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An Evaluation Scheme Driven by Science and Technological Innovation—A Study on the Coupling and Coordination of the Agricultural Science and Technology Innovation-Economy-Ecology Complex System in the Yangtze River Basin of China

Chunlin Xiong [1,*], Yilin Zhang [1] and Weijie Wang [2]

[1] College of Public Administration and Law, Hunan Agricultural University, No. 1, Nongda Road, Furong District, Changsha 410128, China; yilin13211@gmail.com
[2] College of Computer Science and Technology, Hengyang Normal University, Hengyang 421002, China; wwj011224@gmail.com
* Correspondence: xcl17@hunau.edu.cn; Tel.:+86-13787261240

Abstract: This study focuses on 19 provinces in the Yangtze River Basin of China. It gathers relevant data indicators from 2010 to 2021 and constructs an evaluation index system centered on agricultural science and technology innovation. The study evaluates the relationship between agricultural "science and technology innovation-economy-ecology" systems and identifies key obstacle factors using the obstacle degree model. The study draws the following conclusions: Firstly, the comprehensive development level index of the agricultural science and technology innovation system shows an overall linear upward trend (values range from 0.121 to 0.382). Secondly, the comprehensive development level index of the agricultural economic system exhibits an upward trend but with a relatively small overall magnitude (values range from 0.248 to 0.322). Thirdly, the comprehensive development level index of the agricultural ecological system demonstrates significant overall fluctuations, with notable regional disparities (values range from 0.384 to 0.414). Fourthly, the overall agricultural SEE (Science and technological innovation, Economy, Ecology) complex system exhibits a characteristic of "high coupling, low coordination", identifying the main obstacle factors influencing agricultural SEECS based on a formulated approach. Subsequently, the following policy recommendations are proposed: Firstly, enhance the agricultural technological innovation system and promote green and efficient agricultural technology research and development. Secondly, to accelerate the transformation and upgrading of modern agriculture, achieving green and high-quality development of the agricultural economy. Thirdly, to strengthen agricultural ecological environment protection, laying a solid foundation for the healthy and sustainable development of agriculture.

Keywords: Yangtze river basin; agricultural SEE; complex system; coupling coordination

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1. Introduction

Looking back at the history of agricultural development, it is evident that scientific and technological innovation has consistently driven progress in agriculture. This has been crucial for the national economy and overall agricultural production capacity. However, the use of chemical fertilizers, pesticides, and other traditional agricultural innovations has resulted in irreversible negative impacts on the ecological environment. In the new era, China's agricultural innovation technology should prioritize the development of the agricultural economy while also emphasizing the protection of the ecological environment. Striking a balance between these aspects is essential for nurturing green and high-quality agricultural development in the new era. In 2021, the MOA (Ministry of Agriculture and Rural Affairs of China), in conjunction with six other departments, released the "Five-Year Plan for Agricultural Green Development in China (2021–2025)". This plan is designed to prioritize the advancement of agriculture and rural areas by fostering scientific and technological innovation and promoting sustainable agricultural development. In addition, the MOA issued the "Opinions of the Ministry of Agriculture and Rural Affairs on Promoting the Development of Agricultural Science and Technology Socialization Services", which supports the establishment of a market-oriented, integrated agricultural science and technology innovation system. The objective is to enhance food production efficiency, facilitate the shift from traditional to modern agriculture, promote eco-friendly agricultural practices, and mitigate the adverse effects of agricultural production on the environment. The integration of agricultural scientific and technological innovation has led to the creation of modern agricultural machinery and facilities, significantly reducing the labor required in agricultural production, and bolstering technical support for national food security. This approach strives to achieve sustainable, high-quality development of agricultural output and efficiency by green development principles.

The Yangtze River Basin, a pivotal agricultural region in China, contributes over 40% of the nation's total agricultural output value, more than 35% of its water resources, over 40% of forest coverage, and more than 35% of the transaction volume of technological innovation. While extensive research exists on the interplay between "science and innovation-economy" and "science and innovation-ecology" in agriculture, there is a dearth of studies on the composite system of science and innovation, economy, and ecology in rural areas. Similarly, limited attention has been given to the river basin and the science and innovation system as the core of a complex system. Therefore, it is imperative to investigate the coupling and coordination among the three systems of "science and technology innovation, economy, and ecology" in the Yangtze River Basin. Can agricultural scientific and technological innovation in the Yangtze River Basin achieve coupling coordination with its economic benefits and ecological environment? What is the level and trend of this coupling? What are the obstacles that affect the coupling and coordination among these three systems? What causes their disorders and how can they be mitigated? Answers to these questions will facilitate the acceleration of agricultural economic development, effective protection of the ecological environment, and the realization of green and high-quality agricultural development through scientific and technological innovation in the Yangtze River Basin. Furthermore, these findings will provide insights for China to achieve agricultural development through science and technology and establish itself as an agricultural powerhouse.

Literature Review

The synergistic coupling of agricultural economic development and agricultural ecological protection driven by agricultural scientific and technological innovation is an inevitable choice for developing countries in the new era to sustainably promote agricultural modernization and actively respond to changes in the agricultural ecological environment. However, excessive reliance on technology and high resource consumption have precipitated the degradation of the ecological environment, a phenomenon incongruent with the objective of sustainable development. First, the excessive use of pesticides and fertilizers has led to short-term economic growth but has caused soil degradation and water pollution, with long-term impacts on ecosystems. Regional economic development is contingent upon resource exploitation and the expansion of agricultural production. This often occurs at the expense of ecological considerations, resulting in a fundamental conflict between economic growth and the imperative of ecological preservation. Scientific and technological innovation has become an essential option to reduce the damage caused by short-term behavior. While there has been some progress in agricultural scientific and technological innovation in recent years, the supply of this innovation has not kept pace with the actual demand for agriculture. It is essential to boost agricultural scientific and technological innovation. Science and technology can enhance the efficient use of resources, shift the agricultural economy's growth mode from extensive to sustainable growth, increase overall agricultural production capacity, and achieve environmentally friendly and high-quality agricultural development [1]. As the primary industry of the human productive economy, agriculture itself is the result of the invention and the use of tools, the product of innovation [2]. Currently, there are numerous technical challenges in the field of agriculture. The supply of science and technology is unable to meet the requirements for agricultural modernization. It is crucial to significantly improve the supply capacity of agricultural science and technology innovation [3]. The fundamental conditions, goals, and tasks of China's agricultural rural economic development have undergone significant changes. There has been a shift from focusing solely on increasing output to emphasizing improvement in quality. Therefore, there is an urgent need to provide robust support for scientific and technological innovation [4].

Second, the coupling and coordination degree model can be used to measure the degree to which two or more systems promote and interact with each other. It has been widely applied in ecology, agriculture, geography, economics, and other research fields with fruitful results [5,6]. Each element or object in the system has an interaction relationship that affects each other's motion states [7]. We use it to analyze evolutionary relationships between different systems through spatiotemporal dimensions [8]. The relationship between the economy and the ecological environment is highly related, and the internal factors are closely combined to form an interactive coupling system. The coupling coordination degree between ecological environment and urbanization has been applied [9–16] between economic development and the agro-ecological environment [17]. In addition, scholars have also used the model to measure the coordinated development of science and technology and ecology, such as agricultural science and technology innovation and environmental regulation [18].

Third, as far as we know, there are few studies on the coupling and coordinated development of three complex agricultural systems. Recently, scholars have studied the coordinated development of the economy, society, and environment [19–21], studies on provinces have explored the coupling coordination level between the three regional ecological–economic–social systems [22], and relevant studies have recognized the relationship between government support, financial support, and innovation in economic development [11,12,23,24]. With the remarkable growth of the global economy and increasing environmental pressure [11–16,25] we must shift from the traditional development path to the sustainable and coordinated development of scientific and technological innovation, ecology and economy [26]. The sustainable vitality of agricultural systems depends on policies that support farmers' livelihoods and effective technological logic advances [27]. Scholars have studied the scientific innovation subsystem of agriculture [26] and actively put forward beneficial countermeasures and suggestions to promote high-quality economic development [28]. The agricultural complex system is a complex system with rich contents and diverse perspectives [29,30];

Fourth, the literature on agricultural system modeling [31] constructs the index system of regional integrated agricultural systems from different perspectives. For example, by considering land, labor, and financial resources, the social and ecological coupling results related to agricultural intensification were calculated, Ref. [32] established a comprehensive evaluation index system of agricultural economy and the ecological environment from three aspects: "ecological environment status, ecological environment pressure, and ecological environment governance". Ref. [33] established a comprehensive evaluation index system for green agricultural production, including "supply capacity, resource utilization, environmental quality, ecosystem maintenance, and farmers' livelihood". Ref. [34] constructed another evaluation index of the coordination between the ecological environment and social economy by using the dimensions of "ecological environment, economic development, and social development". In the realm of agricultural research, there has been a focus on the interplay between "science and innovation-economy" as well as "science and innovation-ecology", and "economy-ecology" systems. However, there has been a dearth of research concerning the composite system of science and innovation, economy, and ecology in rural areas. Furthermore, within the research on composite systems, there has been a lack of attention given to the science and innovation system. The impact of scientific and technological innovation on the agricultural ecological environment has been a double-edged sword, leading to increased pressure and affecting the sustainable development of the agricultural economy. To address this, a study has been conducted, using 19 provinces in the Yangtze River basin as examples. This study aims to develop a quantitative evaluation index system for rural science and technology innovation, economy, and ecology. The study utilizes an innovative digital-driven evaluation scheme with a focus on the agricultural science and innovation system as the core. By evaluating and discussing the relationship among agricultural science and technology innovation, economy, and ecology in the Yangtze River basin from a temporal and spatial perspective, the study seeks to explore their coupling and coordinated development path. The research on the regional agricultural integrated system serves as a crucial reference for the study of regional agricultural complex systems and the internal interaction of regional agricultural SEECS.

Finally, the green and high-quality development of agriculture requires scientific and technological innovation to drive it. It also needs to achieve a balance between economic development and ecological protection based on scientific and technological elements. The advancement of agriculture in a sustainable and high-quality manner can only be achieved through the coordination of these three factors. The existing scholars mainly focus on the two systems of agricultural “science and innovation-economy”, “science and innovation-ecology” and “economy-ecology”, and pay less attention to the compound system of rural science and innovation, economy and ecology. At the same time, in the research of composite systems, there are few studies centered on science and innovation systems. As a double-edged sword, scientific and technological innovation not only brings the growth of economic benefits but also correspondingly leads to the increasing pressure on the agricultural ecological environment, which in turn, affects the sustainable development of agriculture. In this study, we focus on 19 provinces in the Yangtze River Basin. We are constructing a quantitative evaluation index system for agricultural scientific innovation, economy, and ecology. This is based on previous research by scholars, which we have learned from and summarized. A new digital evaluation method was used to assess and study the connection between agricultural innovation, economy, and ecology in the Yangtze River Basin. This method considered both time and space, using a model to measure the degree of coupling and coordination and to identify the development path for this coupling and coordination. This in-depth analysis is useful for uncovering the level of coupling coordination and dynamic evolution among agricultural science and technology innovation, agricultural economic benefits, and agricultural ecological protection. It also helps to identify obstacles in order to promote the internal interaction of regional agricultural science and technology innovation, and economic and ecological complex systems, which has often been overlooked in previous studies.

This study aims to accurately assess the interplay between agricultural innovation, the economy, and ecology using a systemic approach. It will then propose specific recommendations for the sustainable development of regional agriculture. The paper is structured as follows: Section 2, Materials and Methods will introduce the research area, research framework, index system, data sources, and processing. In Section 3, the research methods will be analyzed using the comprehensive development level model, coupling coordination degree model, and obstacle model. Section 4 will present the results of agricultural SEECS in the Yangtze River Basin. The Section 5 will discuss the research findings, progress, and insights. Finally, Section 6 will provide the research conclusions.

2. Materials and Methods

2.1. Study Area

The focus of this study is the Agricultural Science and Technology Innovation-Economy-Ecology Complex System (SEECS) (S: Science and Technological Innovation; E: Economy; E: Ecology; CS: Science and Technology Innovation-Economy-Ecology Complex System) in the Yangtze River Basin, as shown in Figure 1. This basin encompasses a vast area, including the Yangtze River and its tributaries, spreading across three major economic zones in eastern, central, and western China, and spanning 19 provinces. Covering an immense 1.8 million square kilometers, it accounts for 18.8% of China's land area. The region is abundant in natural resources, with over 24.6 million hectares of cultivated land, representing a quarter of the country's total. Furthermore, the agricultural production value in this area accounts for 40% of the nation's total agricultural output, with food production contributing 40% to the country's total, and rice production alone accounting for 70%. Despite its significance as a major agricultural production base, the Yangtze River Basin faces challenges in water resource management, excessive fertilizer use, and soil pollution. After assessing, measuring, and identifying agricultural SEECS in the Yangtze River Basin, this paper presents policy recommendations to advance the coordinated development of agricultural SEECS, which holds great significance in promoting sustainable agricultural development in the Yangtze River Basin.

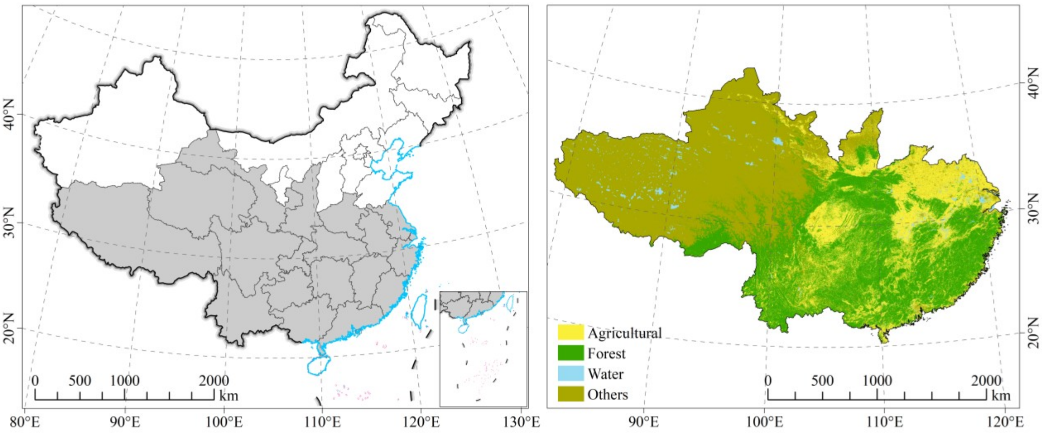


Figure 1. Yangtze River basin region.

2.2. Research Method

The paper examines the utilization of coupling and coordination degree models to analyze the interaction among the agricultural science and technology innovation system, agricultural economic system, and agricultural ecosystem. These models are capable of assessing the degree of mutual promotion and interaction between multiple systems and have found widespread application in various research fields such as ecology, agriculture, geography, and economics, yielding substantial results [5,6]. Within the model, elements or objects within each system possess an interaction relationship that influences each other's states [7]. Additionally, it can analyze the evolutionary relationship between different systems in a space–time dimension [8]. Presently, coupling and coordination degree models are frequently employed to study the relationship between the ecological environment and urbanization [9–16], as well as the interaction between economic development and agro-ecological environment [17]. Scholars have also utilized the model to measure the coordinated development of science and technology and ecology, such as agricultural science and technology innovation and environmental regulation [18]. While there is extensive research on the agricultural ecosystem and economic system, there is a limited exploration of the coupling and coordinated development of the three complex agricultural systems involving scientific and technological innovation, agricultural economy, and agricultural ecology. Consequently, the paper employs the coupling and coordination degree model to analyze the coupling and coordination development of these three complex agricultural systems.

2.3. Research Framework

This paper proposes a research framework aimed at enhancing the coupling and coordination within regional agricultural systems. The study presents a data-driven method for assessing and identifying the services provided by regional agricultural systems. The data-driven approach focuses on regional agricultural data and encompasses data collection, processing, modeling, and application to offer policy recommendations. The data collection process primarily involves gathering information on agricultural science and technology innovation inputs, the agricultural science and technology innovation environment, agricultural economics scale, agricultural economics composition, agricultural ecological pressure, and agricultural ecological resources. The index weight is calculated using the entropy method, and models for coupling coordination degree and obstacle degree are established. Building on these findings, methods for promoting the coupled and coordinated development of regional agriculture are proposed.

Given the context of advancing agricultural modernization and enhancing rural economic and social development, promoting the harmonized development of regional agricultural innovation, economy, and ecological systems holds significant practical value. This study has established an index system comprising three sub-systems, encompassing agricultural innovation, economy, and ecology. Due to the complex nature of regional agricultural systems and the diverse range of data sources, this study has employed a data-driven approach. This research aims to precisely measure, assess, and determine the degree of coupling and the level of coordinated development of regional agricultural ecosystems using a data-driven method. Furthermore, it seeks to present policy recommendations based on quantitative results, to serve as a foundation for decision-making by regional agricultural practitioners and managers. The specific framework is illustrated in Figure 2.

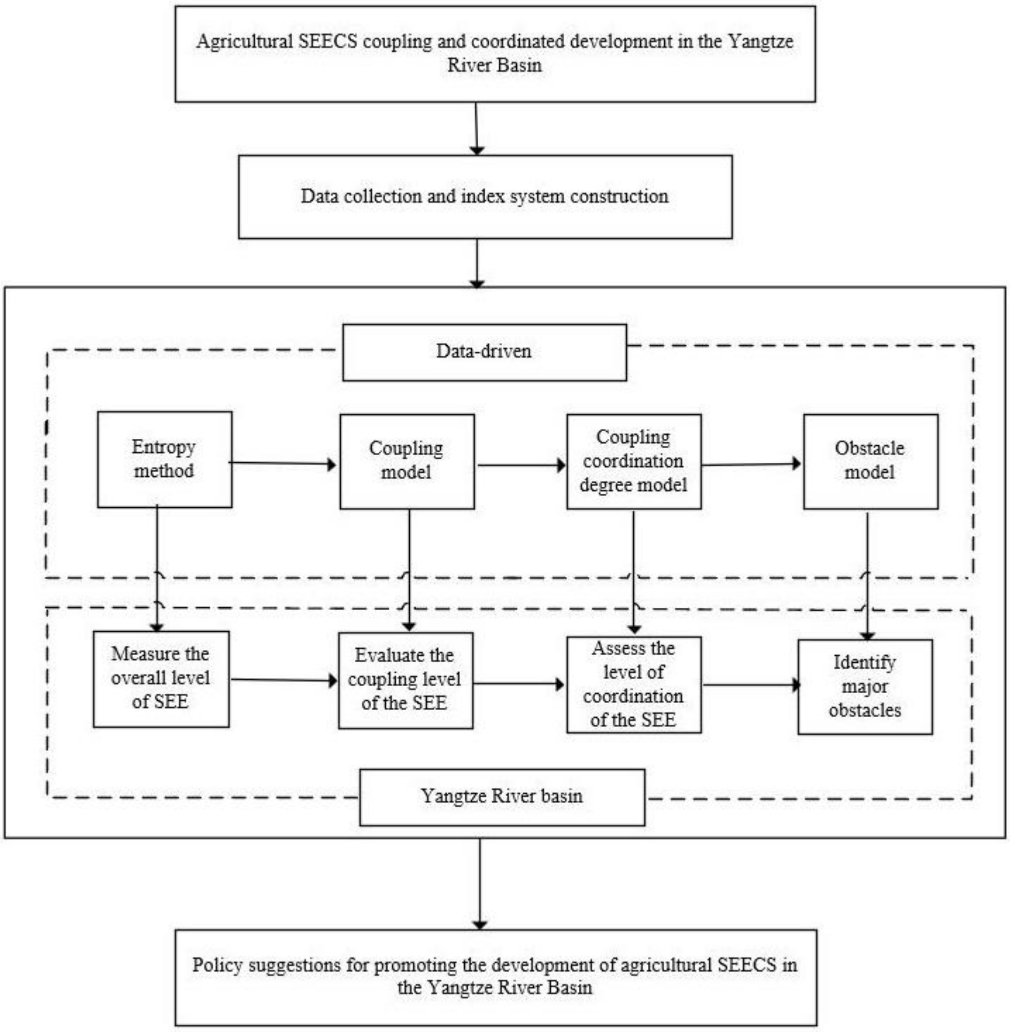


Figure 2. Technical circuit diagram.

2.4. Index System

The agricultural complex system is a complex system with rich contents and diverse perspectives [29,30]. The literature on agricultural system modeling constructs the index system of the regional agricultural integrated system from various perspectives [31]. For example, the social and ecological impacts of agricultural intensification are assessed by considering land, labor, and financial resources. The comprehensive evaluation index system [32] of the agricultural economy and the ecological environment was established from three aspects: "ecological environment condition, ecological environment pressure, and ecological environment management". A comprehensive evaluation index system [33] for green agricultural production has been established, including "supply capacity, resource utilization, environmental quality, ecosystem maintenance, and farmers' livelihood" [34]. Using "ecological environment, economic development, social development dimension", another evaluation index of ecological environment and social economy coordination was constructed.

This study conducted a comprehensive and scientific analysis of the interrelationships within the regional agro-ecological economic system. Drawing from existing research on agricultural composite systems [11–16,35,36], the study carefully selected indicators based on the principles of simplicity, scientific rigor, and quantifiability. The evaluation index system for the agricultural SEECS in the Yangtze River Basin, comprising three systems and 36 indexes, was established to conduct a comparative assessment of the degree of coordination among these systems. The agricultural innovation subsystem encompasses the input, environment, and output of agricultural innovation in the Yangtze River Basin, as outlined by [26,28]. This study introduces three new expenditures related to agricultural science and technology, as well as the degree of the agrarian scale, to provide a more comprehensive understanding of the current state and environment of agricultural science and innovation, building upon previous research indicators. The agricultural economic subsystem refers to the scale, composition, and efficiency of agricultural development in the Yangtze River Basin [37]. In this study, additional indicators of the agricultural development scale, such as the sown area of crops [35], the proportion of agriculture, forestry, and fishery [17], and grain yield per hectare of sown area [38], have been incorporated. This comprehensive approach fully captures the structure of the agricultural sub-industry and more effectively reflects the regional agricultural production efficiency. The agro-ecological subsystem's evaluation index comprises three key aspects: ecological pressure, regional agricultural development resources, and endowment [17]. In this context, new indicators such as agricultural water consumption have been incorporated [17] to comprehensively depict the ecological pressure stemming from agricultural ecological resources and energy usage. Please refer to Table 1 for details.

Table 1. Agricultural SEECS index system in the Yangtze River Basin.

Primary Index	Secondary Index	Three-Level Index	Unit	Direction
Agricultural science and technology innovation system: B1	Agricultural science and technology innovation investment: C1	Agricultural science and technology three expenditures: C11	100 million yuan	+
		Intensity of agricultural Research And Development expenditure: C12	%	+
		Persons employed in urban units of agriculture, forestry, animal husbandry and fishery: C13	ten thousand people	+

Table 1. *Cont.*

Primary Index	Secondary Index	Three-Level Index	Unit	Direction
		Agricultural science and technology fund: C14	ten thousand yuan	+
		Number of agricultural science and technology activities personnel: C15	person/year	+
	Agricultural science and technology innovation environment: C2	Per capita GDP: C21	RMB/person	+
		Level of agricultural mechanization: C22	%	+
		The proportion of typical rural entrepreneurship and innovation counties: C23	%	+
		The proportion of leisure agriculture demonstration counties: C24	%	+
	Agricultural science and technology innovation output: C3	Number of agricultural science and technology patents: C31	piece	+
		Scale of agriculture: C32	hm^2/person	+
		Land productivity: C33	%	+
Agricultural economics system: B2	Agricultural economics scale: C4	Gross agricultural output value: C41	100 million yuan	+
		Grain output: C42	ten thousand tons	+
		Total power of agricultural machinery: C43	10,000 kw/h	+
		Crop sown area: C44	1000 ha	+
	Agricultural economics composition: C5	Proportion of total agricultural output value to gross domestic product: C51	%	+
		Forestry as a proportion of agriculture: C52	%	+
		Pastoralism as a proportion of agriculture: C53	%	+
		Fisheries as a proportion of agriculture: C54	%	+
	Agricultural economics efficiency: C6	Labor productivity in the primary industry: C61	%	
		Growth rate of total agricultural output value: C62	%	+
		Grain yield per hectare sown area: C63	kilogram	+
Agricultural ecological system: B3	Agricultural ecological pressure: C7	Conversion amount of agricultural fertilizer application: C71	Ten thousand tons	+
		The amount of plastic film used in agriculture: C72	ton	-
		Pesticide use: C73	ton	-
		Total rural electricity consumption: C74	TWH	-
		Total agricultural water use: C75	BCM	+
	Agricultural ecological resources: C8	Forest coverage rate: C81	%	+

Table 1. *Cont.*

Primary Index	Secondary Index	Three-Level Index	Unit	Direction
		Cultivated area: C82	1000 ha	+
		Annual sunshine hours: C83	hours	+
		Average annual temperature: C84	°	+
	Agricultural ecological endowment: C9	Per capita green park area: C91	m^2/person	+
		Effective irrigated area: C92	1000 ha	+
		Total planted area: C93	1000 ha	+
		Soil erosion control area: C94	1000 ha	+

2.5. Data Source and Processing

The agricultural data for the Yangtze River Basin can be accessed from statistical reports like the China Statistical Yearbook, China Rural Statistical Yearbook, and China Science and Technology Statistical Yearbook from 2010 to 2021, as well as from the EPS database and Mark Data network.

3. Research Method

3.1. Comprehensive Development Level Model

The calculation steps of the entropy method are as follows:

1. Construct the initial matrix
   Suppose there are m indicators and n research samples, and the initial data matrix is Equation (1):
   In Equation (1), X is the initial data matrix, X_{ij} is the value of the i province of the JTH index of the system. Where i = 1, 2, 3, . . . , n, j = 1, 2, 3, . . . , m. There are 19 provinces in total, with 36 indicators.

$$X = [\mathrm{X_{ij}}]_{n\times m} \tag{1}$$

2. Standardized treatment
   The data in Equation (1) are standardized. If the value of an indicator changes in the same direction as the evaluation result, it is a positive indicator, and the standardized formula is Equation (2):

$$\mathrm{X'_{ij}} = \frac{\mathrm{X_{ij}} - \mathrm{X_{min}}}{\mathrm{X_{max}} - \mathrm{X_{min}}} \tag{2}$$

   On the contrary, the normalization formula of negative indicators is Equation (3):

$$\mathrm{X'_{ij}} = \frac{\mathrm{X_{max}} - \mathrm{X_{ij}}}{\mathrm{X_{max}} - \mathrm{X_{min}}} \tag{3}$$

   The normalized matrix is obtained $Y = [y_{ij}]$.

3. Calculate entropy
   The information entropy value of item j is as follows:

$$e_j = -k\sum_{i=1}^{m} f_{ij}\ln f_{ij}, i = 1,2,\ldots,n; j = 1,2,\ldots,m \tag{4}$$

In Equation (4), e_j represents the entropy value of the item j indicator; k is a constant, k = 1/ln n; f_{ij} is the weight of the item j indicator's item i value. Among them, f_{ij} can be expressed as Equation (5):

$$f_{ij} = y_{ij} / \sum_{i=1}^{n} y_{ij} \tag{5}$$

4. Calculate the weight
   d_j is defined as the consistency degree of contribution degree of each scheme under item j, $d_j = 1 - e_j$. The weight formula of each attribute can be obtained, as shown in Equation (6):
   $$W_j = d_j / \sum_{j=1}^{m} d_j \tag{6}$$
5. Calculate the comprehensive score of each province, as shown in Equation (7):
   $$S_i = \sum_{j=1}^{m} W_j X'_{ij} \tag{7}$$

3.2. Coupling Coordination Degree Model

The coupling coordination degree model assesses the internal coupling coordination degree and stage of a regional agroecosystem. After calculating the regional agricultural SEECS, we determined the coupling degree between regional agricultural innovation, agricultural economy, and agricultural ecosystem using the Equation (8):

$$C(U_1, U_2, \ldots, U_n) = n\left[\left(\frac{(U_1 U_2, \ldots, U_n)}{(U_1 + U_2 + \ldots + U_n)^n}\right)^{\frac{1}{n}}\right] \tag{8}$$

where, n represents the number of systems; C indicates the coupling degree. The value ranges from 0 to 1. This paper involves three systems, and the calculation formula as shown in Equation (9):

$$C(U_3) = 3\left[\left(\frac{(U_1 \cdot U_2 \cdot U_3)}{(U_1 + U_2 + U_3)^3}\right)^{\frac{1}{3}}\right] \tag{9}$$

In Equation (9), U_1 represents the overall level of the regional agricultural science and innovation system, U_2 denotes the overall level of the regional agricultural economic system, and U_3 indicates the overall level of the regional agricultural ecosystem. A higher value signifies a stronger coupling relationship, increased interaction intensity, and a more orderly operational state of the regional agroecosystem. Using the C value and drawing from the research of [39], the coupling coordination degree is categorized into 10 levels using the uniform distribution function method. The division intervals for each level of coupling coordination degree are detailed in Table 2.

Table 2. Classification criteria of coupling coordination degree.

Coupling Coordination Degree D Value Interval	Coordination Level	Degree of Coupling Coordination
(0, 0.1)	1	Hyperdysregulation
[0.1, 0.2)	2	Severe disorder
[0.2, 0.3)	3	Moderate dysregulation
[0.3, 0.4)	4	Mild disorder
[0.4, 0.5)	5	Borderline disorder
[0.5, 0.6)	6	Forced coordination
[0.6, 0.7)	7	Primary coordination
[0.7, 0.8)	8	Intermediate coordination
[0.8, 0.9)	9	Good coordination
[0.9, 1)	10	Quality coordination

According to the mathematical derivation and definition of coupling provided above, this paper constructs a theoretical analytical model of the coupling mechanism as shown in Figure 3. A three-dimensional coordinate system is established with the agricultural science and innovation system at the core, represented by the XYZ axis for the agricultural economic system, agricultural ecosystem system, and agricultural science and innovation system, respectively. The coordinate system contains three planes, AOB, AOC, and BOC, with OA, OB, and OC each having a length of 1. These three two-dimensional planes illustrate the coupling states of three kinds of systems: agricultural "science and innovation-economy", agricultural "science and innovation-ecology", and agricultural "economy-ecology". The cube represents the coupling of the three systems of "scientific innovation, economy, and ecology" in agriculture. Taking the plane BOC as an example to observe the coupling of the two systems, we see that the points on each ray from the origin indicate different degrees of coordination. The closer the degree of coordination is to 1, the higher the level of coordination. The optimal coordination line in Figure 3 is OG, where any point on the diagonal of the square OBGC shows the optimal coordination degree. Points on rays like OK are less coordinated than points on OG. Additionally, the series indifference curve T is used to characterize the development level of the two systems. The farther the indifference curve is from the origin O, the higher the level of development of the two systems—for example, points on T_3 have a higher level of development than points on T_1. Based on the analysis of the above aspects, it can be concluded that under the same coordination degree, the point on the higher indifference curve has a higher development level and its coupling degree is also higher. This analysis applies to the coupling states of the other two two-dimensional planes as well.

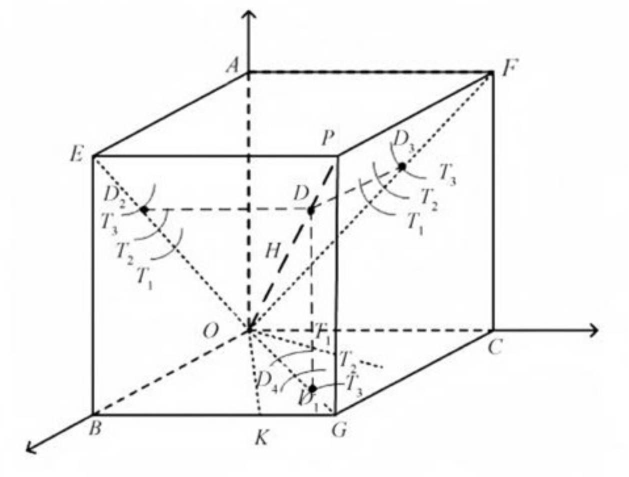


Figure 3. Analysis diagram of the coupling mechanism of the three systems [40].

By extending the above planar two-system coupling to three-system coupling with a positive cube as the carrier, it can be seen that, on the one hand, when the coordination degree of the three types of two-system is 1, the vertical planes of the optimal coordination lines of the three two-system intersect to form the diagonal OP of the cube. This line exactly expresses the coordination degree of the three systems, which means that only when the coordination degree of the three two systems is optimal at the same time, the three systems can achieve optimal coordination. On the other hand, the development mode of the three systems is also determined by the development level of the three two systems. Specifically, in each of the three binary systems represented by plane AOB, AOC, and BOC, there are an infinite number of equal development horizontal lines. For example, taking the BOC plane as an example, T_1, T_2, and T_3, respectively, represent different levels of development, and the farther away from the origin, the higher the level of development of the two systems. This feature also applies to the other two types of binary systems. Therefore, considering the coupling changes in two systems in each of the three planes comprehensively and assuming that the development level of each two systems is the same, point D will appear in space. D not only represents the same development level of the three systems, but because T_3 where it is located is further away from the origin than T_1 and T_2, it can be seen that there is a higher development level of the three systems it represents. Since D is located on the optimal coordination line at the same time, considering the coordination degree and development degree comprehensively, the coupling degree of the three systems can be analyzed: the coupling degree of the two systems is synthesized by the coordination degree and development degree of the three systems, which together constitute the coupling degree of the three systems. As shown in Figure 3, the coordination degree of point D and point H is 1, but the development degree of point D is greater than that of point H. Therefore, in the coupling degree of the three systems, point D is greater than point H.

The research paper focuses on the interconnectedness of agricultural science and innovation, the agricultural economic system, and the agricultural ecology. In the plane coordinate system AOB, the line OE represents the optimal coordination between agricultural science and innovation and the economy. The proximity of the OE line to the origin (O) indicates a lower level of coupling between the two systems. Similarly, in the three-dimensional coordinate system, the line OP represents the optimal coordination among agricultural science and technology innovation, the economy, and ecology. A closer proximity to the origin (O) indicates a lower level of coupling among the three systems. In conclusion, to enhance the coupling among the three systems, efforts should focus on improving the coordination between agricultural science and technology innovation and the economy, between agricultural science and technology innovation and ecology, and between the economy and ecology. This will facilitate the transition towards a more integrated system.

3.3. Obstacle Model

To better understand how regional agricultural subsystems work together and develop, we used the obstacle degree model to identify the factors that hinder their coordination and internal collaboration. The calculation formula is Equation (10):

$$Q_{ij} = \frac{(1 - X'_{ij}) \times w_j}{\sum\limits_{j=1}^{n} (1 - X'_{ij}) \times w_j} \times 100\% \tag{10}$$

$$Q_i = \sum_{j=1}^{n} Q_{ij} \tag{11}$$

In Equations (10) and (11), Q_{ij} represents the degree of impediment to the internal coupling coordination relationship between the second-level indicator j of the primary indicator i in the regional agricultural SEECS. Q_i represents the degree of impediment for the primary indicator, X'_{ij} represents the standardized value of the item j second-level indicator, and w_i is the weight of the item j index.

4. Result Analysis

4.1. Comprehensive Development Level of Agricultural SEECS in the Yangtze River Basin

The comprehensive development level of agricultural SEECS in the Yangtze River Basin was calculated using a specific formula, and the results are illustrated in Figure 4 (on the right). Overall, there is a steady increase from 0.753 in 2010 to 1.118 in 2021. Figure 4 illustrates the fluctuating comprehensive development level of nine secondary indicators of agricultural SEECS in the Yangtze River Basin from 2010 to 2021. The comprehensive development level of the agrarian science and innovation output system (C3), development composition system (C5), and ecological endowment system (C9) is relatively unstable. This reflects the need for the agricultural economy in the Yangtze River basin to prioritize sustainable development and allocate increased investment in agricultural science and innovation. Additionally, it underscores the importance of promoting the deep integration of science, technology, and industry to achieve stability in the comprehensive development of agriculture.

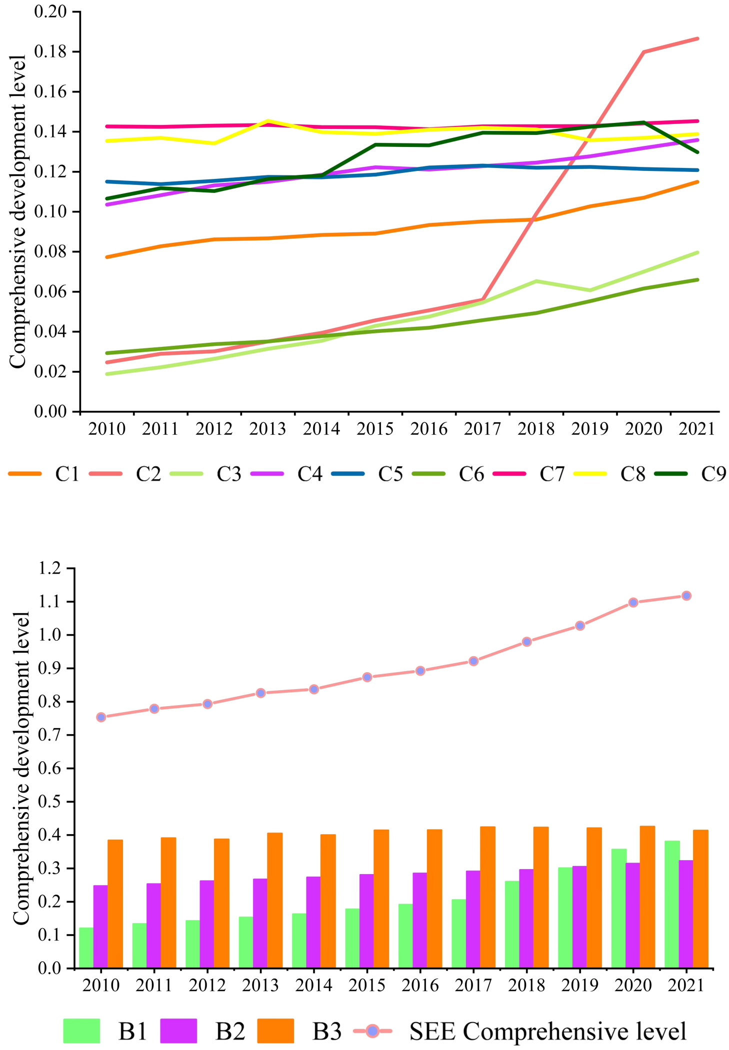


Figure 4. Comprehensive development level of SEECS in agriculture in the Yangtze River Basin.

The comprehensive development index of the agricultural science and technology innovation system (B1) has shown steady growth, rising from 0.121 in 2010 to 0.382 in 2021. This increase is mainly attributed to the issuance of the "Outline of the National Medium- and Long-term Scientific and Technological Development Plan (2006–2020)" by The State Council in 2006, which emphasized the role of scientific and technological innovation in various fields at both national and provincial levels within the Yangtze River Basin. The comprehensive level index of rural science and innovation in the Yangtze River Basin has exhibited a consistent upward trend from 2010 to 2021, with a total increase of 0.261. This growth can be categorized into three stages: the first stage (2010–2015) with slow growth, the second stage (2016–2018) with moderate growth, and the third stage (2019–2021) with the fastest growth rate. Notably, the overall level of the agricultural science and innovation system from 2020 to 2021 surpasses that of the agricultural economic system, demonstrating continuous improvement in the input, environment, and output of agricultural science and innovation within the Yangtze River Basin. However, analyzing the comprehensive index alone is insufficient to unveil the internal dynamics of the rural science and innovation system. Therefore, this study also dissects three subsystems and scrutinizes the index changes within these subsystems (refer to the right side of Figure 4). In terms of the input level of agricultural science and innovation (C1), there has been a linear upward trend from 2010 to 2021, with the level index rising from 0.077 in 2010 to 0.115 in 2021. Regarding the level of agricultural science and innovation environment (C2), a consistent upward trend has been observed from 2010 to 2017, with a prominent upward trend from 2018 to 2021. This sharp increase can be largely attributed to the issuance of "Guiding Opinions on Promoting the Construction and Development of Agricultural High-tech Industry Demonstration Zones" by The State Council in 2018. This initiative, guided by the implementation of innovation-driven development strategies and rural revitalization strategies, has propelled the creation of a pilot area for agricultural innovation-driven development in the Yangtze River Basin, leading to increased support for agricultural science and technology across all regions and departments within the basin. From 2010 to 2021, the level of agricultural science and innovation output (C3) has experienced slight fluctuations but has shown an overall growth trend. The decline in 2018–2019 can be attributed to the low utilization rate of innovation achievements and the absence of an effective transformation mechanism. However, in 2019, in line with the Law on Promoting the Transfer of Scientific and Technological Achievements and relevant policy requirements, efforts were made to cultivate and develop new types of agricultural operation and service entities, enhance the socialized service system for agricultural science and technology, and improve the service functions of technology transfer institutions in agriculture and rural areas. This is intended to guide the transformation and application of agricultural advanced technology achievements in the Yangtze River Basin through technical consulting services.

The comprehensive development index of the agricultural economics system (B2) has shown an upward trend, increasing from 0.248 in 2010 to 0.322 in 2021. This growth can be segmented into two stages: slow growth from 2010 to 2018, and moderate growth from 2019 to 2021. Despite some fluctuations, the analysis also covers changes in the three subsystems of the agricultural economic system (Figure 4). The agricultural development scale (C4) has trended upwards from 0.104 in 2010 to 0.136 in 2021. The agricultural development composition (C5) fluctuated from 2010 to 2021 but showed a downward trend from 2019 to 2021 due to the impact of the epidemic. The agricultural development efficiency (C6) experienced overall linear growth, rising from 0.029 in 2010 to 0.066 in 2021. However, compared to the rapid development of the agricultural science and innovation system, the agricultural economic system's development has been relatively slow. If improvement measures are not implemented, the weak independent innovation capacity in agriculture may hinder the momentum of agricultural scientific innovation. The development trend can be attributed to several factors. First, prior to the 12th Five-Year Plan, China's agricultural infrastructure faced significant challenges, including weak infrastructure and susceptibility to natural disasters and external financial crises, which impeded agricultural development. However, since the onset of the 12th Five-Year Plan period, China has actively promoted the construction of high-standard farmland and water conservancy facilities. In 2012, the demonstration planting of new rice and wheat varieties in the Yangtze River basin facilitated the adoption of high-yield and disease-resistant varieties, thereby enhancing resilience to natural risks. Concurrently, the promotion of agricultural modernization has been aligned with the processes of industrialization and urbanization. Many regions in the Yangtze River Basin have bolstered the establishment of farmers' cooperatives, facilitated the intensification and large-scale production of agricultural products, and improved the bargaining power of farmers. By means of resource integration, ecological management, training of new farmers, and the promotion of agricultural machinery and agronomic techniques, agricultural cooperatives have further solidified the foundation of agricultural development. Secondly, during the 13th Five-Year Plan period, China undertook structural reform on the agricultural supply side, optimized the industrial structure in the Yangtze River basin, curtailed energy-intensive and highly polluting agricultural activities, and advanced green agricultural technologies. In 2017, the introduction of a rural revitalization strategy nationwide, with the Yangtze River Basin as a focal region, prompted local governments to augment investment in agriculture and rural development. Numerous locales have augmented the market competitiveness of local agricultural products through branding initiatives, such as "Yangtze River fresh" and "green rice", leading to enhanced incomes for farmers. Lastly, in 2021, the Office of the Leading Group for the Development of the Yangtze River Economic Belt issued the Implementation Plan for the Protection and Restoration of the Ecological Environment of the Yangtze River (2021–2025), which proposed the implementation of measures encompassing emission reduction, pollution control, and environmental conservation to foster the sustainable development of agriculture. To meet market demand and environmental imperatives, certain areas in the Yangtze River Basin have commenced adjustments to the planting structure, reducing the cultivation of rice and augmenting the production of high-value crops such as vegetables and fruits.

The comprehensive development index of the agricultural ecology system (B3) experiences significant fluctuations. Based on the data, it can be categorized into three development stages: the first stage (2010–2012), the second stage (2013–2016), and the third stage (2017–2021). The first stage is characterized by a long duration with a relatively slow growth rate, the second stage exhibits moderate growth, and the third stage shows the fastest growth. However, compared to the development of the other two subsystems, the assessment value of the agroecosystem has a higher starting point, indicating the abundance of agro-ecological resources in the Yangtze River basin. Analysis of the three subsystems of the agroecosystem reveals significant fluctuations in the two subsystems of agro-ecological pressure (C7) and agro-ecological endowment (C9). The substantial fluctuation is mainly attributable to the rapid development of the agricultural economy, resulting in increased use of agricultural plastic film, higher rural electricity consumption, intensified pressure on the agricultural ecological environment, and affected by drought, flood, wind and other natural disasters, the affected area of crops has increased. Nevertheless, through increased government support, enhanced environmental remediation capability, and adjustments in agricultural production structure, the level of agricultural ecological security in the Yangtze River Basin has qualitatively improved. The observed development trend can be attributed to several factors. Firstly, during the "Twelfth Five-Year Plan" period, the state introduced a strategy to safeguard the Yangtze River, with a focus on ecological priority and green development. This initiative emphasized the coordinated development of agriculture and the ecological environment, the integration of agricultural scientific and technological innovation with ecological protection, and the advancement of new technologies and varieties to enhance agricultural productivity while mitigating environmental impact. The government initiated the establishment of ecological agriculture demonstration zones to promote water-saving irrigation, the use of organic fertilizers in lieu of chemical fertilizers, and the adoption of pesticide reduction technologies and models to minimize agricultural non-point source pollution. Secondly, during the 13th Five-Year Plan period, China intensified its efforts to control agricultural non-point source pollution in the Yangtze River basin. Various projects, such as the "green agriculture" program and the establishment of lake reserves, were implemented. Measures were taken to reduce nitrogen and phosphorus in the breeding industry, recycle livestock and poultry waste resources, and minimize the use of fertilizers and pesticides. China also underscored green development in the Yangtze River Economic Belt and mandated that all localities prioritize ecological protection and restoration while advancing economic development. In 2019, the Yangtze River Basin commenced delineating the ecological protection red line, resulting in the highest proportion of good water quality at 91.7%. This action clearly demarcated the scope of the ecological protection red line and bolstered the protection of critical ecological functions. In 2021, numerous provinces in the Yangtze River Basin set to execute agricultural ecological protection actions, enforce stringent standards for the use of pesticides and fertilizers, and safeguard soil and water resources. China has launched an agricultural sustainable development plan for the Yangtze River Basin, aiming to promote green agricultural development and enhance the quality of agro-ecosystems. This includes measures such as prohibiting agricultural activities that pollute water in specific areas.

4.2. Coupling Coordination Degree

The agricultural data from the Yangtze River Basin were included in the calculation formula for the coupling degree and coupling coordination degree to calculate the coupling degree (C), comprehensive evaluation index (T), and coupling coordination scheduling (D) of its agricultural SEECS. This study covers the period from 2010 to 2021. For a better comparison of the results, the years 2012, 2015, 2018, and 2021 (Figure 5) were chosen.

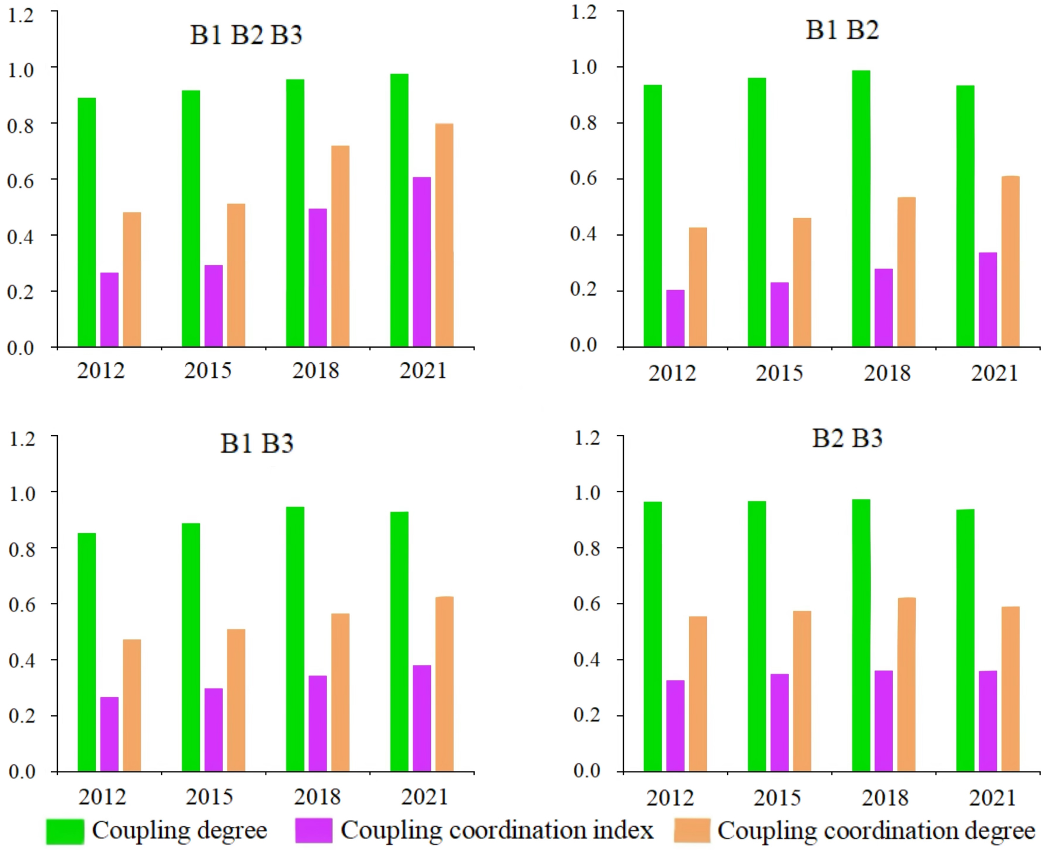
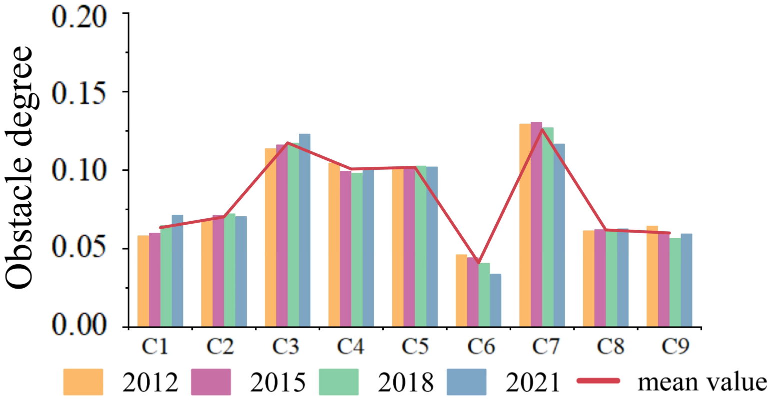


Figure 5. Calculation results of coupling degree, coupling coordination index and coupling coordination degree of agricultural SEECS in the Yangtze River basin (B1 = Agricultural Science and Technology Innovation System; B2 = Agricultural Economic System; B3 = Agricultural ecosystem).

To gain a deeper insight into the trends in agricultural science and innovation, agricultural economy, and agro-ecosystems in 19 provinces of the Yangtze River Basin, and to understand the spatial distribution characteristics of their coordinated development, we analyzed the regional differences in 2012, and 2015, 2018, and 2021. We then used the ArcGIS tool to visualize the coupling coordination degree of the 19 provinces in the Yangtze River Basin, as illustrated in Figure 6.

In our research, we examined the development status of agricultural SEECS in the Yangtze River Basin. According to Figure 5, the coupling degree among the three subsystems is nearly 1, indicating a high level of coupling and strong interaction and correlation, with a rising trend. In 2021, the coupling degree of “agricultural innovation-economic system” in the Yangtze River Basin was the highest at 0.932, while the coupling degree of “agricultural innovation-ecosystem” was relatively low at 0.925.



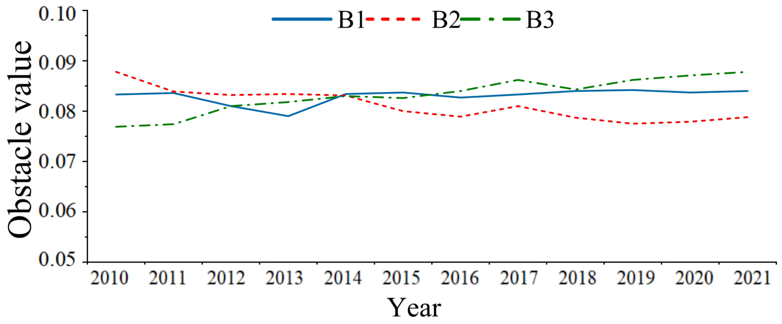


Figure 6. Spatial distribution of SEECS coupling coordination degree in agriculture in the Yangtze River Basin.

Secondly, from 2010 to 2021, the coupling coordination degree among the three subsystems of agricultural science and innovation (B1), economy (B2), and ecology (B3) in the Yangtze River Basin is generally on the rise, but its value is lower than the coupling degree value. As shown in Figure 6, the coupling and coordination degree of agricultural SEECS in the Yangtze River Basin is not high, and there are still great differences in the development level among provinces. Red areas represent moderate dysregulation, orange areas represent mild dysregulation, yellow areas represent borderline dysregulation, light green represents barely coordinated, grass green represents primary coordination, and dark green represents intermediate coordination. Therefore, the coordinated development level of the three subsystems shows the evolution trajectory of "moderate disorder, mild disorder, near disorder, reluctant coordination, primary coordination, intermediate coordination". In 2012, the coupling coordination degree of the provinces in the Yangtze River basin was not high, and most of the provinces were in a stage of imbalance. In 2015, three provinces achieved primary coordination, nine provinces achieved barely coordination, and seven provinces were in a state of imbalance. Compared with the two figures in 2015, the biggest change in 2012 was that two red regions became one red, the original four orange regions were reduced to one, and the original two yellow regions were increased to five. It indicates that the coupling coordination level of agricultural SEECS in the Yangtze River Basin is developing in a good direction. In 2018, eight provinces achieved primary coordination, five provinces achieved barely coordination, and six provinces were in a state of imbalance. Compared with the two maps in 2015 and 2018, the red area turns to an orange area, the whole province is out of the moderate disorder state, the original nine light green areas are reduced to five, and the grassy green areas are increased from the original three to eight, which indicates that the coupling coordination level of agricultural SEECS in the Yangtze River Basin is rapidly developing in a good direction. In 2021, two provinces reached intermediate coordination, nine provinces reached primary coordination, four provinces reached barely coordination, and four provinces were on the verge of imbalance. Compared with the two figures in 2018 and 2021, the biggest change is that the number of orange areas is reduced to 0, the original grassy green areas are increased to nine, and three dark green areas appear. It shows that the coupling coordination level of agricultural SEECS in the Yangtze River Basin is developing in a good direction. In 2021, the coupling coordination degree of the three systems reached 0.798, showing a development trend of intermediate coordination. However, in 2021, the coordinated development level between the two subsystems of agriculture "science and innovation-economy", "science and innovation-ecology" and "economy-ecology" was still in a barely coordinated state. In addition, in 2021, the coupling coordination degree between the two major systems in the agricultural SEECS system of the Yangtze River Basin presents a relationship of "science and innovation-economy" > "science and innovation-ecology" > "economy-ecology". This shows that the agricultural economic system has a strong driving effect on the agricultural science and innovation system, but the agricultural ecosystem lags behind. This is due to its good endowment of agricultural ecological resources, but its economic and innovative benefits have not been fully utilized. At the same time, agricultural scientific innovation accelerates the sustainable development of the economy, but also consumes a lot of ecological resources, causing great pressure on the environment, and the green development of agriculture lags.

The coupling degree among the subsystems of the Agricultural Science and Technology Innovation-Economy-Ecology Complex System in the Yangtze River Basin warrants further enhancement. Notably, the Middle East region exhibits a relatively developed economy, well-established infrastructure, and a high level of scientific and technological advancement, which significantly facilitates the coordinated development of agriculture and ecology. This has resulted in a high level of coupling and coordination among the provinces in the Middle East. In contrast, the western region faces relative economic underdevelopment due to historical, geographical, and resource-related factors, leading to a lower level of coupling and coordination within the SEECS subsystems. Spatial disparities in the coupling coordination degree are primarily attributed to internal development imbalances within each province. The Middle East region, encompassing 11 provinces, is actively contributing to comprehensive, coordinated, and sustainable development, fostering unique models and development strategies tailored to local contexts. These localized initiatives have accelerated provincial innovation in agriculture, science, technology, and ecology, consequently promoting interregional learning and cooperation. A discernible spatial distribution characteristic indicates a gradual decline in the coupling coordination level of the SEECS subsystems across provinces, reflecting an overarching state of "high coupling, low coordination". This disparity has the potential to exacerbate social and economic inequality, intensify regional competition, and impede cooperation. Special attention is thus imperative to facilitate the harmonized development of agricultural science and technology innovation and economic ecology, thereby establishing a virtuous cycle mechanism. Strengthening inter-provincial cooperation and exchanges, encouraging adaptive governance at the local level, and cultivating development models in line with local characteristics are the necessary conditions for effectively improving the coupling degree and coordination of the agricultural SEECS in the Yangtze River Basin. Policymakers should also prioritize ecological conservation and ensure the harmonized development of science and technology innovation, economy, and ecology to promote sustainable regional agriculture.

4.3. Degree of Coupling Coordination Disorder

According to the formula, the obstacle degree model identified and ranked the obstacle factors affecting agricultural SEECS coupling coordination in the Yangtze River basin. The obstacle degree of the primary index (B1B3) and secondary index (C1C9) is illustrated in Figure 7.

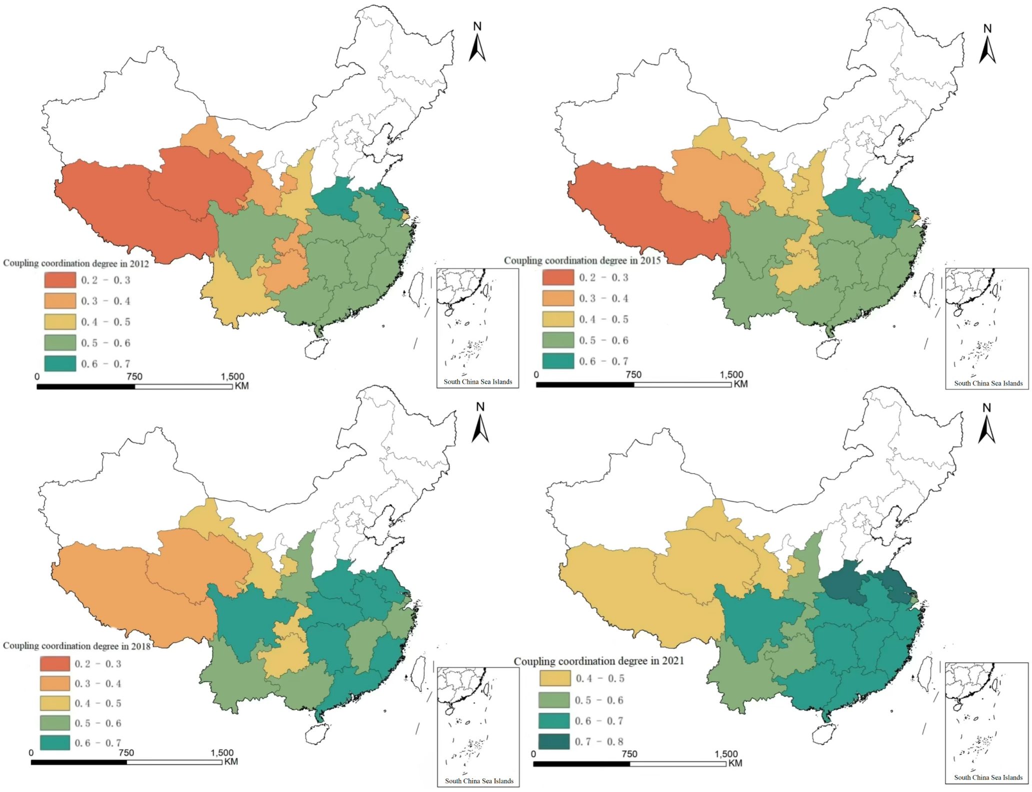


Figure 7. Calculation results of SEECS obstacle degree in agriculture in the Yangtze River Basin.

Further, the ranking of agricultural SEECS three-level index barriers in the Yangtze River Basin is shown in Figure 8:

Figure 8. Ranking of various obstacle factors in agricultural SEECS in the Yangtze River Basin.

It is evident from Figures 7 and 8 that the barriers to coordinated development differ significantly among the three agricultural SEECS in the Yangtze River Basin. The average obstacle degree of the first-level indicators is B3 > B1 > B2, while the second-level indicators rank as C7 > C3 > C5 > C4 > C2 > C1 > C8 > C9 > C6. From 2010 to 2021, the barrier values fluctuated, with the barrier degree of the science and innovation and ecological subsystems being higher, while the economic subsystem had a smaller barrier degree. Between 2016 and 2021, the barrier value of the ecological subsystem increased and had the largest barrier degree, followed by the science and innovation subsystem. In comparison, the barrier value of the economic subsystem showed a decreasing trend, reaching only 0.0788 by 2021, which was small compared to the science and innovation and ecological subsystems. Firstly, agro-ecosystem (B3) poses the main obstacle to the coupled and coordinated development of agro-ecosystems in the Yangtze River Basin.

Pesticide use (C73), agricultural plastic film use (C72), and total rural electricity use (C74) are the main obstacles to agro-ecological stress (C7). This is primarily due to natural disasters, high resource consumption, and environmental pollution faced by agricultural development in the Yangtze River Basin. For example, China's total agricultural electricity consumption in 2021 was about 1.04 times that of 2010. Secondly, the main obstacles to the agricultural innovation system (B1) are the number of agricultural technology patents (C31) and the degree of agricultural scale (C32) in the output of agricultural innovation (C9). For instance, the results of the sixth national technology forecast show that China's leading agricultural technology accounts for only 10%, with running technology at 39% and following technology at 51%. China's reliance on foreign agricultural technology is evident, with insufficient domestic high-tech supply in fields such as animal and plant breeding, agricultural mechanization, agricultural information technology, and agricultural green technology. The government and society must continue supporting agricultural innovation. Finally, the main obstacles to the development of the agricultural economic system (B2) are the proportion of the total output value of agriculture to the gross domestic product (C51) and the proportion of animal husbandry in agriculture (C53) in the agricultural economics composition (C5). This indicates the need for continued optimization of the agricultural and industrial structure of the Yangtze River basin. The ecological subsystem has consistently been a significant factor constraining the coordinated development of agricultural SEECS in the Yangtze River Basin. The key to achieving coordinated development shortly lies in considering the development of science and innovation and economic subsystems, while focusing on improving the development level of ecological subsystems.

5. Discussion

5.1. Research Progressiveness and Enlightenment

In comparison to existing literature [11], this study presents several advantages and contributions. Firstly, we have established a relatively comprehensive evaluation index system for regional agricultural Sustainable Ecological, Economic, and Social development. This index system encompasses three main systems: agricultural science and innovation, economy, and ecology. The evaluation index consists of factors such as agricultural science and technology expenditure, agricultural water pressure, and the proportion of agriculture, forestry, and fishery. Focusing on Shaanxi Province [26], it has noted a significant improvement in the comprehensive development level and coupling coordination of the three systems, economic development, scientific and technological innovation, and ecological environment, indicating a positive trend of steady improvement. However, with the modernization and digital transformation of agriculture, the sustainable development of agriculture relies heavily on the strong support of the agricultural social service system and scientific and technological innovation. Secondly, we have employed a data-driven approach to objectively measure, evaluate, and identify the coupling and coordinated development level of the regional agricultural "science and technology innovation-economy-ecology" system. The [41] study on the technological innovation efficiency and eco-economic efficiency of Beijing–Tianjin–Hebei revealed that the growth rate of eco-economic efficiency was significantly lower than that of technological innovation efficiency. Finally, the paper proposes several policy suggestions to promote the green and sustainable development of the Yangtze River Basin, which holds great significance for the coupling and coordination research of the three agricultural systems, "science and technology innovation, economy, and ecology" in the Yangtze River Basin. In summary, we have gained the following management insights: the scientific and technological innovation of traditional agriculture is a double-edged sword. While it promotes the development of the agricultural economy, the use of fertilizers, pesticides, and other achievements has also brought irreversible negative impacts and damage to the ecological environment. From the perspective of system theory and overall optimization, promoting the coordinated development of the three systems of agricultural science and innovation, economy, and ecology, harnessing the mutual support of these systems can effectively advance the green and sustainable development of agriculture. This approach can also aid in accelerating the development of the agricultural economy in the Yangtze River basin, effectively protecting the ecological environment, and realizing scientific and technological innovation to promote the green and high-quality development of agriculture. Furthermore, it can provide inspiration for China to achieve the scientific and technological development of agriculture and build itself as an agricultural power.

5.2. Analysis Result

According to the analysis of the comprehensive level index of agricultural science and innovation, it is evident that there is a consistent upward trend in the Yangtze River Basin from 2010 to 2021, with an increase of 0.261. However, the growth rate varies significantly across three development stages: 2010–2015, 2016–2018, and 2019–2021. The first stage exhibits a slow growth rate, the second stage demonstrates a moderate growth rate, and the third stage shows the fastest growth rate. Looking at the subsystems, the input level of agricultural science and innovation (C1) steadily increases annually, the agricultural science and innovation environment (C2) displays an upward trend, and the agricultural science and innovation output (C3) shows an overall increasing trend, despite slight fluctuations. Tapping into the potential of the agricultural science and innovation system can effectively elevate the quality of agriculture in the Yangtze River basin.

The comprehensive level index of the agricultural economy in the Yangtze River Basin has shown an upward trend from 2010 to 2021, with an overall increase of 0.074. This period can be divided into two stages: 2010 to 2018 and 2019 to 2021. The first stage exhibited a slow growth rate, while the second stage showed a moderate growth rate. Analysis of the three subsystems reveals that the agricultural economics scale (C4) experienced an upward trend, the agricultural economics composition (C5) fluctuated, and the agricultural economics efficiency (C6) demonstrated a linear growth trend. It is worth noting that the agricultural economic system’s development lags behind the rapid progress in agricultural science and innovation.

The comprehensive agro-ecological level index suggests that the overall agro-ecological comprehensive level index of the Yangtze River Basin will experience significant fluctuations from 2010 to 2021, with an increase of 0.293. This period can be divided into three distinct stages: The first stage (2010–2012) saw slow but steady growth, the second stage (2013–2016) showed moderate progress, and the third stage (2017–2021) exhibited the fastest growth. Upon analyzing its corresponding three subsystems, it was observed that the agro-ecological pressure (C7) and agro-ecological endowment (C9) subsystems underwent significant fluctuations. These changes were attributed to the rapid development of the agricultural economy, leading to increased usage of agricultural plastic film, higher rural electricity consumption, and elevated agro-ecological environmental pressure.

The assessment of the coupling coordination degree of agricultural SEECS in the Yangtze River Basin from 2010 to 2021 revealed the following results: the coupling degree among these subsystems is close to 1, indicating a high level of interaction and correlation. There is a rising trend in the coupling degree, demonstrating strong interconnections among the subsystems. The spatial distribution of the agricultural SEECS in the Yangtze River Basin shows a gradual decrease from east to west, characterized by “high coupling and low coordination”. The coordination degree between science and innovation and ecological, economic, and ecological systems requires improvement. The regional spatial differences in the coupling coordination degrees of the three systems illustrate that rural innovation, agricultural economy, and agricultural ecology are interdependent, both promoting and hampering each other. The overall spatial difference in the coupling coordination degree of the three systems has been decreasing, and the gap between provinces has significantly narrowed. These findings suggest that the implementation of a regional coordinated development strategy in the Yangtze River Basin is yielding positive results.

The research findings on the degree of obstacles to agricultural SEECS in the Yangtze River Basin from 2010 to 2021 indicate significant variations in their obstruction levels to coordinated development. The average obstacle degree ranking of the primary indicators is B3 > B1 > B2, whilst the secondary indicators' average obstacle degree ranking is C7 > C3 > C5 > C4 > C2 > C1 > C8 > C9 > C6.

5.3. Countermeasures and Suggestions

This study examines the 19 provinces in China's Yangtze River Basin, using methods such as the entropy method, coupling degree model, coupling coordination degree model, and coupling coordination obstacle degree model to construct an evaluation index system for the coupling of agricultural technological innovation, agricultural economy, and agricultural ecology. The analysis was conducted on raw data from 2010 to 2021. Based on this research, the data analysis reveals that the eastern provinces in the Yangtze River Basin have higher levels of coupling coordination, while the western provinces exhibit lower levels. The spatial differences in coupling coordination among the three systems primarily stem from the uneven development within the provinces. Consequently, several recommendations have been proposed based on the research findings.

Improving the agricultural science and technology innovation system to promote green and efficient agricultural technology research and development.

In pursuit of promoting the high-quality development of the agricultural economy and attaining high-level protection of the agricultural ecological environment, our focus is on the continual enhancement of the agricultural science and technology innovation system. Initially, our endeavor is to discern the critical issues within agricultural scientific and technological innovation. This necessitates a comprehensive assessment of the scientific and technological deficiencies, impediments, and challenges in the advancement of green and efficient agriculture. Subsequently, we are committed to prioritizing and targeting the development of new green pesticides, degradable agricultural film, and other research and development projects to effectively address these issues. Notably, the Netherlands has achieved year-round stable crop production through advanced greenhouse agriculture, thereby augmenting resource efficiency with automation, control systems, and climate-smart technologies. Similarly, precision agriculture in the United States integrates satellite positioning, sensor technology, and data analytics to enable precise fertilization and irrigation based on soil and climate conditions, thereby reducing resource wastage and enhancing yields. Moreover, we are dedicated to reinforcing collaborative research in agricultural scientific and technological innovation. This involves enhancing the transformation of scientific and technological accomplishments, establishing platforms for their transformation, simplifying the process, and providing technology transfer and market docking services. Furthermore, we aspire to incentivize green agricultural technologies that have undergone successful transformation, thereby stimulating the enthusiasm of scientific researchers. Additionally, we encourage cooperation among diverse regions, higher education institutions, research institutes, enterprises, and other departments to conduct joint technology research and development and transform results. This will facilitate the integration of agricultural science and technology innovation resources across regions and departments, leveraging respective advantages to address key issues in green and efficient agricultural science and technology. Furthermore, we are committed to amplifying investment in agricultural scientific and technological innovation. For instance, in response to water scarcity, Israel has developed advanced drip irrigation technology to enhance water use efficiency in arid areas. We aim to bolster government financial support for agricultural science and technology research and development while leading demonstrations and establishing a dedicated fund for the research and development of green agricultural technology. This will encourage widespread participation of social funds and provide financial guarantees for green and efficient agricultural science and technology innovation and research and development. Additionally, we seek to refine the incentive mechanism for agricultural scientific and technological innovation. This entails establishing an agricultural science and technology innovation performance evaluation system to regularly assess project progress and efficacy, and make corresponding financial support and policy adjustments. Furthermore, we are committed to fully implementing a system for revealing and ranking leaders, commending and rewarding outstanding scientific research teams and individuals, and increasing the share of profits from the transformation of scientific and technological achievements for researchers. This will attract exceptional talent to engage in green and efficient agricultural scientific and technological innovation, fostering internal motivation. Lastly, we aim to optimize the oversight mechanism for agricultural scientific and technological innovation. We intend to align the management and evaluation process of green and efficient agricultural science and technology innovation projects with science and technology output performance. This will involve streamlining the intricate management and evaluation processes, thereby allowing researchers to dedicate more time and effort to research and development activities.

Accelerate the transformation and upgrading of modern agriculture to achieve green and high-quality development of the agricultural economy.

The advancement of agriculture and green agriculture through the application of science and technology is imperative to facilitate the transformation and modernization of agricultural practices, fostering intensive, large-scale, rational, and efficient agricultural development. To commence, we emphasize supply-side reform as the catalyst to expedite the establishment of a modern agricultural industrial system. It is essential for localities to align with evolving market demands for high-quality agricultural products, necessitating specific market channels, consumer groups, and increased capital investment. Fluctuations in market demand and insufficient income to cover costs may result in sales difficulties and economic losses for farmers. Therefore, it is paramount to adhere to the principles of diversity, complementarity, and circularity, effectively combining agricultural structure adjustment with the cultivation of characteristic and advantageous industries. This approach involves tailored adjustments to the internal structure of planting, animal husbandry, and fishery in accordance with local conditions, thereby promoting holistic development encompassing grain, economy, and feed. Integration across agriculture, animal husbandry, and fishery, as well as between planting and cultivation, and the comprehensive development of the primary, secondary, and tertiary industries will extend the industrial and value chain, ultimately refining the agricultural industrial structure and enhance economic, ecological, and social benefits. Secondly, we are committed to expediting the establishment of a modern agricultural production system, underpinned by a proficient workforce and advanced technical equipment. Accelerated cultivation of new professional farmers equipped with cultural knowledge, high skill levels, and robust innovation and entrepreneurship capabilities is imperative. The incorporation of the Internet of Things, artificial intelligence, and big data technology will facilitate the establishment of an intelligent agricultural management system, enhancing agricultural production efficiency. Encouraging the deployment of modern equipment such as drones and intelligent irrigation systems will serve to modernize agricultural practices, elevating the level of improved agricultural varieties, mechanization, science and technology, and information technology. This shift from resource-dependent practices to scientific and technological innovation endeavors to improve agricultural resource utilization, land yield, and labor productivity, promoting organic and ecological agriculture, reducing the use of fertilizers and pesticides, and enhancing soil health. Finally, our emphasis on land system and production organization innovation seeks to accelerate the establishment of a modern agricultural management system. Supporting the development of farmers' cooperatives and family farms to achieve large-scale and intensive operations, providing training and services, and enhancing farmers' organizational capacity and market competitiveness are key priorities. Innovations in land transfer, land treatment, and land ownership will promote the collective development of family management, collective management, cooperative management, and enterprise management. Cultivating finance, information, agricultural machinery, and technical services as service entities, and exploring cooperation models across different business entities such as "company + base + farmer", "supermarket + base + farmer", and "technology company + base + cooperative" are integral to our endeavors.

Actively fostering comprehensive cooperative relations between production, supply and marketing, credit, and e-commerce, and developing various forms of appropriate scale operations, are core components of our strategy. Fourth, expedite the establishment of a modern agricultural market system by prioritizing brand development and market expansion. This entails identifying the core values and characteristics of the brand in line with the demands of the target market, with a focus on highlighting organic, ecological, or local attributes. A strong brand image can enhance the value of agricultural products, enabling green agricultural products to distinguish themselves in the competitive market while bolstering consumer awareness and loyalty. Furthermore, proactive participation in agricultural exhibitions and food fairs is essential for showcasing the brand image and directly engaging with consumers and buyers. In addition, diversifying sales channels, including traditional markets and online e-commerce platforms, is crucial to broadening market access. Fifth, it is imperative to fortify environmental conservation and resource management while expediting the establishment of a modern agricultural resource system. This involves implementing efficient irrigation systems and promoting water-saving irrigation technologies such as drip irrigation and spray irrigation to optimize water usage and minimize waste. Moreover, advocating for the construction of rainwater harvesting systems can reduce reliance on groundwater and surface water, thereby enhancing water resource sustainability. Regular soil testing is essential for gauging nutrient composition and pollution levels, informing tailored soil improvement initiatives. Furthermore, raising farmers' awareness of environmental protection and resource management through diverse channels and encouraging the adoption of environmental preservation measures is crucial. Additionally, organizing regular agricultural technology training programs to promote green production methods and resource management techniques is vital for enhancing farmers' practical capabilities.

Strengthening agricultural ecological environment protection to solidify the foundation for healthy and sustainable agricultural development.

Ensure the prioritization of agricultural ecological environmental protection and the advancement of green agricultural scientific and technological innovation and economic development. Firstly, we will enhance the legal framework for safeguarding the agricultural ecological environment. This will involve addressing fundamental issues such as responsibility for protection and methods of protection, defining the environmental protection principles for agricultural production, establishing relevant legal obligations, reviewing policies and regulations on agricultural ecological environmental protection, and developing a comprehensive, rational, scientific, standardized, and effective legal system for agro-ecological environmental protection. Industry standards for organic agriculture and eco-agriculture will be developed and promoted to ensure product quality and environmental friendliness, and to provide legal and regulatory support for strengthening agro-ecological environmental protection, advancing green agricultural science and technology, and fostering eco-circular agriculture. Secondly, we will intensify public awareness and education on agricultural ecological environmental protection. This will involve collaboration with schools, businesses, associations, and other entities to conduct widespread public awareness campaigns through online and offline channels. Regular lectures will be organized in communities, schools, and farmer communities, inviting experts and scholars to share successful practices and stories of ecological agriculture to enhance public understanding of ecological conservation. Additionally, we will strengthen ecological environment education and green technology training to empower agricultural producers with ecological knowledge and green technology, creating a scenario where everyone is aware of and utilizes agricultural ecological environmental protection. Thirdly, we will enhance policy support and incentive mechanisms. Governments will offer direct financial subsidies for eco-agriculture projects to encourage farmers to adopt sustainable agricultural practices and establish a special ecological agriculture development fund to provide financial support for the promotion of ecological agriculture technologies. Tax relief for farmers and enterprises that adopt ecological agriculture technology, such as reducing value-added tax and income tax, will be provided to incentivize more participation in ecological agriculture construction. Fourthly, we will reinforce supervision and management of agricultural ecological and environmental protection. This will involve establishing an efficient agro-ecological environment supervision mechanism, delineating and managing ecological red lines and arable land red lines, protecting important biological habitats, integrating resources, and improving resource utilization efficiency. Efforts will be made to prevent and control pollution from non-point agricultural sources, improve the quality and safety of agricultural products, and establish a complete system of standards covering soil management, water resources utilization, crop cultivation, and disease and pest control to ensure appropriate norms and requirements in all aspects. Regular evaluation of the implementation effect of ecological agriculture standards will be conducted to promote the healthy and sustainable development of agriculture.

6. Conclusions

The framework of "science and innovation-economy-ecology" in agriculture represents a dynamic development process, with each element being influenced by a variety of complex factors that interact with one another. Over time, agricultural science and innovation have played a central role in advancing the agricultural economy. However, this progress has also led to increased consumption of ecological resources, placing greater pressure on agricultural ecology. As the agricultural economy invests more in agricultural science and innovation and ecological resources, it positively impacts the environmental aspects of agricultural science and innovation, thereby mitigating the strain on agricultural ecology. The agro-ecological environment serves as a conducive backdrop for driving agricultural innovation and achieving sustainable economic development. Agricultural science and innovation must promote green and high-quality economic and ecological development, promoting agricultural sustainability. This study suggests that leveraging agricultural scientific and technological innovation can drive improvements in agricultural economic efficiency, while effectively enhancing the ecological environment, ultimately leading to a mutually beneficial outcome. Hence, a complex interdependent relationship exists among these three interconnected systems.

Firstly, in this study, the evaluation of the agricultural science and innovation system in the Yangtze River Basin is centered around three main aspects: science and innovation, economy, and ecology. The study takes into account factors such as agricultural science and technology expenditures, agricultural water pressure, and the proportion of agriculture, forestry, and fishery to enrich the understanding of agricultural systems. The study uses a coupled coordination degree model to calculate the development of agricultural systems in the Yangtze River basin and identifies key constraints through the obstacle degree model. This provides a quantitative basis for targeted regional agricultural policies. However, the comprehensiveness and accuracy of the indicator system need improvement, and future research should focus on enriching the index of the agricultural science and innovation system. Secondly, the research also uses data-driven methods based on regional agricultural development data to measure the level of coupling and coordination, providing methodological support for quantitative evaluation. By screening the key constraints through the obstacle model, the study reveals the influence of each factor on the development of the agricultural complex system, providing a quantitative basis for the design of targeted regional agricultural policies. Third, the results of the research can inspire China to realize agricultural development through science and technology, improve the efficiency of agricultural resource utilization, and provide new ideas for the research of regional agricultural integrated systems. However, it is important to note that the comprehensiveness and accuracy of the index system need to be improved, with a focus on enriching the index of the agricultural science and innovation system and improving the accuracy of evaluation results in future research.

In this study, we take the Yangtze River Basin as a case study, this research employs an evaluation framework centered on the agricultural science and technology innovation system to construct an assessment index system for the coupling and coordinated development of the farming agricultural SEECS in the Yangtze River Basin. Utilizing a coupling coordination degree model, the study calculates the status of agricultural SEECS coupling and coordinated development in the basin. The analysis further employs an obstacle degree model to identify key constraints and reveal the impact of various factors on the coupling and coordination of agricultural SEECS development. This provides a quantitative basis for region-specific agrarian policy-making. However, the comprehensive nature and accuracy of the indicator system require enhancement, given that regional agricultural systems encompass multiple subsystems and datasets. Expanding the scope to a national level and incorporating indices such as agricultural carbon emissions and non-point source pollution within the farming ecosystem would improve the accuracy of the evaluation results, thus enhancing the representativeness and value of the research.

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