacts on agricultural output, carbon emissions, and agricultural pollutants [40,41]. The measurement of agricultural eco-efficiency encompasses various indicators, including agricultural production inputs, output value, and carbon emissions, which effectively correspond to the new changes that occur during the farmland transfer process. This study can enhance and build upon existing achievements in two key aspects: Firstly, we developed a comprehensive evaluation index system for farmland transfer, which provides a more nuanced interpretation of the level of regional farmland transfer. Current studies often rely on singular indicators, such as “farmland transfer area” or “farmland transfer rate”, to characterize farmland transfer [42–44]. However, using a limited selection of indicators is inadequate when farmland transfer progresses to a middle or high stage. Taking China as an example, the proportion of farmland transfer area to the total farmland area has exceeded one-third, transitioning from a period of rapid growth to a phase of slow growth. In certain regions, where farmland resources or economic development levels are constrained, the “farmland transfer area” and “farmland transfer rate” have not experienced significant changes over consecutive years. Therefore, developing an indicator system that reflects both the endogenous and external driving forces of farmland transfer can address the limitations of relying on a single indicator. This approach will provide a more accurate representation of the current state of regional farmland transfer levels. Secondly, we employed coupling degree and coupling coordination degree models to elucidate the relationship between farmland transfer and agricultural eco-efficiency, as well as the varying stages of this relationship within each evaluation unit. Previous studies have frequently utilized various regression analyses to investigate the impacts of farmland

transfer or large-scale management on agricultural ecology [43,45], primarily focusing on determining whether farmland transfer enhances agricultural eco-efficiency [46–49], with the goal of a comprehensive analysis and assessment. Our research employs multiple modeling methods to quantitatively analyze the relationship between farmland transfer and agricultural eco-efficiency across various administrative units [50–52]. This approach highlights the temporal characteristics and spatial variations of the relationship in each evaluation unit. Such insights are valuable for identifying the development stages and regional promotion strategies concerning the interplay between these two factors at both the national and provincial levels.

In the specific operational process, we considered various factors, including transfer scale, transfer foundation, transfer channels, external participation, internal carrying capacity, differentiation of farmers' occupations, and transfer norms, in order to develop an evaluation index system for farmland transfer. Additionally, we constructed an evaluation index system for agricultural eco-efficiency based on three aspects: agricultural production input indicators, expected output indicators, and unexpected output indicators. Furthermore, we integrated coupling degree models, coupling coordination models, relative development models, and spatial analysis methods to quantitatively assess the coupling degree, coupling coordination level, and relative development level of farmland transfer and agricultural eco-efficiency in each provincial unit. Finally, we discuss the level of agricultural production efficiency at various coupling coordination levels between farmland transfer and agricultural eco-efficiency, and we propose relevant development suggestions.

2. Materials and Indicators

2.1. Coupling Mechanism

“Coupling” is a concept originating from physics, used to describe the interaction between two or more independent but interrelated systems. The mutual influence and interaction between farmland transfer and agricultural eco-efficiency, along with the methodology employed in this study to examine the relationship between the two, are illustrated in Figure 1.

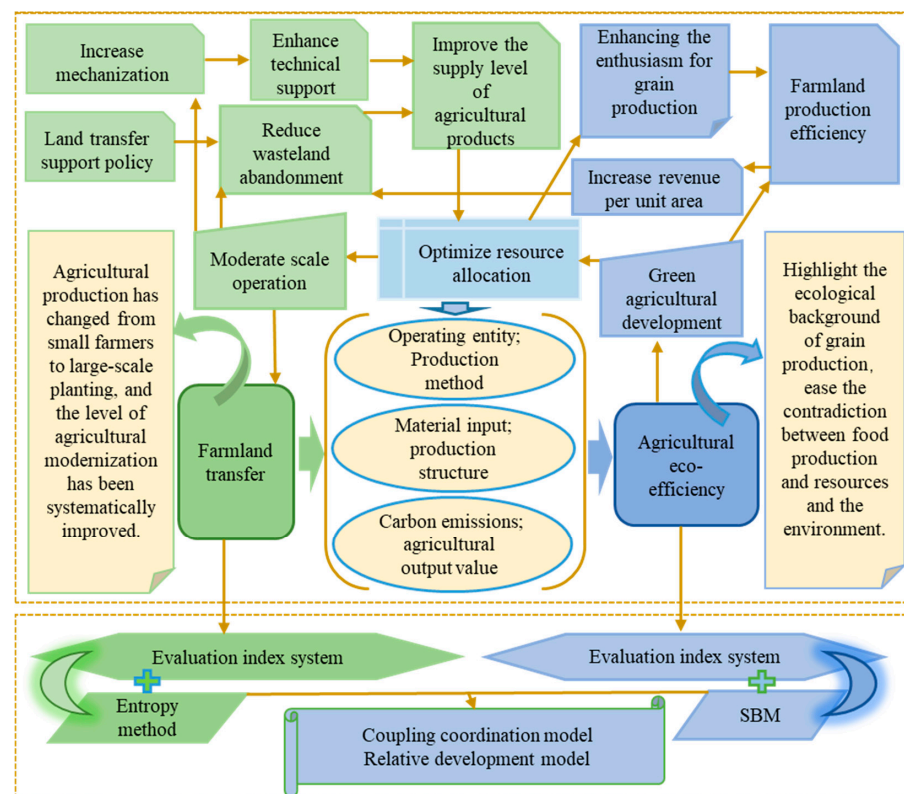


Figure 1. Coupling relationship between farmland transfer and agricultural eco-efficiency.

The essence of farmland transfer does not fundamentally change the agricultural production attributes of the land; rather, it plays a role in promoting an increase in total agricultural output by adjusting the structure of producers and the composition of material inputs. This achieves the effects of reducing agricultural carbon emissions and decreasing agricultural non-point source pollution, thereby steering the development of agricultural eco-efficiency in a better direction. The impact of farmland transfer on agricultural eco-efficiency can be observed in several aspects, including the entities involved in the transfer, the area of farmland transferred, and the allocation of resources. Firstly, farmland transfer represents a process in which agricultural producers shift from smallholder farming to large-scale farming operations. Large-scale farmers are generally more inclined to adopt advanced agricultural technologies and management practices, which can significantly enhance the intensity and coverage of green, low-carbon planting technologies. This transition plays a positive role in reducing agricultural carbon emissions, thereby decreasing undesirable agricultural outputs and improving the overall level of agricultural eco-efficiency. Secondly, the transfer of farmland refers to the process of leasing or investing in land, which generates rental income that can significantly reduce the idling or abandonment of agricultural land. This, in turn, expands the area available for crop cultivation. The increase in planting area not only enhances agricultural yields but also improves the reclamation rate of abandoned land, effectively mitigating the ecological risks associated with land abandonment. Thirdly, the transfer of farmland is a process aimed at achieving large-scale, contiguous management. As the area of farmland managed by large grain producers, family farms, and other new agricultural operators continues to expand, it will effectively enhance the coordinated distribution of agricultural production factors, improve the utilization rate of these factors, and potentially reduce the use of chemical inputs such as pesticides and fertilizers. This, in turn, can decrease agricultural non-point source pollution and positively contribute to improving soil quality and restoring regional ecosystems.

Agricultural eco-efficiency must achieve high output and economic benefits while minimizing resource consumption and reducing environmental pollution. This is an essential requirement for advancing farmland to a higher stage, which involves protecting the ecological environment, improving the efficiency of agricultural resource utilization, promoting agricultural transformation and upgrading, and comprehensively enhancing the output level and quality of farmland. The core components of agricultural economic efficiency encompass both economic and eco-efficiency, and their influence on the transfer of farmland can be analyzed from these two perspectives. From the standpoint of eco-efficiency, enhancing agricultural eco-efficiency optimizes the inputs of agricultural materials and the structure of crop production. By comprehensively adjusting the agricultural industrial framework, it gradually steers the agricultural sector towards high added value, advanced technology, and environmentally sustainable practices. This improvement enhances the quality and standards of agricultural products, thereby increasing the income of agricultural producers and operators. Consequently, this will bolster the willingness and motivation of large-scale operators to transfer farmland, while also driving up rental prices for farmland, which facilitates its movement and allocation. From the perspective of eco-efficiency, the most significant characteristic of agricultural eco-efficiency is the effective utilization of agricultural resources and the reduction in environmental pollution. Agricultural technological innovation can facilitate the rational allocation and efficient use of these resources. The implementation of new technologies, such as smart agriculture and precision agriculture, can steer the agricultural sector toward a more environmentally friendly and intelligent approach, leading to enhancements in the agricultural ecological environment and promoting sustainable agricultural development. This process and its outcomes serve as both a constraint and a guarantee for the transfer of farmland. The transfer of farmland involves separating land contracting rights from actual operating rights. To successfully transition farmland to a stage of quality enhancement, it is essential to continuously raise awareness among agricultural operators regarding ecological environmental protection, minimize the excessive use of chemical fertilizers and pesticides, and gradually establish a pattern of coordinated development aligned with agricultural green development.

The transfer of farmland and agricultural eco-efficiency are two independent yet interconnected systems. The interaction between these two systems has positive impacts, as previously mentioned, as well as certain contradictions and conflicts. The transfer of farmland aims to increase grain production and economic benefits, while agricultural eco-efficiency seeks to achieve greater agricultural output with reduced resource consumption and minimized environmental pollution. It is challenging to maximize both economic and ecological benefits simultaneously. This study evaluated the level of coupling coordination between farmland transfer and agricultural eco-efficiency, introducing a relative development model and farmland production efficiency indicators. This approach provides a more comprehensive analysis of the complex relationships between farmland transfer and agricultural eco-efficiency in China.

2.2. Evaluation Indicators for Farmland Transfer

Based on relevant research findings, this study developed a system of 13 indicators that encompass the area of farmland transfer and the rate of farmland transfer. It offers a comprehensive interpretation of the level of farmland transfer by examining various aspects, including transfer scale, transfer foundation, transfer channels, external participation, internal carrying capacity, differentiation of farmers' occupations, and transfer norms. Among the evaluation indicators for transfer scale, two commonly used metrics are "farmland transfer area" and "farmland transfer rate". The former reflects the total scale of farmland transfer within a region, while the latter indicates the relative scale of such transfers. The transfer foundation includes two key indicators: "number of large-scale planters" and "average farmland area per household". Large-scale plants are defined as those operating on more than 6.67 hectares; this group serves as the backbone of large-scale agricultural operations and plays a crucial role in the development of family farms. Furthermore, regions with a larger average farmland area per household are generally more conducive to larger-scale transfer activities. The channels of farmland transfer encompass two key indicators: "proportion of rental (subcontracted)" and "proportion of equity cooperation". Rental (subcontracted) and equity cooperation are the two primary methods of farmland transfer. Investigating the differences in the roles that these two methods play in the farmland transfer process across various regions can offer valuable insights for promoting farmland transfer in specific areas. External participation encompasses the "proportion rented to external parties" and the "proportion transferred to enterprises", which indicate the transfer of farmland to populations outside the region and to non-agricultural industries, respectively. A higher level of participation from external populations or industries is more conducive to the flow of farmland. The internal carrying capacity encompasses both the "proportion transferred to rural households" and the "proportion transferred to cooperatives". In the statistical data, the area of farmland allocated to farmers also includes the area designated for family farms. Additionally, professional cooperatives mandate that over 80% of their members be farmers. Consequently, these two proportions serve as the primary components of the internal transfer of farmland in rural areas, reflecting the capacity and proportional distribution of these areas to manage the transfer of farmland. The differentiation of farmers' occupations is indicated by the "proportion of migrant workers". As the non-agricultural employment characteristics of farmers increase, their connection to farmland diminishes, resulting in greater mobility of farmland. The transfer norms encompass the "proportion of transfer contracts signed" and the "proportion of farmland used for growing food crops". Executing farmland transfer contracts effectively safeguards and delineates the rights and responsibilities of both parties involved. The phrase "proportion of farmland used for growing food crops" primarily refers to the phenomena of "non-agriculturalization" and "non-grainization" during the farmland transfer. These changes have altered the agricultural production characteristics of farmland to some extent, thereby threatening food security. This issue must be addressed to ensure the integrity of farmland transfers. The specific classifications and indicators are detailed in Table 1.

Table 1. Evaluation index system for the level of farmland transfer.

Guideline Layer	Abbreviation	Indicator Layer
Transfer scale	Z1	Farmland transfer area: This term refers to the total area of farmland that farming households, operating under a household contracting system, transfer to other operators. This transfer occurs through methods such as rental (subcontracting) or equity cooperation, adhering to the principles of legality, voluntariness, and compensation.
		Farmland transfer rate: This term refers to the proportion of farmland management rights transferred from family-contracted farmland to the total area of family-contracted farmland, expressed as a percentage.
Transfer foundation	Z2	Number of large-scale planters Average farmland area per household
Transfer channels	Z3	Proportion of rental (subcontracting) Proportion of equity cooperation
External participation	Z4	Proportion rented to external parties: This term refers to the share of the area of contracted farmland that farmers lease to individuals or entities who are not registered or residing in the same township for agricultural production, relative to the total area of farmland transferred among farming households.
		Proportion transferred to enterprises
Internal carrying capacity	Z5	Proportion transferred to rural households Proportion transferred to cooperatives
Differentiation of farmers' occupations	Z6	Proportion of migrant workers: This term refers to the ratio of rural laborers who leave their hometowns to work in other locations for a cumulative total of more than three months within a year, compared to the total number of laborers.
Transfer norms	Z7	Proportion of transfer contracts signed Proportion of farmland used for growing food crops

Note: Number of large-scale planters refers to the count of farmers whose farmland exceeds 6.67 hectares.

2.3. Agricultural Eco-Efficiency Evaluation Indicators

The evaluation of agricultural eco-efficiency typically involves the construction of an index system that considers inputs, expected outputs, and unexpected outputs [53]. The specific indicators are shown in Table 2. The selection of input indicators comprehensively considers various factors influencing agricultural production, including labor, farmland, and capital. The labor indicator is determined by the number of individuals employed in the primary industry. The farmland indicator is based on the area dedicated to cultivated crops. Capital indicators encompass infrastructure development and investments in agricultural inputs, which include effective irrigated area, fertilizer application, total power of agricultural machinery, rural electricity consumption, pesticide usage, agricultural film usage, and diesel consumption. These indicators not only represent the fundamental and essential components of agricultural production inputs but are also closely linked to the efficiency and quality of agricultural output; they serve as critical metrics for assessing agricultural modernization and ecological sustainability. In addition, concerning the selection of expected output indicators, some studies have jointly utilized total agricultural output value and grain production. This study posits that, although there are distinctions between physical quantities and monetary values, an inclusion relationship exists; the total agricultural output value encompasses a broader spectrum of content than grain production. Therefore, only the total agricultural output value is selected as the expected output indicator. The non-expected output indicator chosen is “agricultural carbon emissions”, as these emissions have a direct impact on agricultural eco-efficiency. Agricultural carbon emissions primarily arise from the use of production inputs such as chemical fertilizers, pesticides, and agricultural plastic films, as well as from agricultural activities such as

livestock farming. The excessive application of chemical substances can lead to an increase in carbon emissions, resulting in pollution issues in agricultural environments, such as soil and water bodies. This pollution adversely affects the production environment and the quality of crops, thereby diminishing agricultural eco-efficiency. In this study, nine carbon source factors were identified for calculating carbon emissions in agriculture: chemical fertilizers, pesticides, agricultural films, agricultural diesel, irrigation, land tillage, early rice, medium rice, and late rice. Additionally, carbon emissions generated during the intestinal fermentation and manure management processes in cattle, pig, and sheep farming were included in the comprehensive calculation. This approach effectively reflects the environmental pollution issues arising from the input of production factors in agriculture and the livestock farming processes in animal husbandry. Therefore, this study incorporated agricultural carbon emissions into the agricultural eco-efficiency evaluation system as an undesirable output indicator.

Table 2. Agricultural eco-efficiency evaluation index system.

Guideline Layer	Indicator Layer
Input index	Number of employees in the primary industry
	Crop planting area
	Effective irrigation area
	Amount of fertilizer applied
	Total power of agricultural machinery
	Rural electricity consumption
	Amount of pesticide used
	Amount of agricultural film used
	Amount of diesel fuel used
Expected output indicator	Total agricultural output value
Non-expected output indicator	Agricultural Carbon Emissions

2.4. Agricultural Carbon Emission Evaluation Indicators

Agricultural carbon emissions generally encompass two primary components: emissions resulting from crop cultivation and emissions associated with animal husbandry. Emissions from crop cultivation mainly arise from land use practices and rice production, whereas emissions from animal husbandry are primarily generated through intestinal fermentation and manure management in livestock and poultry farming. When calculating carbon emissions from agricultural land use, it is essential to consider various factors, including emissions from agricultural irrigation, land tillage, and the use of fertilizers, pesticides, agricultural films, and diesel in crop cultivation [54]. Carbon emissions from rice cultivation are calculated using specific carbon emission coefficients for early, medium, and late rice varieties [55]. In contrast, carbon emissions resulting from intestinal fermentation and manure management are determined based on the year-end livestock inventory of cattle, pigs, and sheep [56]. Finally, CO₂, N₂O, and CH₄ are converted into carbon equivalents (c) uniformly [57]. The conversion standard indicates that the greenhouse effect of 1 kg of methane (CH₄) is equivalent to that of 25 kg of carbon dioxide (CO₂). Similarly, the greenhouse effect of 1 kg of nitrous oxide (N₂O) is equivalent to that of 298 kg of CO₂. Additionally, the carbon equivalent of 1 kg of CO₂ is 0.2727 kg of C. The corresponding carbon emission coefficients can be found in Table 3.

Table 3. Carbon source factors and carbon emission coefficients for agricultural carbon emissions.

Category	Carbon Source Factor	Carbon Emission Coefficient	
Agricultural land utilization	Fertilizer	0.8956 t (C)/t	
	Pesticide	4.934 t (C)/t	
	Agricultural film	5.180 t (C)/t	
	Diesel	0.5927 t (C)/t	
	Irrigation	0.26648 t (C)/hm ²	
	Plowing	0.3126 t (C)/hm ²	
Rice cultivation	Early rice	0.1623–1.1939 t (C)/hm ²	
	Medium-grain rice	0.3798–4.4605 t (C)/hm ²	
	Late rice	0.5182–3.5864 t (C)/hm ²	
Livestock and poultry breeding	Intestinal fermentation	Cow	0.5566 t (C)/(head·a)
		Pig	0.0068 t (C)/(head·a)
		Sheep	0.0627 t (C)/(head·a)
	Fecal management	Cow	0.996–1.32 kg (N ₂ O)/(head·a); 1.625–7.137 kg (CH ₄)/(head·a)
		Pig	0.157–0.266 kg (N ₂ O)/(head·a); 1.12–5.85 kg (CH ₄)/(head·a)
		Sheep	0.057–0.113 kg (N ₂ O)/(head·a); 0.155–0.505 kg (CH ₄)/(head·a)

3. Methods and Data Sources

3.1. Entropy Method

This study utilized the entropy method to compute the farmland transfer index [58]. The entropy method is a comprehensive evaluation technique for multiple indicators. The entropy method for calculating weights and entropy values is presented in Formulas (1)–(3). This method accurately identifies the relationships between indicators during the calculation process. For instance, it can reveal complementary relationships among indicators, indicating that certain indicators can provide supplementary information. Additionally, it can detect redundant relationships between indicators, thereby eliminating unnecessary information. The entropy method effectively addresses the randomness issue that subjective weighting methods cannot avoid, promoting a more scientific assignment of indicator weights. For detailed indicators, please refer to Table 1. The specific calculation process for the weight and farmland transfer index is outlined as follows.

First, standardize the data using Formula (1):

$$x_{ij} = \frac{X_j - \min(X_j)}{\max(X_j) - \min(X_j)} \quad (1)$$

where x_j represents the value of the j -th indicator, $\max(x_j)$ and $\min(x_j)$ represent the maximum and minimum values of the j -th indicator, respectively; and x_{ij} represents the standardized value of the j -th indicator for the i -th decision-making unit.

Second, determine the weight of the indicators:

$$y_{ij} = x_{ij} / \sum_{i=1}^m x_{ij} \quad (2)$$

where y_{ij} represents the weight of the j -th indicator of the i -th decision unit, and m represents the number of decision units.

Third, calculate the entropy value and coefficient of variation. Calculate the entropy value using Formula (3):

$$e_i = -\frac{1}{\ln m} \sum_{i=1}^m y_{ij} \ln y_{ij} \quad (3)$$

where if $y_{ij} = 0$, define $\lim_{y_{ij} \rightarrow 0} y_{ij} \ln y_{ij} = 0$ to ensure meaningful standardization when the value is zero. Calculate the coefficient of variation using Formula (4):

$$g_j = 1 - e_j \quad (4)$$

Fourth, calculate the composite index as follows:

$$w_j = g_j / \sum_{j=0}^n g_j \quad (5)$$

First, determine the weight of the j -th indicator in the evaluation of farmland transfer using Formula (5). Then calculate the farmland transfer index using Formula (6):

$$T_i = \sum_{j=0}^n w_j y_{ij} \quad (6)$$

3.2. SBM Model Based on Unexpected Output

This study employed the SBM-DEA model to assess agricultural eco-efficiency [59]. The SBM model incorporates undesirable outputs, thereby extending the DEA method. This model not only considers the undesirable outputs of each decision-making unit but also effectively addresses the slack variable issue associated with input-output variables; it presents significant advantages over traditional DEA models. The specific formula is as follows:

$$\min \rho = \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{S_i^-}{x_{i0}}}{1 + \frac{1}{s_1 + s_2} \left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b} \right)} \quad (7)$$

where

$$\begin{aligned} x_{i0} &= X\lambda + S_i^-; \\ y_{r0}^g &= Y^g\lambda - s_r^g; \\ y_{r0}^b &= Y^b\lambda + s_r^b; \\ S_i^- &\geq 0, s_r^g \geq 0, s_r^b \geq 0, \lambda \geq 0. \end{aligned}$$

where X represents the input term of the decision-making unit, Y^g denotes the expected output term, and Y^b signifies the unexpected output term. X and Y represent the mean matrices of the input and output factors, respectively. S_i^- represents the input slack variable, s_r^g indicates the expected output slack variable, and s_r^b denotes the unexpected output slack variable. λ represents the weight vector, while ρ signifies the efficiency value.

3.3. Coupling Coordination Model

Referring to the research findings of existing scholars, a coupling model of farmland transfer and agricultural eco-efficiency was constructed. This model more effectively illustrates the degree of mutual influence between the two systems, particularly the variation in coupling levels across different regions [60]. The calculation formula is as follows.

$$C = \sqrt{[1 - (U_2 - U_1)] \times \frac{U_1}{U_2}} \quad (8)$$

In the calculation, the symbols representing the values of the two subsystems of farmland transfer and agricultural eco-efficiency are denoted differently from the previous ones, indicated by U_i . Here, $U_i \in [0, 1]$, with $\max U_i = U_2$. C represents the coupling degree, with a range of $[0, 1]$. A value of C closer to 1 signifies a stronger interaction between farmland transfer and agricultural eco-efficiency, indicating a higher degree of coupling between the two. Conversely, a value of C closer to 0 suggests a weaker relationship between farmland transfer and agricultural eco-efficiency, reflecting a lower degree of coupling between the two.

Furthermore, a coupled coordination model was employed to analyze the coupling coordination status of farmland transfer and agricultural eco-efficiency. While the coupling model effectively illustrates the strength of interaction between farmland transfer and agricultural eco-efficiency, it does not offer a comprehensive perspective on the overall

coordination level. Therefore, the introduction of a coupled coordination model is essential for evaluating the development level and coordination of these two aspects. The specific formula is as follows.

$$D = \sqrt{C \times I} \quad (9)$$

$$I = a \times U_1 + b \times U_2 \quad (10)$$

In Formula (9), D represents the coupling coordination degree, with a value range of $[0, 1]$. When the value of D is close to 1, it indicates a higher degree of coordination between the two systems; conversely, when the value of D is closer to 0, it indicates that the relationship between the two is not significant, and the mutual influence is weak. In Formula (10), I represents the comprehensive development index, while a and b are undetermined coefficients for farmland transfer and agricultural eco-efficiency, respectively, set as $a = b = 0.5$ [61].

To analyze the coupling and coordination status between farmland transfer and agricultural eco-efficiency more clearly, we classified the coupling degree (C value) and the coupling coordination degree (D value) into specific grade intervals. For detailed standards, please refer to Table 4 [58].

Table 4. Range of values and classification of coupling degree and coupling coordination degree.

	Value Range	Grade or Stage
Coupling degree (C)	$0 \leq C \leq 0.3$	Low level coupling
	$0.3 < C \leq 0.5$	Antagonistic stage
	$0.5 < C \leq 0.8$	Running-in stage
	$0.8 < C \leq 1.0$	High level coupling
Coupling coordination degree (D)	$0.2 < D \leq 0.3$	Severe imbalance
	$0.3 < D \leq 0.4$	Moderate imbalance
	$0.4 < D \leq 0.5$	Mild imbalance
	$0.5 < D \leq 0.6$	Primary coordination
	$0.6 < D \leq 0.7$	Intermediate coordination
	$0.7 < D \leq 0.8$	Advanced coordination
	$0.8 < D \leq 1.0$	Top coordination

3.4. Relative Development Model

We introduced the relative development model to assess the relationship between farmland transfer and agricultural eco-efficiency [58]. The model is as follows:

$$\theta = U_1 / U_2 \quad (11)$$

where θ represents the relative degree of development, while U_1 and U_2 represent the farmland transfer index and agricultural eco-efficiency respectively. Please refer to Table 5 for specific classification criteria.

Table 5. Range of values and stage division of relative development degree.

Range of Values	Stage
$0 < \theta \leq 0.9$	Farmland transfer lags behind agricultural eco-efficiency
$0.9 < \theta \leq 1.1$	Both develop synchronously
$\theta > 1.1$	Agricultural eco-efficiency lags behind the transfer of farmland

3.5. Data Sources

This study selected 30 provincial-level administrative units in China as evaluation units, excluding Hong Kong, Macau, Taiwan, and Tibet. The study period spanned from 2015 to 2022. Data related to farmland transfer were primarily sourced from the *China Rural Operation and Management Statistical Yearbook* (2015–2018) and the *China Rural Policy and*

Reform Statistical Yearbook (2019–2022). The farmland area mentioned in this text pertains specifically to the farmland managed under household contract agreements. Additionally, the area of farmland transfer refers to the transfer of land management rights for household-contracted farmland. It is important to note that this concept is not entirely synonymous with the classification of farmland in land use terminology. While data concerning agricultural eco-efficiency were mainly obtained from the CNKI database (<https://data.cnki.net/>, accessed on 13 May 2024), additional data were collected from the website of the National Bureau of Statistics of China (<https://data.stats.gov.cn/>, accessed on 13 May 2024). Among these, in certain years, the data for “number of employees in the primary industry” in Beijing, Zhejiang, Hainan, and Liaoning are missing. The average values from the preceding and following years were used as substitutes. Since fluctuations in population numbers are closely related to the years before and after, there are typically no significant increases or decreases, resulting in minimal impact on the calculation results.

4. Results

4.1. Evaluation of the Spatiotemporal Changes in Farmland Transfers in China

4.1.1. Overall Changes in the Index of Farmland Transfer

The overall trend of the farmland transfer index in China exhibited an upward trajectory during the study period, particularly in lower-level regions. According to the calculations using the entropy value method, between 2015 and 2022, the farmland transfer index for 30 provincial-level units in China demonstrated varying degrees of increase in total, minimum, average, and median values, with the exception of a decrease in the maximum value. As illustrated in Table 6, the maximum value decreased from 0.73 to 0.64, while the total, minimum, average, and median values increased from 8.50, 0.11, 0.28, and 0.27 to 9.39, 0.16, 0.31, and 0.30, respectively. Overall, maintaining stability or achieving further growth in farmland transfer levels in high-level regions is challenging; however, there is significant potential for improvement in middle and low-level regions.

Table 6. Changes in the index of farmland transfer.

	2015	2016	2017	2018	2019	2020	2021	2022	Trend Chart
Efficiency summary	8.50	8.72	8.95	8.96	9.00	9.32	9.26	9.39	
Mean value	0.28	0.29	0.30	0.30	0.30	0.31	0.31	0.31	
Maximum value	0.73	0.67	0.67	0.64	0.65	0.67	0.63	0.64	
Minimum value	0.11	0.11	0.10	0.12	0.14	0.14	0.15	0.16	
Median value	0.27	0.28	0.29	0.30	0.30	0.30	0.30	0.30	

4.1.2. Classification of Farmland Transfer Index Levels

Based on the natural fracture method in ArcGIS 10.3 software, the farmland transfer index was classified into five levels: highest, high, medium, low, and lowest. As shown in Figure 2, there has not been much change in the regional scope of the highest and lowest levels, while the number of regions in the high level has increased. Specifically, (1) the highest level has long been limited to Heilongjiang, with the farmland transfer index remaining between 0.63–0.73. The lowest level mainly includes Guangxi, Fujian, and Beijing, with the highest farmland transfer coefficient in these three provinces reaching only 0.21. (2) The high level mainly includes Inner Mongolia, Ningxia, Jilin, Xinjiang, Anhui, and Jiangsu, among which Inner Mongolia, Jiangsu, and Anhui have long been in the high level, with farmland transfer indices consistently above 0.36, while Ningxia, Jilin, and Xinjiang have seen rapid growth in farmland transfer indices in recent years. (3) The spatial layout of the medium and low levels shows characteristics of contiguous and intersecting areas. The medium level shows a trend of moving southward, with several provinces adjacent to Inner

Mongolia gradually changing from medium to low levels, while provinces further south such as Guizhou, Hunan, and Jiangxi are gradually adjusting from low to medium levels.

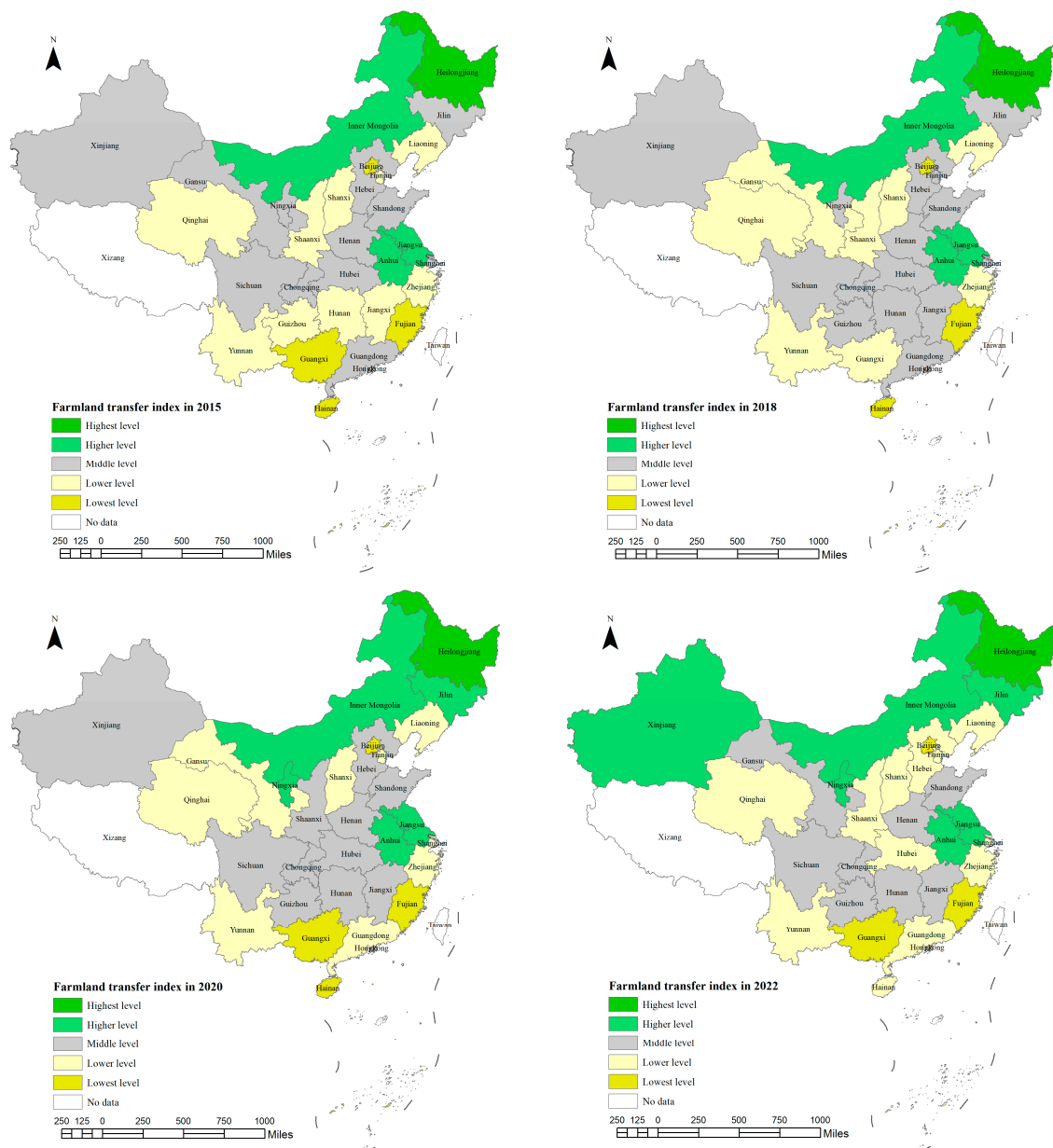


Figure 2. Classification and spatial changes of China's farmland transfer index from 2015 to 2022.

4.1.3. Main Factors Influencing Farmland Transfer Index

"Transfer foundation" is the most significant factor influencing the farmland transfer index. Figure S1 illustrates the changes in the weights of various indicators affecting the farmland transfer index from 2015 to 2022. The weight of "transfer foundation" remains above 0.3, and the weights of "transfer scale", "transfer channel", and "external participation" all exceed 0.1. Although the weights of "internal carrying capacity", "differentiation of farmers' occupations", and "transfer norms" are relatively low, their values are demonstrating a year-on-year increasing trend. From the perspective of individual indicators, "number of large-scale planters", "proportion of equity cooperation", and "average farmland area per household" are key factors influencing the farmland transfer index. In 2022, all of these indicators' weights exceeded 0.1. According to Figure S2, the high-value areas for the "number of large-scale farmers" and "average farmland area per household" are

primarily located in major grain-producing regions such as Heilongjiang, Inner Mongolia, and Jilin, while the high-value areas for the “proportion of equity cooperation” are found in Guizhou, Guangdong, and Chongqing.

4.2. Evaluation of Agricultural Eco-Efficiency

4.2.1. Overall Changes in Agricultural Eco-Efficiency

The overall level of agricultural eco-efficiency has not changed significantly, showing a trend of fluctuating decrease in high-value areas and stable growth in low-value areas. As shown in Figure 3, from 2015 to 2022, the average value of agricultural eco-efficiency in China consistently remained around 1.1, with the median stable at around 1.0, indicating relatively small changes in indicators representing the average level. Comparing the maximum and minimum values, the coefficient of variation increased from 1.103 to 1.901, with the fluctuation of the highest value being the main reason. Specifically, the maximum value varied between 1.649 and 2.606, with the highest value occurring in 2017. Although there has been a slight decrease in recent years, the overall level still remains relatively high. The minimum value increased from 0.439 to 0.496, showing a steady growth trend.

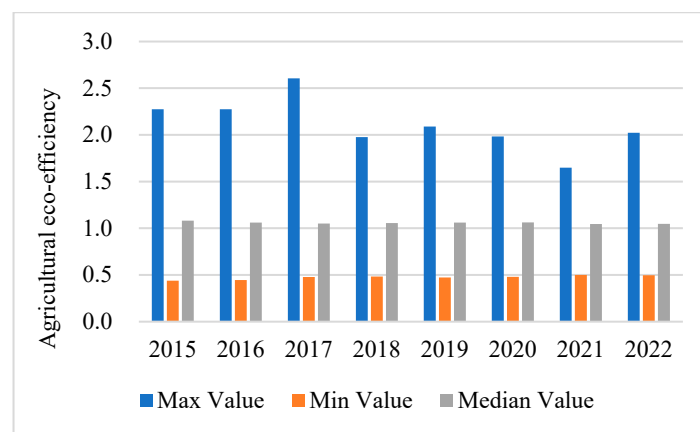


Figure 3. Maximum, minimum, and median values of agricultural eco-efficiency from 2015 to 2022.

4.2.2. Classification of Agricultural Eco-Efficiency Levels

Based on the natural fracture method in ArcGIS software, agricultural eco-efficiency was classified into five levels: highest, high, medium, low, and lowest. From Figure 4, it can be observed that (1) the highest level is mainly in Beijing, Qinghai, Hainan, Shanghai, Fujian, and Guizhou. Among them, the highest level from 2015 to 2020 mainly included Beijing, Hainan, and Qinghai, while from 2021 to 2022 it mainly included Shanghai, Fujian, and Guizhou. Although the efficiency values of Beijing, Hainan, and Qinghai have decreased in the past two years, they still remain in the high level category. (2) Several provinces along the border from Heilongjiang to Yunnan are generally at medium level or above, making this a region with relatively high agricultural eco-efficiency. (3) The low and lowest level are mainly along the Inner Mongolia–Shanxi–Gansu–Ningxia–Xinjiang line. Especially since 2019, the levels of agricultural eco-efficiency along the Zhejiang–Yunnan route have generally improved. As a result, several provinces along the Inner Mongolia–Xinjiang route have become characterized by overall low agricultural eco-efficiency.

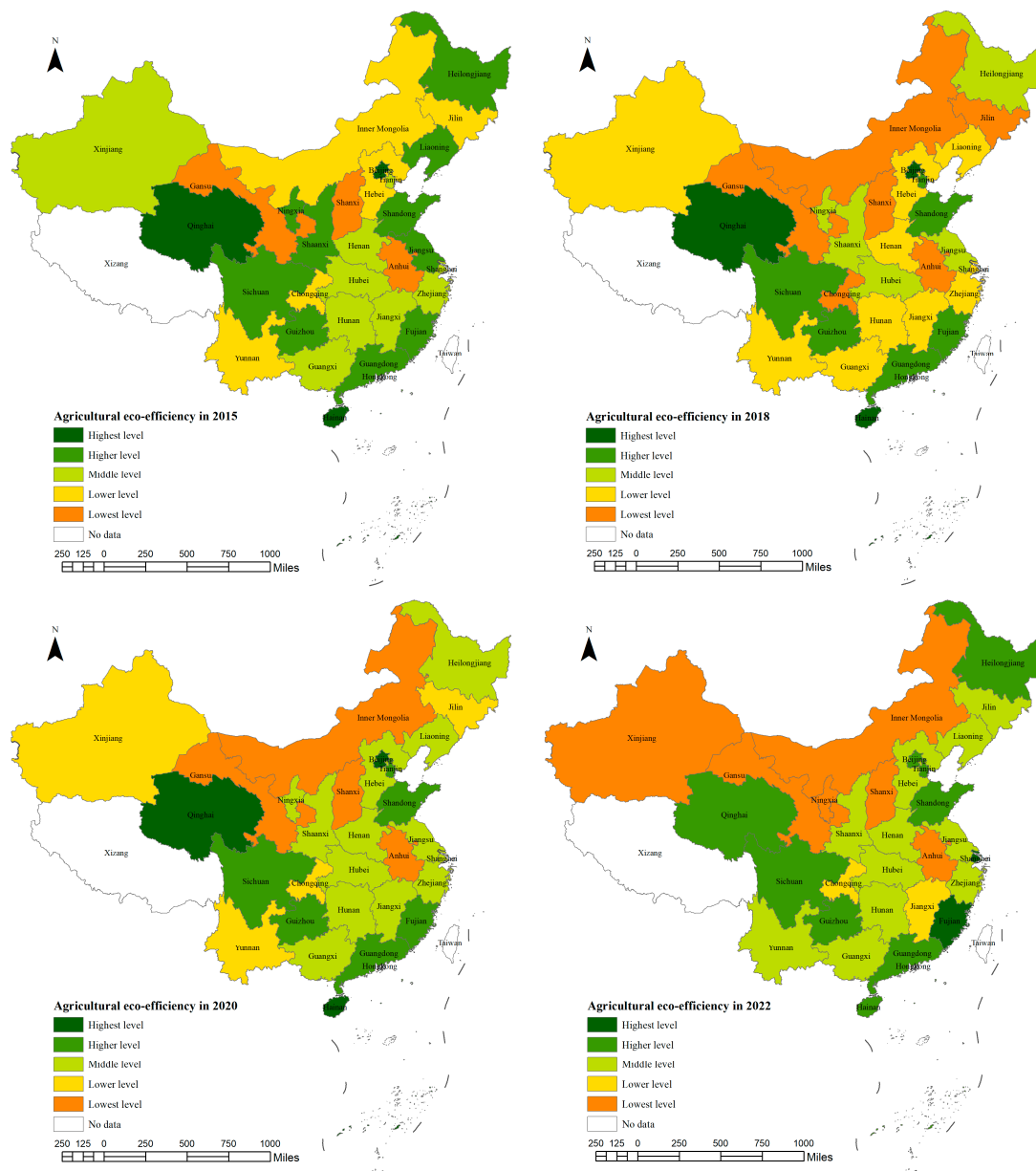


Figure 4. Spatial pattern of agricultural eco-efficiency levels from 2015 to 2022.

4.3. Analysis of Coupling and Coordination Between Farmland Transfer and Agricultural Eco-Efficiency

4.3.1. Coupling Farmland Transfer Results with Agricultural Eco-Efficiency

The results of the coupling degree between the index of farmland transfer in China and agricultural eco-efficiency indicate that from 2015 to 2022, the coupling degree of farmland transfer and agricultural eco-efficiency in various provinces of China was mostly in the running-in stage ($0.5 < C \leq 0.8$). The highest and lowest levels both increased, from 0.956 and 0.150 to 0.988 and 0.255, respectively. Figure 5 shows the spatial distribution and changes in the coupling degree level of farmland transfer and agricultural eco-efficiency in China. High-level coupling accounts for about 30%, mainly concentrated in the northeastern and northwestern regions such as Heilongjiang, Jilin, Inner Mongolia, Ningxia, Gansu, and Xinjiang, as well as in individual provinces in North and Central China, such as Anhui and Shanxi, which have gradually entered the high-level coupling category. Provinces in the adjustment stage account for about 50%, spatially including parts of North, Central, South, and Southwest China. Provinces in the low-level coupling and antagonistic stages

together account for about 20%, mainly represented by Beijing, Hainan, Qinghai, and Fujian. Although the coupling degree of these provinces has been increasing year by year, it still remains below 0.5 in most years.

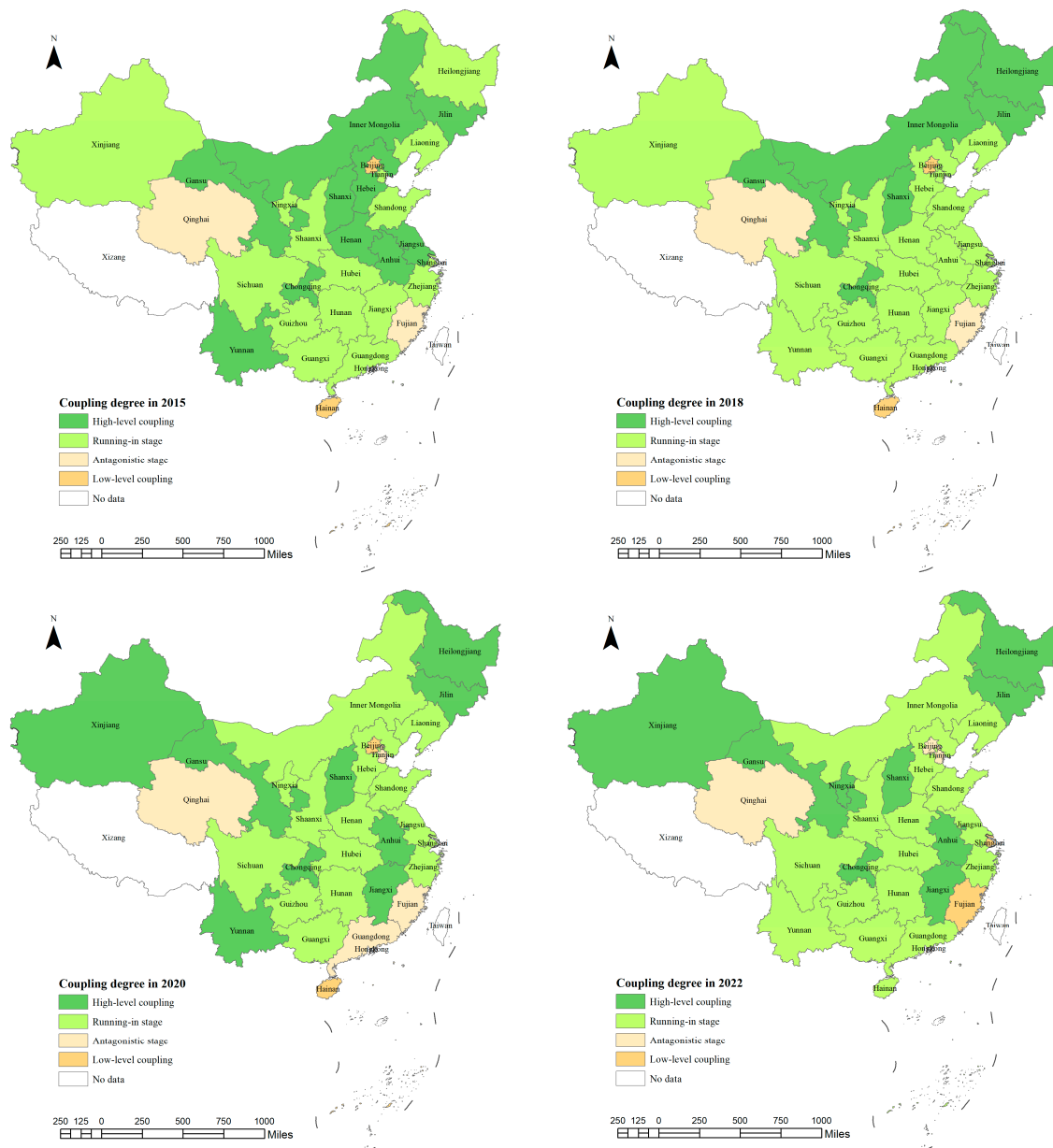


Figure 5. Coupling degree of farmland transfer and agricultural eco-efficiency from 2015 to 2022.

4.3.2. Coupling Coordination Results of Farmland Transfer and Agricultural Eco-Efficiency

According to the classification of coupling coordination degree, the overall level of coupling coordination between farmland transfer and agricultural eco-efficiency in China has transitioned from imbalance to coordination. Higher-level areas have emerged, while lower-level areas have disappeared, indicating an increasingly positive development trend. Generally, the coupling coordination degree between farmland transfer and agricultural eco-efficiency in China is greater than 0.4. The number of provinces classified as having a moderate imbalance accounts for less than 10%, and the severe imbalance level has completely disappeared since 2020. Looking at the timeline, in 2015, the coupling coordination degree between farmland transfer and agricultural eco-efficiency was mainly at the mild imbalance level, with primary coordination, intermediate coordination, moderate imbalance, and severe

imbalance also being present. In 2018, the advanced coordination level appeared. By 2022, the primary coordination level became the most covered level among provinces, followed by mild imbalance, moderate imbalance, advanced coordination, and intermediate coordination, with the proportions of provinces covered by these levels being 56.7%, 30.0%, 6.7%, 3.3%, and 3.3%, respectively. Examining the spatial distribution of high-level coupling coordination areas in Figure 6, Heilongjiang has consistently been at the highest level of coupling coordination, with the coupling coordination degree increasing from 0.68 to 0.76. Jiangsu, Chongqing, Jilin, Ningxia, Henan, and Xinjiang are generally in the high-level area of primary coordination, with Jiangsu, Jilin, and Ningxia reaching the intermediate coordination level in individual years. It is evident that the advanced coordination level with a coupling coordination degree greater than 0.7 only covers one province, (Heilongjiang), and the intermediate coordination level with a coupling coordination degree greater than 0.6 also only includes one province on average each year. The challenge of progressing from the primary coordination level to higher levels is relatively high.

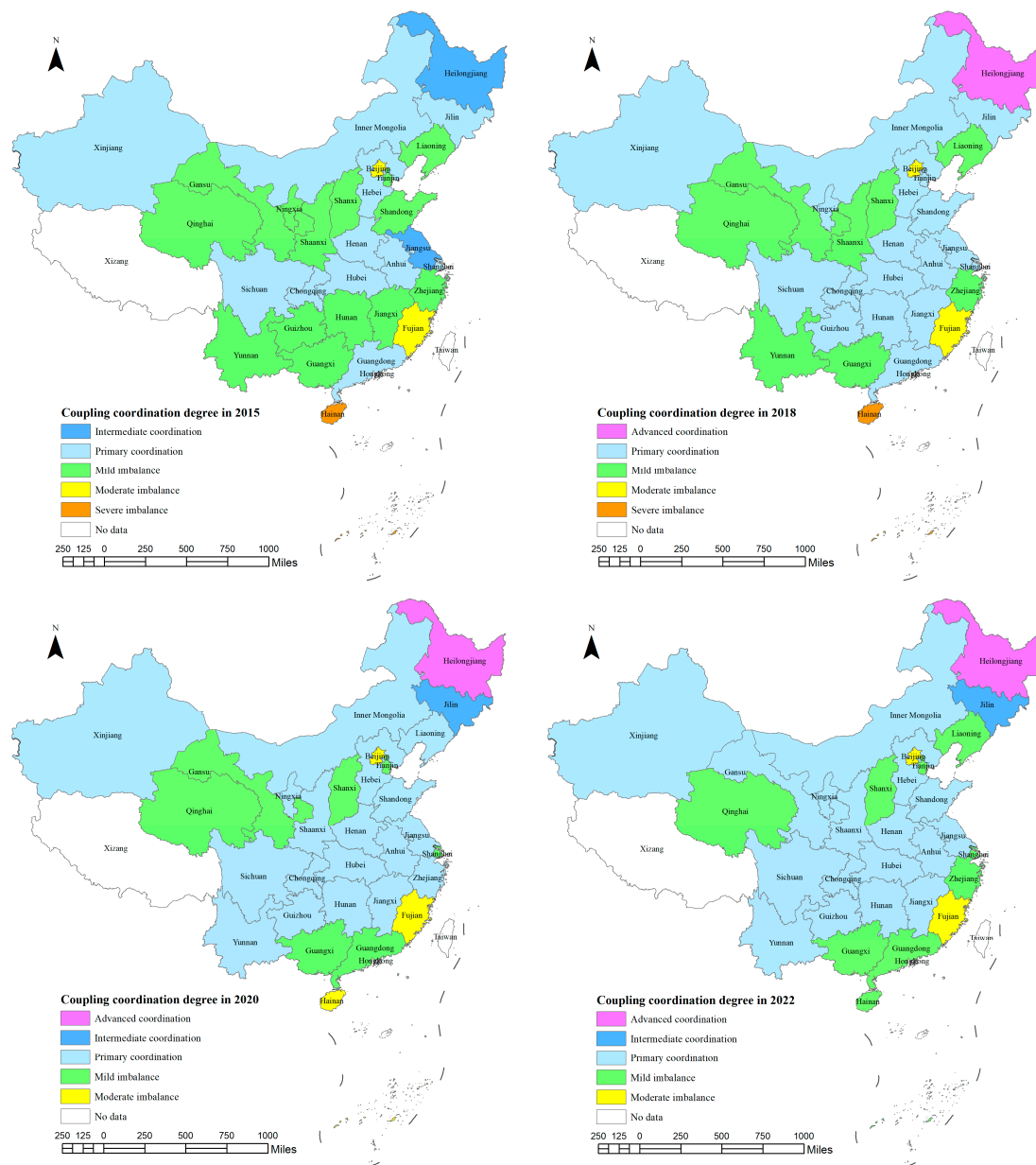


Figure 6. Coupling coordination results of farmland transfer and agricultural eco-efficiency from 2015 to 2022.

4.3.3. Results of the Relative Development Degree of Farmland Transfer and Agricultural Eco-Efficiency

The results of the relative development degree of farmland transfer and agricultural eco-efficiency in China show that approximately 75% of provinces are lagging behind in farmland transfer level, 10% are in synchronization, and 15% are lagging behind in agricultural eco-efficiency. According to Table 7, (1) the rate of farmland transfer in most provinces lagged behind agricultural eco-efficiency during the study period, with Beijing, Shanghai, and Fujian being the most notable examples, exhibiting relative development levels between 0.2 and 0.3. (2) Provinces where farmland transfer and agricultural eco-efficiency developed synchronously included Shaanxi and Chongqing. In contrast, provinces where agricultural eco-efficiency lagged behind the level of farmland transfer were represented by Inner Mongolia and Anhui. Additionally, the relative development levels of Hebei, Jilin, Heilongjiang, Yunnan, Gansu, and Xinjiang in various years were also approximately 1.1; however, this synchronous state was not stable.

Table 7. Relative development results of farmland transfer and agricultural eco-efficiency from 2015 to 2022.

	2015	2017	2020	2022		2015	2017	2020	2022
Beijing	0.16	0.17	0.18	0.24	Henan	0.74	0.84	0.68	0.71
Tianjin	0.51	0.73	0.35	0.40	Hubei	0.59	0.68	0.56	0.49
Hebei	0.92	0.94	0.57	0.58	Hunan	0.54	0.72	0.58	0.64
Shanxi	0.93	1.01	1.01	0.98	Guangdong	0.58	0.62	0.40	0.43
Inner Mongolia	1.28	1.76	1.62	1.56	Guangxi	0.39	0.53	0.40	0.41
Liaoning	0.48	0.65	0.50	0.45	Hainan	0.12	0.13	0.17	0.41
Jilin	0.84	1.06	1.07	0.74	Chongqing	0.88	0.91	0.91	0.91
Heilongjiang	1.42	1.48	1.15	1.07	Sichuan	0.49	0.64	0.46	0.52
Shanghai	0.57	0.75	0.52	0.27	Guizhou	0.42	0.59	0.44	0.46
Jiangsu	0.74	0.89	0.70	0.73	Yunnan	0.81	0.99	0.75	0.56
Zhejiang	0.55	0.64	0.54	0.48	Shaanxi	0.39	0.63	0.55	0.55
Anhui	1.39	1.72	1.30	1.35	Gansu	1.43	1.54	1.09	1.19
Fujian	0.29	0.33	0.27	0.22	Qinghai	0.30	0.33	0.29	0.39
Jiangxi	0.59	0.78	0.78	0.81	Ningxia	0.52	0.82	0.71	1.26
Shandong	0.44	0.59	0.52	0.51	Xinjiang	0.72	0.78	1.02	1.37

4.4. Farmland Production Efficiency at Different Levels of Coupling Coordination

This study employed unit area grain yield as a measure of the production efficiency of farmland and subsequently analyzed the levels of production efficiency across various coupling coordination levels. Currently, farmland production efficiency across various provincial units ranges from 5287.1 to 7054.0 kg per hectare. The highest farmland production efficiency was observed at the intermediate coordination level, while the lowest efficiency was found at the advanced coordination level. By examining Table 8, we observed that the levels of farmland production efficiency are associated with various coupling coordination levels. (1) The advanced coordination level exhibits the lowest farmland production efficiency, whereas the intermediate coordination and moderate imbalance levels demonstrate relatively high levels of efficiency. A notable characteristic of these three levels is the limited number of provinces represented. For instance, the advanced coordination level includes only Heilongjiang, the intermediate coordination level comprises either Jiangsu or Jilin, and the moderate imbalance level consists solely of Beijing and Fujian. Consequently, the grain yield per unit area from just one or two provinces reflects the farmland production efficiency for that specific coupling coordination level. (2) The farmland production efficiency at the primary coordination level is generally high, with some years demonstrating that the grain yield per unit area ranks first among all levels. The number of provinces included in this category accounts for more than half of China, encompassing over 60% of the main grain-producing regions. (3) The farmland production efficiency at the mild imbalance level is relatively low. This category includes provinces such as Shanxi,

Qinghai, Shaanxi, Gansu, and Guangxi, where the grain yield per unit area typically falls below the national average in China.

Table 8. Relative development results of farmland transfer and agricultural eco-efficiency from 2015 to 2022.

	2015	2016	2017	2018	2019	2020	2021	2022
Advanced coordination				5280.9	5233.0	5223.0	5406.9	5287.1
Intermediate coordination	5646.0	4813.9	5599.8			6693.4	5344.6	7054.0
Primary coordination	5802.7	5429.1	5884.8	5881.1	5932.7	5864.8	5952.6	5825.5
Mild imbalance	5177.4	5215.2	5038.6	4822.5	5273.4	4934.9	5627.8	5667.9
Moderate imbalance	5749.0	7815.5	5635.3	5991.1	5835.6	5882.1	6073.7	6060.2
Severe imbalance	4990.1	6105.0		5141.4	6170.2			

Note: The unit is kilograms per hectare.

From the perspective of provincial units, there is a lack of effective synchronization between the farmland transfer index, agricultural eco-efficiency, and grain yield per unit area. Based on Table 9, it is evident that only a few regions can attain high levels of both the farmland transfer index and unit area grain yield. For instance, provinces with a high farmland transfer index, such as Heilongjiang, Inner Mongolia, Ningxia, and Anhui, generally exhibit lower unit area grain yields. The high-level areas of agricultural eco-efficiency and unit area grain yield exhibit a certain degree of similarity. For instance, Shanghai and Fujian demonstrate the highest agricultural eco-efficiency, with unit area grain yields of 7785.0 kg and 6073.2 kg per hectare, respectively. However, at other levels of agricultural eco-efficiency, the correlation with unit area grain yield is relatively weak. It is evident that there is no synchronous relationship among the unit area grain yield, farmland transfer index, and agricultural eco-efficiency with respect to development levels, at least at the current stage, and there is a lack of clear consistency.

Table 9. Grain yield levels by grade of farmland transfer index and agricultural eco-efficiency in 2022.

Province	Farmland Transfer Index	Grain Yield Per Unit Area	Province	Agricultural Eco-Efficiency	Grain Yield Per Unit Area
Heilongjiang	●●●●●	●●	Shanghai	●●●●●	●●●●●
Inner Mongolia	●●●●	●●●	Fujian	●●●●●	●●●●
Ningxia	●●●●	●●	Guizhou	●●●●	●
Anhui	●●●●	●●●	Qinghai	●●●●	●
Jilin	●●●●	●●●●●	Beijing	●●●●	●●●
Xinjiang	●●●●	●●●●●	Tianjin	●●●●	●●●●●
Jiangsu	●●●●	●●●●●	Guangdong	●●●●	●●●
Henan	●●●	●●●●	Shandong	●●●●	●●●●
Guizhou	●●●	●	Hainan	●●●●	●●
Chongqing	●●●	●●	Sichuan	●●●●	●●
Hunan	●●●	●●●●	Heilongjiang	●●●●	●●
Shandong	●●●	●●●●	Hubei	●●●	●●●●
Sichuan	●●●	●●	Liaoning	●●●	●●●●●
Jiangxi	●●●	●●●	Hunan	●●●	●●●●
Gansu	●●●	●	Shaanxi	●●●	●
Hebei	●●	●●●	Jiangsu	●●●	●●●●●
Shaanxi	●●	●	Jilin	●●●	●●●●●
Yunnan	●●	●	Guangxi	●●●	●●
Hubei	●●	●●●	Hebei	●●●	●●●
Shanghai	●●	●●●●●	Henan	●●●	●●●●
Guangdong	●●	●●●	Zhejiang	●●●	●●●●
Qinghai	●●	●	Yunnan	●●●	●
Tianjin	●●	●●●●●	Jiangxi	●●	●●●

Table 9. Cont.

Province	Farmland Transfer Index	Grain Yield Per Unit Area	Province	Agricultural Eco-Efficiency	Grain Yield Per Unit Area
Liaoning	••	•••••	Chongqing	••	••
Hainan	••	••	Ningxia	•	••
Shanxi	••	•	Anhui	•	•••
Zhejiang	••	••••	Inner Mongolia	•	•••
Guangxi	•	••	Xinjiang	•	•••••
Fujian	•	••••	Gansu	•	•
Beijing	•	•••	Shanxi	•	•

Note: The number of dots in the Table, from 1 to 5, corresponds to the lowest, lower, middle, higher, and highest in the classification.

5. Discussion

Our research findings indicate that regions in China characterized by a high degree of coupling and coordination between farmland transfer and agricultural eco-efficiency typically encompass areas with a high farmland transfer index. However, provinces such as Shanghai, Fujian, and Beijing, which exhibit exceptionally high agricultural eco-efficiency, demonstrate a very low farmland transfer index, leading to diminished levels of coupling and coordination. We believe that this situation highlights at least two significant issues: Firstly, there is significant polarization in the development of farmland transfer and agricultural eco-efficiency in certain provinces of China. For instance, in economically developed regions such as Beijing and Shanghai, agricultural carbon emissions are relatively low. In comparison to these low emissions, the input of farmland production factors and the total agricultural output value exhibit a relative advantage, resulting in higher agricultural eco-efficiency. However, these areas are not traditional agricultural regions or major production centers for agricultural products, and they possess a limited amount of farmland, leading to insufficient farmland transfer activities. Consequently, the calculations of the farmland transfer index do not demonstrate an advantage. This results in a clear phenomenon of “high in one aspect and low in another” between agricultural eco-efficiency and farmland transfer in these regions, which likely accounts for their low degree of coupling and coupling coordination. Secondly, in the coupling coordination model that we are currently utilizing, the coefficients for the farmland transfer subsystem and the agricultural eco-efficiency subsystem were assigned equal values, both set at 0.5 [61–63]. This approach is commonly adopted by many researchers. However, this practice largely dictates that the farmland transfer index and the agricultural eco-efficiency index can only establish a more favorable coupling coordination relationship if they are synchronized as closely as possible.

Furthermore, we are intrigued by the absence of a clear synchronous relationship between farmland production efficiency and the level of coupling coordination. For instance, using data from 2022, the average grain yield per unit area for advanced coordination, intermediate coordination, primary coordination, mild imbalance, and moderate imbalance was 5287.1, 7054.0, 5825.5, 5667.9, and 6060.2 kg/hectare, respectively. There appears to be a lack of correlation between the level of coupling coordination and the efficiency of farmland production. Similarly, the degree of alignment between farmland production efficiency, the farmland transfer index, and agricultural eco-efficiency is not high. It is understood that whether the goal is to promote farmland transfer or enhance agricultural eco-efficiency, achieving a high level of farmland production efficiency is essential. However, farmland production efficiency is affected by various factors, including natural conditions, agricultural infrastructure, and technological advancements. This complexity makes it challenging to find regions where both farmland transfer levels and agricultural eco-efficiency are high, while also maintaining elevated levels of farmland production efficiency. Based on existing research on farmland transfer and agricultural eco-efficiency, (1) there is no definitive conclusion regarding whether regions with a high level of farmland transfer achieve a higher grain yield per unit area. Farmland transfer activities significantly reduce the abandonment

and idleness of farmland, contributing to an increase in the area dedicated to crop cultivation, which, in turn, supports the overall rise in grain production. However, there remains no standard answer as to whether large-scale operations or smallholder farming is more efficient [64]. In fact, many studies have indicated that the meticulous farming practices employed by smallholders can result in higher grain yields per unit area. (2) There has been relatively little research integrating agricultural eco-efficiency with grain yield per unit area. Some studies have confirmed that grain yield per unit area positively impacts agricultural eco-efficiency; however, the degree of influence is not significant. Consequently, there is not necessarily a direct correlation between the two. Through a detailed comparison, we found that the farmland transfer index, agricultural eco-efficiency, coupling coordination level, and grain yield per unit area in several major grain-producing areas are all at medium to high levels. These regions may exhibit common characteristics that warrant further exploration in the future.

5.1. Shortcomings

The shortcomings of this study are primarily evident in two areas: Firstly, we lack data on farmland transfer over a longer timescale. Although the period that we studied spanned from 2015 to 2022—a transitional phase from rapid growth to slow growth in the process of farmland transfer in China—it had a certain degree of representativeness and typicality. However, if longer time-series data were available, the results of our farmland transfer index and its coupling with agricultural eco-efficiency might have exhibited more significant variations, providing more informative insights. Secondly, the selection of unexpected output indicators in the evaluation index system for agricultural eco-efficiency is crucial. Currently, there is a lack of consensus within the academic community regarding the choice of unexpected output indicators. In this study, we selected agricultural carbon emissions as the unexpected output indicator. Agricultural carbon emissions represent an unavoidable negative consequence of the agricultural production process. The calculation results indicate that its impact on agricultural eco-efficiency is substantial. However, as we explore the coupling and coordination issues between farmland transfer and agricultural eco-efficiency, we must consider whether there is a difference in agricultural carbon emissions generated by production and operational activities on transferred versus non-transferred farmland. How significant is this difference? By investigating the relationship between these two factors, we can more effectively assess the rationality and scientific validity of the selection of unexpected output indicators.

5.2. Future Research Directions

Based on the research framework established in this study and the conclusions drawn from the results, we believe that the next phase of deepening the research can begin with the following four aspects: Firstly, it is possible to enhance the exploration of regional classifications regarding coupling coordination results. Whether considering the farmland transfer index, agricultural eco-efficiency, or the evaluation results of the coupling and coordination of the two, our analysis is based on provincial administrative units. If we classify the research results based on the primary grain-producing regions, major grain-selling areas, grain production and sales balance zones, or GDP levels, we can derive more targeted recommendations. We can explore regional classification methods repeatedly in future operations, aiming to identify more relevant classification techniques. Secondly, we can explore the findings of this study from the perspective of farmers operating at different scales. This macro-scale study concludes that “transfer foundation”, “transfer scale”, and “transfer channels” are crucial factors for effectively promoting farmland transfer. We can investigate the primary driving forces of micro-level groups in the farmland transfer process, particularly focusing on small-scale operators, by utilizing questionnaire surveys. Additionally, we can analyze the discrepancies between our findings and the conclusions drawn from macro-scale research, ultimately proposing more effective recommendations for agricultural production and the development of farmer management [65]. Thirdly,

we should examine the method of assigning coefficients to the coupling coordination model. Equivalent assignment is a common practice; some studies have suggested that, when exploring the coupling and coordination relationship between two variables, if one aspect is the primary focus of research, the assignment of that aspect can be appropriately increased [66]. Nevertheless, empirical research on this topic remains relatively scarce. In addition to the aforementioned ideas, within the research framework of this study, multiple operations of the coupling coordination model can be conducted based on different levels of farmland transfer. This approach allows for the exploration of the differences and rationality of coupling coordination results under equivalent assignment, ultimately leading to the identification of more scientific and effective assignment methods. Fourthly, we should investigate strategies to enhance the productivity of farmland in regions characterized by higher levels of coupling and coordination. Although there is no significant correlation between the efficiency of farmland production and the level of coupling coordination, the coupling coordination levels of farmland transfer and agricultural eco-efficiency, as well as the overall yield per unit area of grain in several major grain-producing provinces such as Jilin, Jiangsu, Henan, Hunan, and Shandong, are at an upper-middle level. We can employ the difference-in-differences method to perform a comparative feature analysis between the aforementioned provinces and other regions, with the aim of identifying key influencing factors and pathways of action.

6. Conclusions

This study quantitatively measured and evaluated farmland transfer, agricultural eco-efficiency, and the coupling and coordination relationship between the two in China. The farmland transfer in China has experienced a first round of relatively rapid growth and is currently in an upward phase, albeit with a slower growth rate. The key forces further driving farmland transfer are in regions with medium-to-low levels and low weight indicators. These regions mainly include Inner Mongolia, Jiangsu, Anhui, Ningxia, Jilin, Xinjiang, Guizhou, Hunan, and Jiangxi. The low weight indicators encompass external participation, internal carrying capacity, differentiation of farmers' occupations, and transfer norms. The focus is on enhancing the capacity of enterprises, farmers, and cooperatives in these regions to undertake farmland transfer, increasing the proportion of farmers working outside, and improving the standardization of transfer contracts, which can effectively promote the farmland transfer process in the region. Regarding the coupling degree and coordination, the coupling degree between farmland transfer and agricultural eco-efficiency in China is mostly in the running-in stage, covering parts of North, Central, South, and Southwest China. From 2015 to 2022, the level of coupling coordination indicated the largest number of provinces transitioning from mild imbalance to primary coordination. In 2022, the levels of coupling coordination include advanced coordination, intermediate coordination, primary coordination, mild imbalance, and moderate imbalance. The proportions of provinces covered by these levels were 3.3%, 3.3%, 56.7%, 30.0%, and 6.7%, respectively. The high-level regions mainly included Heilongjiang, Jiangsu, Chongqing, Jilin, Ningxia, Henan, and Xinjiang, with approximately 75% of these regions having farmland transfer levels lagging behind agricultural eco-efficiency. Upon introducing the farmland production efficiency indicator, it was observed that there is no clear synchronous state between the level of coupling coordination and farmland production efficiency. Only the farmland production efficiency of primary coordination is roughly equivalent to the level of coupling coordination, with both being at a relatively high level.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture14122172/s1>, Figure S1. Weight changes of various indicators of farmland transfer from 2015 to 2022. Figure S2. Regional Disparities in 2022 Single Indicator Values.

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